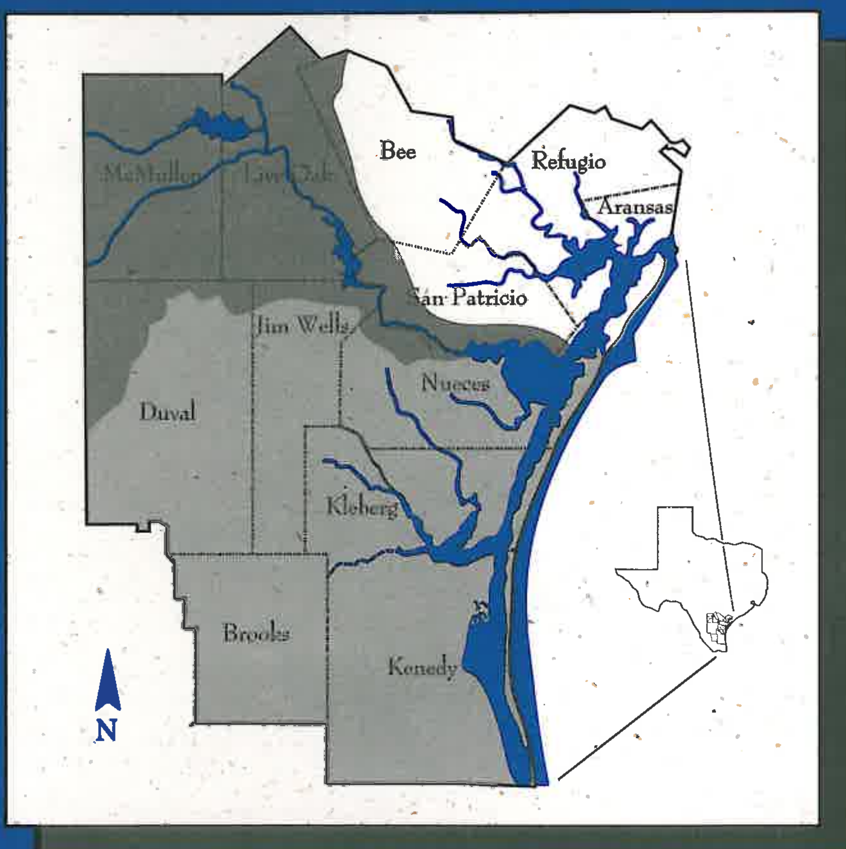
Process and Trends of Circulation Within the Corpus Christi Bay National Estuary Program Study Area

Publication CCBNEP – 21
November 1997

George H. Ward
Center for Research in Water Resources
University of Texas at Austin

Submitted to:
Coastal Bend Bays & Estuaries Program
1305 N. Shoreline Blvd. Ste 205
Corpus Christi, Texas 78401

Processes and Trends of Circulation Within the Corpus Christi Bay National Estuary Program Study Area



Corpus Christi Bay National Estuary Program
CCBNEP-21 • November 1997

This project has been funded in part by the United States Environmental Protection Agency under assistance agreement #CE-9963-01-2 to the Texas Natural Resource Conservation Commission. The contents of this document do not necessarily represent the views of the United States Environmental Protection Agency or the Texas Natural Resource Conservation Commission, nor do the contents of this document necessarily constitute the views or policy of the Corpus Christi Bay National Estuary Program Management Conference or its members. The information presented is intended to provide background information, including the professional opinion of the authors, for the Management Conference deliberations while drafting official policy in the Comprehensive Conservation and Management Plan (CCMP). The mention of trade names or commercial products does not in any way constitute an endorsement or recommendation for use.

Processes and Trends of Circulation Within the Corpus Christi Bay National Estuary Program Study Area

George H. Ward
Principal Investigator

Center for Research in Water Resources
The University of Texas at Austin
J.J. Pickle Research Campus
10100 Burnet Road, Bldg. 119
Austin, Texas 78758-4497
512/471-3131
Fax: 512/471-0072

Publication CCBNEP-21
November 1997

Natural Resources Center, Suite 3300, TAMU-CC • 6300 Ocean Drive • Corpus Christi, TX 78412
512/980-3420 • FAX 512/980-3437 • CCBNEP home page: //www.sci.tamucc.edu/ccbnep

Published and distributed
by the
Texas Natural Resource Conservation Commission
Post Office Box 13087
Austin, Texas 78711-3087

CORPUS CHRISTI BAY NATIONAL ESTUARY PROGRAM

The Corpus Christi Bay National Estuary Program (CCBNEP) is a four-year, community based effort to identify the problems facing the bays and estuaries of the Coastal Bend, and to develop a long-range, Comprehensive Conservation and Management Plan. The Program's fundamental purpose is to protect, restore, or enhance the quality of water, sediments, and living resources found within the 600 square mile estuarine portion of the study area.

The Coastal Bend bay system is one of 28 estuaries that have been designated as an **Estuary of National Significance** under a program established by the United States Congress through the Water Quality Act of 1987. This bay system was so designated in 1992 because of its benefits to Texas and the nation. For example:

- Corpus Christi Bay is the gateway to the nation's sixth largest port, and home to the third largest refinery and petrochemical complex. The Port generates over $1 billion of revenue for related businesses, more than $60 million in state and local taxes, and more than 31,000 jobs for Coastal Bend residents.
- The bays and estuaries are famous for their recreational and commercial fisheries production. A study by Texas Agricultural Experiment Station in 1987 found that these industries, along with other recreational activities, contributed nearly $760 million to the local economy, with a statewide impact of $1.3 billion, that year.
- Of the approximately 100 estuaries around the nation, the Coastal Bend ranks fourth in agricultural acreage. Row crops -- cotton, sorghum, and corn -- and livestock generated $480 million in 1994 with a statewide economic impact of $1.6 billion.
- There are over 3200 documented species of plants and animals in the Coastal Bend, including several species that are classified as endangered or threatened. Nearly 500 bird species live in or pass through the region every year, making the Coastal Bend one of the premier bird watching spots in the world.

The CCBNEP is gathering new and historical data to understand environmental status and trends in the bay ecosystem, determine sources of pollution, causes of habitat declines and risks to human health, and to identify specific management actions to be implemented over the course of several years. The 'priority issues' under investigation include:

- altered freshwater inflow
- declines in living resources
- loss of wetlands and other habitats
- bay debris
- degradation of water quality
- altered estuarine circulation
- selected public health issues

The **COASTAL BEND BAYS PLAN** that will result from these efforts will be the beginning of a well-coordinated and goal-directed future for this regional resource.

STUDY AREA DESCRIPTION

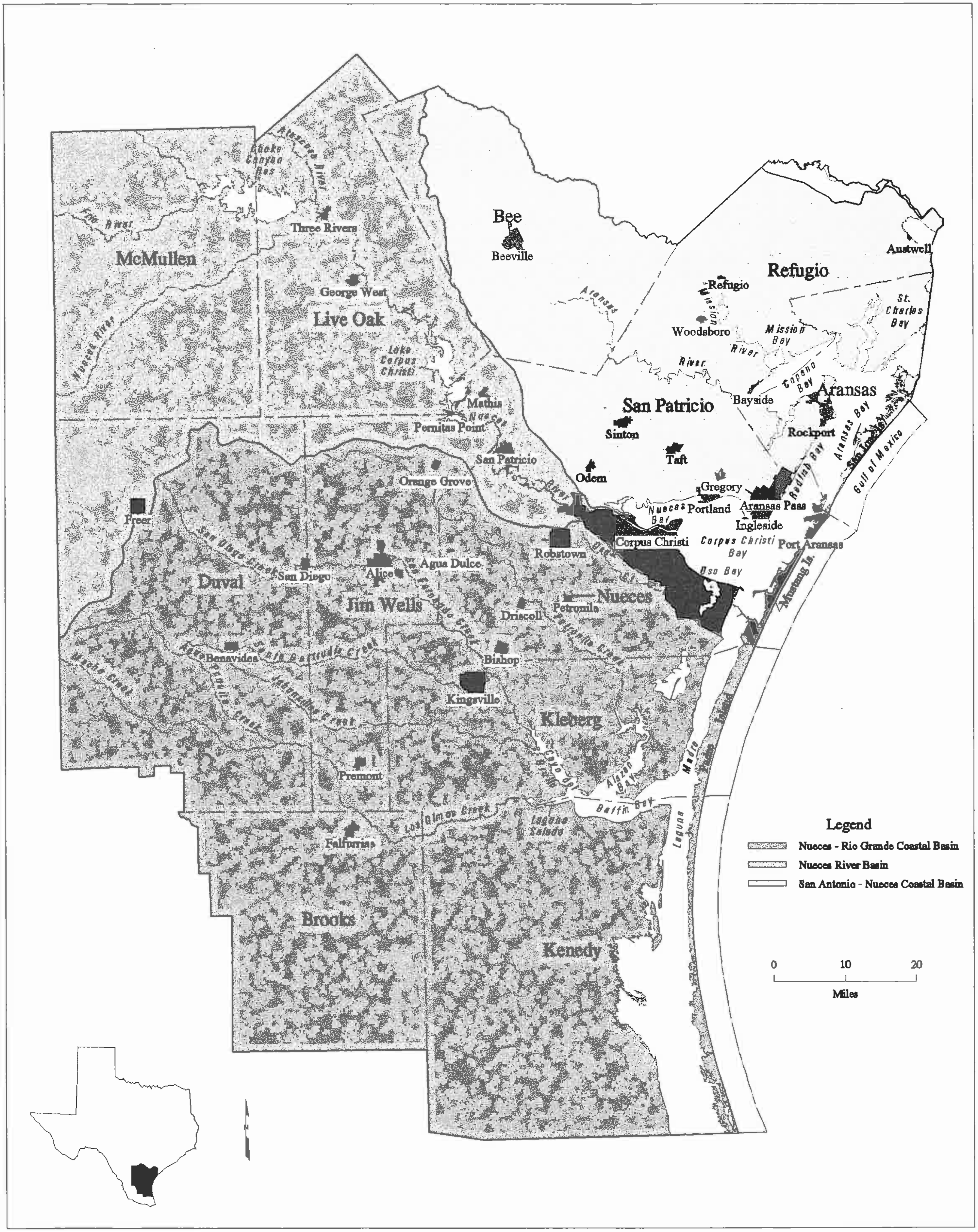
The CCBNEP study area includes three of the seven major estuary systems of the Texas Gulf Coast. These estuaries, the Aransas, Corpus Christi, and Upper Laguna Madre are shallow and biologically productive. Although connected, the estuaries are biogeographically distinct and increase in salinity from north to south. The Laguna Madre is unusual in being only one of three hypersaline lagoon systems in the world. The study area is bounded on its eastern edge by a series of barrier islands, including the world's longest -- Padre Island.

Recognizing that successful management of coastal waters requires an ecosystems approach and careful consideration of all sources of pollutants, the CCBNEP study area includes the 12 counties of the Coastal Bend: Refugio, Aransas, Nueces, San Patricio, Kleberg, Kenedy, Bee, Live Oak, McMullen, Duval, Jim Wells, and Brooks.

This region is part of the Gulf Coast and South Texas Plain which are characterized by gently sloping plains. Soils are generally clay to sandy loams. There are three major rivers (Aransas, Mission, and Nueces), few natural lakes, and two reservoirs (Lake Corpus Christi and Choke Canyon Reservoir) in the region. The natural vegetation is a mixture of coastal prairie and mesquite chaparral savanna. Land use is largely devoted to rangeland (61%), with cropland and pastureland (27%) and other mixed uses (12%)

The region is semi-arid with a subtropical climate (average annual rainfall varies from 25 to 38 inches, and is highly variable from year to year). Summers are hot and humid, while winters are generally mild with occasional freezes. Hurricanes and tropical storms periodically affect the region.

On the following page is a regional map showing the three bay systems that comprise the CCBNEP study area.



Corpus Christi Bay National Estuary Program Study Area

PROCESSES AND TRENDS OF CIRCULATION WITHIN THE CCBNEP STUDY AREA

Principal Investigator:

George H. Ward
Center for Research in Water Resources
The University of Texas at Austin

EXECUTIVE SUMMARY

The movement of water in an estuary and the hydrodynamic processes producing that movement are referred to collectively as "circulation." From the standpoint of management of the Corpus Christi Bay environment, the primary importance of circulation is in the transport of waterborne parameters. When management actions devolve to achieving a desirable concentration range of some waterborne parameter, almost always the governing circulation processes must first be identified and quantified. The prime objective of this study is characterization of the spatial variation and temporal trends of estuarine circulation within the Corpus Christi Bay National Estuary Program (CCBNEP) study area, using an approach of inferring the nature of circulation and transport processes from a hydrographic history of the Corpus Christi Bay system.

At its largest scale, the CCBNEP study area is comprised of half a dozen shallow basins, interconnected by highly constricted conduits. This basic morphology underlies much of the hydrodynamic behavior of the system. An important class of forcings are those that result in transport of water between the basins, most important of which is the differences in water levels between the basins, which drive flows through the conduits. There are two primary sources of water-level variation driving exchange between the bays and the Gulf of Mexico: periodicities which are primarily of tidal origin and synoptic-scale meteorological disturbances which are nonperiodic except for the annual cycle of climatology.

With respect to tidal periodicities, in the Gulf of Mexico the astronomical tide is dominated by three main components: the 12.4-hour semidiurnal and 24.8-hour lunar diurnal tides, and the 13.6-day fortnightly cycle in the magnitude of declination of the moon. The relative importance of these three components changes with passage through the connecting conduits: the slower, longer-period variations are passed through but the shorter-period variations are significantly filtered out, in other words, the basins act as stilling wells. The most quickly changing tidal component, the 12.4-hr semidiurnal only barely leaks through Aransas Pass, so the interior tide becomes even more dominated by the 24.8-hr signal (which is itself severely attenuated) and the 13.6-day fortnightly signal. After the signal propagates through several such connections to the interior basins of Copano, Nueces and the Upper Laguna, the main tidal variation that survives is the fortnightly, tracking the declination of the moon.

There is an even slower, poorly understood change in Gulf water levels that is transmitted into the bays, practically unattenuated, namely the secular semi-annual rise and fall. This is quasi-periodic, with maxima in spring and fall, and minima in winter and summer. But this semi-annual variation exhibits considerable year-to-year differences, both in timing of when the seasonal extremes occur and in their magnitudes. The fall maximum is usually the highest level that water normally attains, and the winter minimum the lowest, though the summer minimum is most dependable in its date of occurrence.

Frontal passages produce water-level variations and accompanying transports of water. The primary mechanism is the change in direct wind stress on the water surface. As the front approaches the coastline, onshore wind flow is increased, setting up water levels along the coastline. With the frontal passage, winds turn abruptly to the northern quadrant, reversing the direction of stress. The area over which the winds operate and their duration are both important in the magnitude of the response. There is a direct downwind set-up of water levels across a component bay, and there is an indirect water exchange caused by a frontal-induced water-level difference between basins. By far, the most important is the exchange between the study area bays and the adjacent Gulf of Mexico. Two classes of fronts were studied: the relatively short-lived low-energy "equinoctial" frontal passages, that do not force a response in the large waterbody of the Gulf; and the large-scale, longer duration "outbreak" fronts that result in exchange between the Gulf and the interior bays. The frontal response of the Gulf of Mexico is the single most important factor determining the total response of the bay.

The sudden change in surface wind stress that occurs during a frontal passage produces a direct set-up across the bay and an associated cross-bay transport. This response is virtually immediate, the water surface tracking closely the direction and speed of wind. The cross-bay transports are about the same magnitude for both equinoctial and polar-outbreak fronts. However, the volume of water exchanged is much greater for the polar-outbreak fronts since a response to the Gulf is involved. This is on the same order as the great declination tide, and for the outer bays (Copano, Nueces, Upper Laguna) is generally larger than the great-declination tide. The cross-bay transports occur much more quickly but entail smaller water-level changes and smaller volumes. These volumes are generally on the order of 1% of the volume of the bay. The exception is the Upper Laguna, which is an extremely shallow system whose axis aligns with frontal northerly winds, for which the transport is 10% of the volume and the direction of transport is down the longitudinal axis of the system.

Based upon the prism (the volume of water from low stage to high stage transported into the bay from the larger basin, ultimately the Gulf) of each of these exchange events, and the time period over which this transport occurs, the main conclusions are: (1) for each time scale the volume of water exchanged diminishes with distance from the Gulf; (2) the seasonal variation is much larger in volume exchanged than the diurnal and fortnightly (which includes outbreak fronts); however, in terms of the rate of exchange, i.e. volume per unit time, the diurnal tide is greatest; (3) the volumes involved are on the order of, or less than, 10% of the volume of the bay. The prominent exceptions to the last conclusion are the shallow bays of Nueces and the Upper Laguna, for which the volume exchanged is an appreciable fraction of the total volume of the system. For the

Laguna in particular, the seasonal exchange of volume is approximately equal to its low-tide volume.

Another source of water exchange is the throughflow imposed on the bay system. By far, the most important throughflow is due to freshwater inflow from the drainageways of the watersheds, governed by the regional hydroclimatology. There are also two forced throughflows due to cooling-water circulation of power plants, which are geographically restricted and affect only a relatively small portion of the systems in which they are imposed.

By estuarine standards, the long-term average freshwater throughflow is small in the Corpus Christi Bay system: the freshwater replacement time for the system of about 50 months. There is a substantial gradient in hydroclimatology across the system, with decreasing inflow and increasing evaporative deficit with distance south. The large evaporative deficit at the surface is an important part of the freshwater budget, more than doubling the freshwater replacement time. (There is another potential source of inflow not accounted for, from the San Antonio Bay system through Ayres Bay, so the hydroclimatological gradient, if anything, is understated.) The inflow history of the system can be succinctly described as widely spaced, large influx events, on the order of the volume of the system, superposed on a chronic continuing inflow deficit. On a long-term basis, the diversions for human use have been non-negligible but minor compared to the natural watershed inflows and evaporative losses. However, during the frequent droughts, which are endemic to the region, the relative importance of the diversions becomes much greater.

In summary, there are two separate classes of water-volume transport affecting the Coastal Bend bays: the bi-directional exchange between the basins of the system, and the unidirectional throughflow forced by influxes and surface losses. These can represent either a displacement or a dilution of water in a basin; which of these depends upon the volume and time-scale of the exchange in comparison to the rate of internal mixing. By "internal mixing" is meant movement and exchange of water masses within a component bay. In Corpus Christi Bay, these are mainly due to small-scale turbulence, movement of water across the bay forced by frontal passages, and circulation gyres, spun up primarily by sustained winds. There is some indication of a double wind-driven gyre in the main body of Corpus Christi Bay, counterclockwise in the southern segment and clockwise in the northern. Horizontal mixing in Corpus Christi Bay by these processes is rather slow, requiring many tens of days to mix out a steep gradient. Mixing processes in the vertical are sufficiently intense that vertical stratification in waterborne parameters is minimal. Though the rate of water movement is less for the semifortnightly and seasonal prisms, the duration of time over which this new water is in the component bay would allow more mixing with resident waters. Thus these exchanges are viewed as representing more true dilution capability, in contrast to the shorter term diurnal tide and frontal set-ups which effect only water-mass displacement. The shallow systems of Nueces Bay and the Upper Laguna, in particular, would be effectively diluted by the seasonal secular variation.

The principal physical modifications to the system over the past century have been enlargement and/or closure of inlets, channelization, dredged material disposal and hydraulic fill, shell dredging, construction of barriers to flow and exchange, and construction of dams on the rivers. Stabilization of Aransas Pass for navigation dates from approximately 1880, with the modern jetty systems being completed by 1916. This probably increased the tidal prism by about 10%. The deepdraft project to Corpus Christi began in 1926 and has been incremented since then through 1980 at a nearly constant volumetric rate in time. The GIWW across the upper bays was completed in 1945. This channel through the Upper Laguna Madre and across the Mud Flats was completed in 1949. Overall, the major channel systems represent a re-configuring of about 10% of the volume of the system. "Re-configuring" is used, because the dredged material is not removed from the system, but discharged largely to unconfined disposal areas adjacent to the channels.

The single most significant physical modification to the Corpus Christi system in terms of its circulation was not the stabilization and jettying of the inlet, or the dredging of a deep channel across the midsection of the bay, or the installation of barriers, but rather the opening of the Turtle Cove mudflats to deepdraft dimensions in 1925-26. These mudflats, lying between Harbor Island and Mustang Island, historically were a barrier to exchange between Aransas Pass and Corpus Christi Bay. The main tidal communication was with the upper system of Aransas-Copano, as evidenced by deep scouring in Lydia Ann Channel, and the navigational superiority of the Aransas-Copano system (versus Corpus Christi Bay) in the Nineteenth Century. Very little diurnal tide would have been capable of passing the Turtle Cove/Redfish Bay flats into Corpus Christi Bay. Once this passage was opened, however, the tidal behavior became more like the modern system, in which Corpus Christi Bay is the primary co-oscillating basin, and tidal propagation into Aransas and Copano is attenuated and lagged.

There is no evidence that the modification to the Aransas Pass-Turtle Cove inlet to Corpus Christi Bay was responsible for the closure of Corpus Christi Pass. This appears, rather, to have been a natural event, probably due to the southward convergence of littoral drift along the Gulf shoreface. This same proclivity to shoaling has doomed other artificial inlet projects along lower Mustang Island and upper Padre Island. Moreover, these "exchange" passes—when open—have accomplished very little exchange between the Gulf and the interior bay, due to their small cross section.

The Corpus Christi Inner Harbor evolved over the period 1925-1960 as a series of turning basins and connecting canals. The most important physical modification associated with this was the "reclamation" of shallow water along the south shore of Nueces Bay. Approximately 15% of the area of Nueces Bay has been converted to fast land. Nueces Bay was also the main focus of commercial shell dredging activity in the study area, dating back to the operation of the Southern Alkali plant at Avery Point in 1934. A volume of mudshell equal to about 50% of the volume of Nueces Bay has been removed, mainly in the period 1950-68. One of the steam-electric station throughflows has operated in Nueces Bay since the 1930's, circulating water from the main turning basin and therefore upper Corpus

Christi Bay to the southeast corner of Nueces Bay; since the mid-1960's the circulating rate has been equivalent to 100% of the volume of Nueces Bay per month.

Circulation changes in the Upper Laguna Madre are difficult to sort out. Installation of a major barrier, the JFK Causeway, occurred simultaneously with the dredging of the GIWW in 1949, generally viewed as an improvement to its circulation, which was accompanied by creation of another major barrier, the cordon of spoil banks and islands lying along the longitudinal axis of the Upper Laguna. On balance, it appears that opening the GIWW through Bulkhead Flats probably has improved exchange between Corpus Christi Bay and the Upper Laguna, despite the presence of the Causeway. Nor is there any evidence that the Causeway—with its inlets for the GIWW and Humble Channel—has reduced exchange compared to the natural constriction of Bulkhead Flats. Both of these inlets through the Causeway have scoured since 1949, a factor of two for the GIWW and a factor of four for the Humble Channel.

The most important effect of the GIWW is to facilitate admitting the longer-period components, especially the fortnightly exchanges and the secular seasonal variation. The GIWW transmits the seasonal rise through both the Bulkhead Flats and the Mud Flats barriers of the Upper Laguna with little attenuation, and appears to be almost as effective in transmitting the fortnightly prism, associated with lunar declination and outbreak fronts. These are on the order of 100% of the volume of the Upper Laguna, and their time frame is long enough that substantial mixing with resident water should be accomplished by internal processes. On the other hand, the GIWW is considered to be ineffective in transmitting shorter-term responses, i.e. tides and frontal set-up, both at the northern and southern ends of the Upper Laguna. Diurnal tides are virtually absent in the Laguna, and the response of water movement under a frontal passage appears to behave exactly as it did in the years before the GIWW was dredged. The Upper Laguna is the location of the second steam-electric throughflow in the system, in which cooling water is pumped from the Laguna and discharged to Oso Bay, thence back to lower Corpus Christi Bay. The circulation rate since the mid-1970's is equivalent to 65% of the Upper Laguna volume per month, though in fact confined to the northernmost section of the lagoon.

Two major reservoir projects have been implemented in the study area, both on the Nueces: Lake Corpus Christi in 1958 and Choke Canyon in 1982. These reservoirs have two impacts on flow in the Nueces: reduction in inflow and alteration of the time signal of inflow. The first is a consequence of their purpose of water supply, in that they allow a net consumption of freshwater, mainly due to diversions, but also due to evaporation and infiltration losses. Based upon recent rates of consumption, there is about a 15% net reduction in inflow (long-term average, and counting return flows) to Corpus Christi Bay *per se*. The second impact of the LCC/CC reservoirs is to produce a greatly smoothed time signal of freshwater inflow, with decreased freshet peaks, and increased hydrograph time bases. Peaked impulses of inflow are important to Corpus Christi Bay hydrography in two ways. First, they promote overbanking and flooding of the

Nueces delta. Under LCC operation, events that were large enough to result in significant inundation of the delta occurred only about once every two years. With Choke Canyon on line, this return frequency is estimated to increase to once every three years. Second, impulse freshets are more effective in salinity extrusion, because the bay water is replaced rather than diluted.

The traditional indicator of the effects of freshwater inflow on an estuary is the salinity regime. Quantification of the impact of these reservoirs from salinity observations in the system is difficult, however, because there are other factors which exert strong influences on salinity, including evaporation, exchange of water between the estuary and the Gulf, and–especially–highly variable hydroclimate of the watershed. In Nueces Bay, Corpus Christi Bay, and Copano Bay there are long-period increasing time trends in salinity and also long-period declining trends in inflow. Most of the inflow trend is considered to be hydroclimatological in origin, and the likely cause of the salinity trends. There is no indication from the analyses performed in this study that a salinity-driven density current operates in Corpus Christi Bay, at least frequently enough to influence large-scale exchange with the sea. This implies that the deepdraft channel has probably contributed little to the increasing trend in salinity. This conclusion is in marked contrast to the situation of the bays on the upper Texas coast, Matagorda, Galveston and Sabine Lake.

At the largest scale, one important aspect of Corpus Christi Bay circulation is that, in comparison to the bays on the upper Texas coast, it is not as well flushed and therefore has a greater tendency to concentrate waterborne substances. While the present level of loadings to the Corpus Christi system is much less than those to Sabine Lake or Galveston Bay, these flushing considerations suggest that a wasteload will have a magnified effect in the Corpus system because it is so relatively poorly flushed. Since Corpus Christi Bay is potentially more sensitive to wasteloads, prudence and vigilance in its management are necessary.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF FIGURES
(continued)

LIST OF FIGURES
(continued)

LIST OF TABLES

LIST OF TABLES
(continued)

ABBREVIATIONS AND ACRONYMS

ac-ft	acre-feet
API	American Petroleum Institute
BEG	Bureau of Economic Geology
BP	Before Present
CBI	Conrad Blucher Institute of TAMU–Corpus Christi
CCBNEP	Corpus Christi Bay National Estuary Program
CCBNEP WQ	Water and sediment quality project of CCBNEP
CCNC	Corpus Christi Navigation Company
CCSC	Corpus Christi Ship Channel
CDT	Central Daylight Time
cfd	cubic feet per day
cfs	cubic feet per second
CP&L	Central Power and Light
CST	Central Standard Time
cu m	cubic metres
cu yds	cubic yards
DMRP	Dredged Material Research Program, of USCE
DWT	dead weight tons
EH&A	Espey, Huston & Associates, Inc.
EPA	Environmental Protection Agency, also USEPA
FROPA	frontal passage
ft	feet
ftp	file transfer protocol
FY	fiscal year
GBNEP	Galveston Bay National Estuary Program
GIS	Geographical information system
GIWW	Gulf Intracoastal Waterway
GCM	General circulation model, global climate model
GOM	Gulf of Mexico
GMT	Greenwich Mean Time
ha	hectare
HBA	Harland Bartholomew and Associates
HDR	Henningson, Durham and Richardson, Inc.
HOR	Humble Oil & Refining Corp.
HSPF	Hydrological Simulation Program FORTRAN
in	(as abbreviation) inches
km	kilometres
LCC/CC	Lake Corpus Christi/Choke Canyon reservoir system
LNRA	Lower Nueces River Authority
m	metres
m^3s^{-1}	cubic metres per second
mb	millibar
Mcy	million cubic yards
MGD	million gallons per day
MLT	mean low tide
Mm^3	million cubic metres
MSI	Marine Science Institute of UTA

ABBREVIATIONS AND ACRONYMS (continued)

MSL	mean sea level
MW	megawatts
NAS	Naval Air Station
NCDC	National Climatic Data Center of NOAA
NEI	National Estuarine Inventory, of NOS
NGVD	National Geodetic Vertical Datum
NHC	National Hurricane Center of NOAA
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service of NOAA
P-E	Net of precipitation less evaporation
PI	Principal Investigator
ppm	parts per million
ppt	parts per thousand
r	linear correlation coefficient
RRF	River Reach File of EPA
SAAP RR	San Antonio Aransas Pass Railroad
SCS	Soil Conservation Service
SES	steam-electric station
SWRI	Southwest Research Institute
TAMU	Texas A&M University
TCOON	Texas Coastal Ocean Observation Network
TDWR	Texas Department of Water Resources
TGFOC	Texas Game, Fish and Oyster Commission
TNRCC	Texas Natural Resource Conservation Commission
TPWD	Texas Parks & Wildlife Department
TSS	total suspended solids
TWC	Texas Water Commission
TWDB	Texas Water Development Board
UCT	also UTC, Coordinated Universal Time
USCE	U.S. Corps of Engineers, U.S. Army Corps of Engineers, U.S. Army Engineer
USC&GS	U.S. Coast & Geodetic Survey
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency, also EPA
USF&WS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UTA	University of Texas at Austin
UTC	also UCT, Coordinated Universal Time
UTM-E or N	Universal Transverse Mercator, Easting or Northing
WPA	Works Projects Administration
Z	UCT, UTC, GMT

PREFACE

This report attempts to address the processes of circulation within Corpus Christi Bay from a historical perspective. It therefore has relied upon the information base compiled by other workers or made available through various agencies. The author is especially grateful to the following for generously providing data and information about the system:

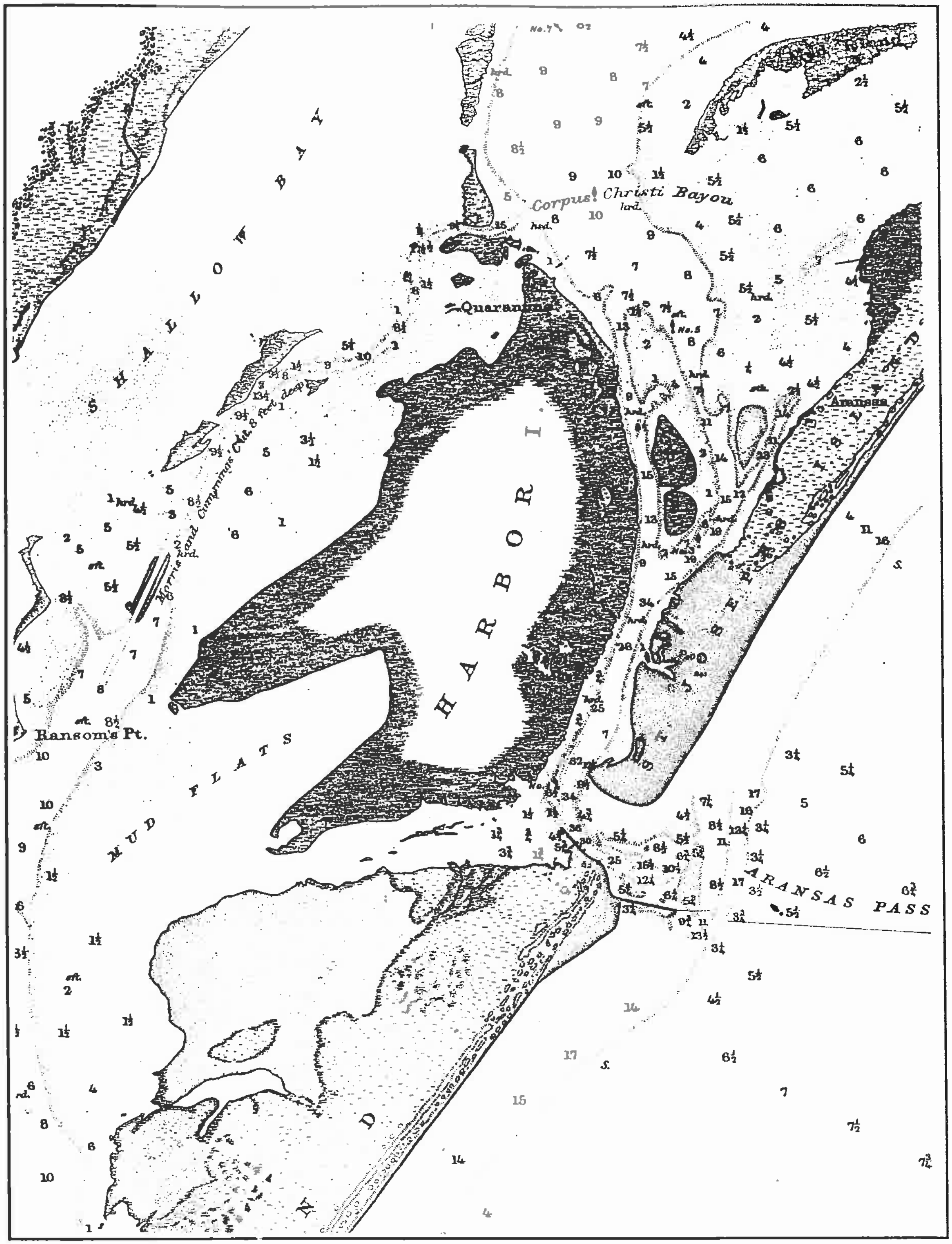
Ray Allen, Central Power and Light;
Neal Armstrong, University of Texas at Austin;
William Asquith, U.S. Geological Survey;
Bill Behrens, University of Texas at Austin;
David Brock, Bays and Estuaries Program, Texas Water Development Board;
John Buckner, Coastal Bend Council of Governments;
Paul Carangelo, Port of Corpus Christi Authority;
B.J. Copeland, North Carolina State University;
Rocky Freund, Conrad Blucher Institute of Texas A&M—Corpus Christi;
Al Green, Texas Parks and Wildlife;
Robert Hauch, Galveston District Corps of Engineers;
Martin Howland, Galveston District Corps of Engineers;
Marshall Jennings, U.S. Geological Survey;
Bill Longley, Bays and Estuaries Program, Texas Water Development Board;
Larry McEachron, Texas Parks and Wildlife;
Paul Montagna, Marine Science Institute, University of Texas;
Bob Morton, Bureau of Economic Geology, University of Texas;
Greg Mosier, U.S. Geological Survey;
Bruce Moulton, Texas Natural Resource Conservation Commission;
Paul Orlando, National Ocean Service
Mike Speed, Conrad Blucher Institute of Texas A&M—Corpus Christi (now at Texas A&M University, College Station);
Sid Tanner, Galveston District Corps of Engineers;
Terry Whitledge, Marine Science Institute, University of Texas.

This is a project that, in many respects, got out of hand. By its nature, the subject matter is a morass of disparate and recondite detail, that first must be assembled and reconciled, and then may or may not offer any insight. The Law of Diminishing Returns has dogged the prosecution of the work almost from the outset, like some grim-faced golem brandishing the bludgeons of limited budget and contractual deadline. Yet this writer has found it difficult to draw the line, when one more cardboard box or musty file may yield up some invaluable piece of information. Even with the closure of this report, the project seems unfinished: several important tasks, beyond the scope of this project, but still needing to be carried out, are presented in the final section as "Recommendations."

During the production of this report, a remarkable document has been on this writer's desk, a copy of Blunt's 1837 *American Coast Pilot*—from which the epigraph for Chapter 4 was taken—exhumed from deep storage in the UT library system. When the ink was set on its pages, Beethoven and Goethe had been gone less than a decade, Liszt was on his Années de Pèlerinage with Marie d'Agoult, and Brahms was a child of four. Closer to home, Travis and Bowie had been dead a year, and the Texas Republic, led by Gen. Houston, was in dubious straits. This particular copy was purchased January 1840 in New Orleans for $4.50, according to an inscription on the inside cover. Its leather binding is battered and scarred, and its pages are waterstained. Notices to Mariners clipped from newspapers dated from the 1840's have been meticulously tipped onto the applicable pages, and there are hand corrections to coordinates and bearings throughout. It is clear that this *Pilot* is not just a collection copy that has been shuffled from library to library, but rather that it was *used*: it probably was a fixture on the bridge of some antebellum ship sailing (NB, *sailing*) the waters of the Carribean and tropical American coasts. The lifetime of this *Pilot* almost exactly encompasses the historical evolution of Corpus Christi, dating from just before Col. Kinney established his trading post on the northwest shore of the bay. It has been a constant reminder to this writer of the time frame treated by this project, and what a relatively short time period that really represents. It is also symbolic of how much information has been lost during this period, which we are now trying to reconstruct. The operative time scale of circulation is many decades, and a data record of this duration is necessary to infer trends and postulate cause-and-effect. In Corpus Christi Bay, good, sound hydrographic measurements are not a modern technological innovation, but have been made dating back nearly to 1850, including bathymetry, mapping, tidal variation, meteorology, salinity and current measurement. Yet these data have not been preserved for various reasons (which have been railed about in Ward and Armstrong, 1997a, and references therein).

A note about the units. Generally data are reported in their original unit system of measurement, not only for convenience but to avoid distorting the implicit precision by numerical conversions. The shifts among British, metric, and nautical units may cause some frustration to a few readers. However, the coastal zone represents the intersection of concerns of the scientist, the engineer and the mariner, and most workers have come to use all three systems interchangeably. When derived or converted values are used, the SI system is favored. ("Metre," by the way, is the official SI spelling, not an affectation. "Rôle," on the other hand, is an affectation.)

A note about terminology. This writer is aware that the Latin "data" is the plural of "datum," but subscribes to the use of the English "data" as a collective noun, whose plurality is determined by the sense of the usage, see, e.g., the *American Heritage Dictionary (2nd College Edition)*. Any readers who find this offensive should pencil in "data set" and all will be well. A different class of readers may be offended by the term "spoil," in reference to the disposition of dredged sediments. Historically, this evolved as a technical term equivalent to "hydraulic fill" or "dredged material," which doesn't necessarily spoil anything. The term is still in use in this sense (see, e.g., NOS navigation charts), but in this report it is used in discussion of historical practices consonant with the terminology of the time. Similarly, dredged material "disposal" is favored over the politically correct but less definite "placement."



Aransas Pass in 1887, from U.S. Coast Survey navigation chart

1. INTRODUCTION: THE NATURE AND RÔLE OF CIRCULATION

> Corpus Christi Bay is entered from the southern end of Aransas Bay through a narrow channel between two islands. ... Corpus Christi is situated on the west shore of the bay. Although the terminus of a railroad from the interior, it has little commerce.
>
> — United States Coast Pilot, 1908

The movement of water throughout an estuary and the associated transport and mixing of waterborne constituents are central to the water quality and habitat features of that estuary. The hydrodynamic processes and the resulting water movement are referred to collectively as "circulation." Among several properties which distinguish estuaries and their management from other watercourses, such as streams and lakes, Ward and Montague (1996) place the complexity of hydrodynamic processes at the top of the list. This is certainly true of the Corpus Christi Bay system.

The prime objective of this study, as stated in the project Work Plan, is characterization of the spatial and temporal trends of estuarine circulation within the Corpus Christi Bay National Estuary Program (CCBNEP) study area. This study area extends from the landbridge in the Laguna Madre to the lower boundary of San Antonio Bay, and encompasses the component bay systems of Mesquite, Aransas-Copano, Corpus Christi and Nueces, Baffin and the upper Laguna Madre. This area does not have a specific geographical name, which poses a problem in referring to it. We attempt to differentiate between the Corpus Christi Bay "system," i.e. the CCBNEP study area, and the subregion of Corpus Christi Bay proper by appropriate qualifiers when necessary, but generally rely upon the context to clarify. We refer to Aransas, Copano and their secondary systems (including Mesquite) as the upper bays, and to Baffin Bay and the Upper Laguna Madre as the lower bays.

Characterization of circulation in any estuary is a challenging task; in a system as complex as Corpus Christi Bay it is daunting. Circulation in Corpus Christi Bay (which in the context of this section means the CCBNEP study area) is highly variable in both time and space, being controlled by the interplay of bathymetry and physiography, tides, meteorology, freshwater inflows, and density currents, as well as being modulated by other factors including surface waves, Coriolis acceleration, ship traffic, etc. The tide is, of course, the most obvious marine influence on estuary hydrography. As the tide propagates into the estuary it is generally attenuated and lagged by the frictional loss associated with the constricted watercourse. Since it is a broad, shallow water body, Corpus Christi Bay is particularly responsive to meteorological forcing, of which the wind is the most important agent. Wind generates short-crested waves that can become efficacious mixing agents, but wind can also generate autonomous circulations ("gyres") within the estuary. Suddenly varying winds can induce "wind tides" by effecting an abrupt water-level differential between the adjacent sea and the estuary, and within the estuary itself. The density current, a prime vehicle for salinity intrusion, is the current generated by the *horizontal* salinity gradient, and is enhanced in the deeper sections of an estuary.

Strictly, circulation would be characterized by determining and mapping the current velocity throughout Corpus Christi Bay over the full range of external conditions to which the system is subject. This project was to rely upon data already available from other sources, both present and historical. Thus, if we seek to characterize circulation by compiling the historical record of current measurements, this would have been a short and unsatisfying project: there are very few sets of current data from the Corpus Christi Bay study area.

Circulation must instead be characterized by a broader suite of data, and the operating transport mechanisms generally must be inferred rather than directly measured. These types of data are described in more detail in the following sections. For now, we observe that they fall into two broad categories:

- variables which respond to current velocity and related hydrodynamic processes;

- variables known, or thought, to exert controls on circulation.

Examples of the first category of data include water-level variations in the interior of the system, distribution and movement of waterborne tracers, and patterns of erosion and deposition. Examples of the second category are bay morphology (including internal barriers and channels), ocean tides, meteorology, and freshwater inflow.

Prosecution of the primary objective of this study, of characterizing spatial-temporal trends in the study area, entailed three subordinate objectives, *viz.*:

(1) compilation and analysis of a comprehensive data and information base;

(2) quantitative establishment of time and space variation (including "trends") in circulation;

(3) identification of possible causal mechanisms linking the principal controls to circulation, transport, and distribution of key hydrographic variables.

This project is intended to provide a foundation for further scientific study of the Corpus Christi Bay system, for identifying and prioritizing specific circulation-related problems affecting the quality of the Bay, for formulation and specification of future monitoring programs for the Bay, and for a general understanding of the controls and responses of Bay water quality and habitats, which must underlie rational management of the resources of the system. The basic approach of this project as envisioned by the CCBNEP in its original Scope of Work was to construct a hydrographic history of the Corpus Christi Bay system, from which the nature of circulation and transport processes can be inferred. The phrase "hydrographic history" has been broadly interpreted in the actual project prosecution to include not only those events and processes that may have altered the hydrodynamic system within, say, the past century, but also to mean the manifestation of hydrodynamic processes on a range of shorter time scales.

Characterization of circulation necessitates clear identification of the operative time-space scale. Fluctuations in hydrodynamic variables occur on a range of scales, governed by the external controls on the estuary. Second-to-minute time variations in currents and density are due to turbulence and play a major part in diffusion, mixing and dissipation. The 12.4 and 24.8-hour tidal signals are a particularly strong component of time fluctuations, and there are longer period variations that effect slower filling and evacuation of the estuary. Meteorological sources of variation are numerous, and depend upon the regional climatology, which in the study area changes dramatically with the season. Frontal passages in winter, in particular, exert a fluctuation with several days periodicity. The spatial scale of motion is intimately related to time scale, because the observed fluctuation in time is frequently associated with displacements of water masses of different properties. The space scale associated with the tidal period is the *tidal excursion*, the horizontal distance moved by a parcel of water on the flooding tide.

To first approximation, water movement in an estuary can be viewed as oscillatory tidal motion superposed on larger-scale longer-term circulations. A key distinction in analyzing estuary circulations is therefore made between the shorter period *intratidal* motion and that on longer-term *intertidal* scales. The large-scale spatial structure of estuary hydrography and spatial gradients in water quality are typically governed by processes on a scale of several-to-many tidal excursions, and therefore are addressed on an intertidal basis. The fundamental time scale formed the organizational basis for this report, which proceeds from short time-space scales (Chapter 4) including tides, seiches, and wind-shift responses, to longer time-space scales (Chapter 5) in which is addressed the large-scale water mass exchanges within the system. Of course, the general morphology of the system governs all of its hydrodynamic responses on any space-time scale, so this is addressed first (Chapter 2) to establish the setting for the remainder of the report. There is an even longer, decadal time scale that provides the backdrop of long-term historical evolution of the bay. This is summarized in Chapter 3.

Particular note is made of two important aspects of the project technical approach. First, this project was intended to rely primarily upon recent and ongoing projects, especially of the CCBNEP, for economies of time and effort. Second, the project analyses were to be based upon field data from the system. Modeling, as a source of information, was to be avoided. With respect to the first, the intention was to conserve project resources for the analytical effort, rather than in the labor-intensive activity of recovering historical information. Of course, to determine trends in circulation on decadal time scales must of necessity involve older information. But the law of diminishing returns had to be scrupulously borne in mind to control the scope. This report is not a history of Corpus Christi Bay, but an exploration of its hydrodynamics including a historical perspective. The second feature, of eschewing modeling, may seem curious given the increasing rôle that these analytical tools are playing in the management of estuaries, including Corpus Christi Bay, and the resources that are being devoted to model development by both state and federal agencies. There were several reasons for this, all stemming from the fundamental "imperfection" of modeling, and the uncertainties of model validation when the observational data base is so sparse. (See Ward, 1991, for a critique of the modeling process.)

This report, the principal product of the study, presents the analyses and conclusions in a narrative format. It is primarily a historical and descriptive document, addressed to a professional but non-specialist readership. Thus the report relies upon graphics and text for principal communication of the results. While some of the concepts involved are technical (e.g., hydraulic capacity, tidal prism, mixing coefficients, etc.), mathematical or detailed quantitative analyses are relegated to the appendices. All of the above caveats about models notwithstanding, conceptual and simplified mathematical models are employed in several places to clarify or communicate the physical behavior of a circulation process. The presentation also relies upon the graphic displays of the Exhibits, which are to be operated on a personal computer. To extrapolate the well-known Chinese proverb, one animation is worth a thousand pictures—and therefore a million words. The reader is strongly encouraged to load and activate the Exhibit files at the appropriate place in the presentation, and to thank Providence that a million words have been avoided.

2. HYDROGRAPHIC SETTING OF THE CORPUS CHRISTI BAY SYSTEM

> The drought that pervades the season from the close of April to September is often mollified by copious and refreshing showers, which sometimes distribute their favours very unequally. The unequal distribution of rain is indeed considered by husbandmen the chief defect in the climate of Texas.
>
> — Kennedy, *Texas,* 1841

2.1 Morphology

The geographic area of this study, the embayments of the Coastal Bend, is a part of an interconnected system of lagoonal bays extending along the Texas coastline between the Rio Grande and the Brazos River. The degree of interconnection is highly variable, however, and extensive shoals or physiographic barriers subdivide this system into quasi-autonomous basins. Those within the present study area are the Upper Laguna Madre and Baffin Bay, Corpus Christi Bay and Nueces Bay, Aransas and Copano Bay, and their various tertiary and tributary embayments. Location maps including isobaths (where these can be reliably constructed) are provided in Figs. 2-1 through 2-4. Sources for the bathymetry included NOS navigation charts, USGS 7.5-minute quadrangles (especially 1950's vintage), Elliott (1958), Carothers et al., (1959), and White et al. (1983, 1989).

Dimensions of the component bays are summarized in Table 2-1. Surface areas were compiled from two sources. First, the digital EPA River Reach File was spatially integrated on a geographic information system (GIS). These are listed in the first column of Table 2-1. Second, the CCBNEP Hydrographic Segmentation developed in the Water and Sediment Quality project (Ward and Armstrong, 1997a) was superposed on a digital map of the water boundaries of the system, and spatial integration carried out on a GIS for each segment. The segments were then summed to determine area within the respective component bays. (In both cases, the internal reefs, barriers, and emergent sediment disposal areas were not subtracted from the total surface area.)

From a geological perspective these are transitory—even evanescent—systems, created by a recent rise in sea level during which river valleys were flooded and barrier islands were formed. From a historical perspective, the principal features of this region are more or less fixed, though their detailed structure has varied as a result of both natural and human actions. The principal morphological features may be delineated with three broad brushstrokes: (1) shallow, wide bays, separated by rather higher peninsulas of land, (2) isolated from the sea by a relatively narrow, low barrier island, (3) and with which conflow drainage channels from higher inland areas. The next level of detail is overlaid with somewhat narrower and more controlled brushstrokes: (1) interruptions in the barrier island, the inlets connecting bay and sea, (2) shoals on either end of the inlets, more extensive on the bay side, (3) peninsulas constraining the connections between bays, or between bay and drainageway, (4) zones of reefs and shoals. Finally, as sort of a fine-scale impasto, are added

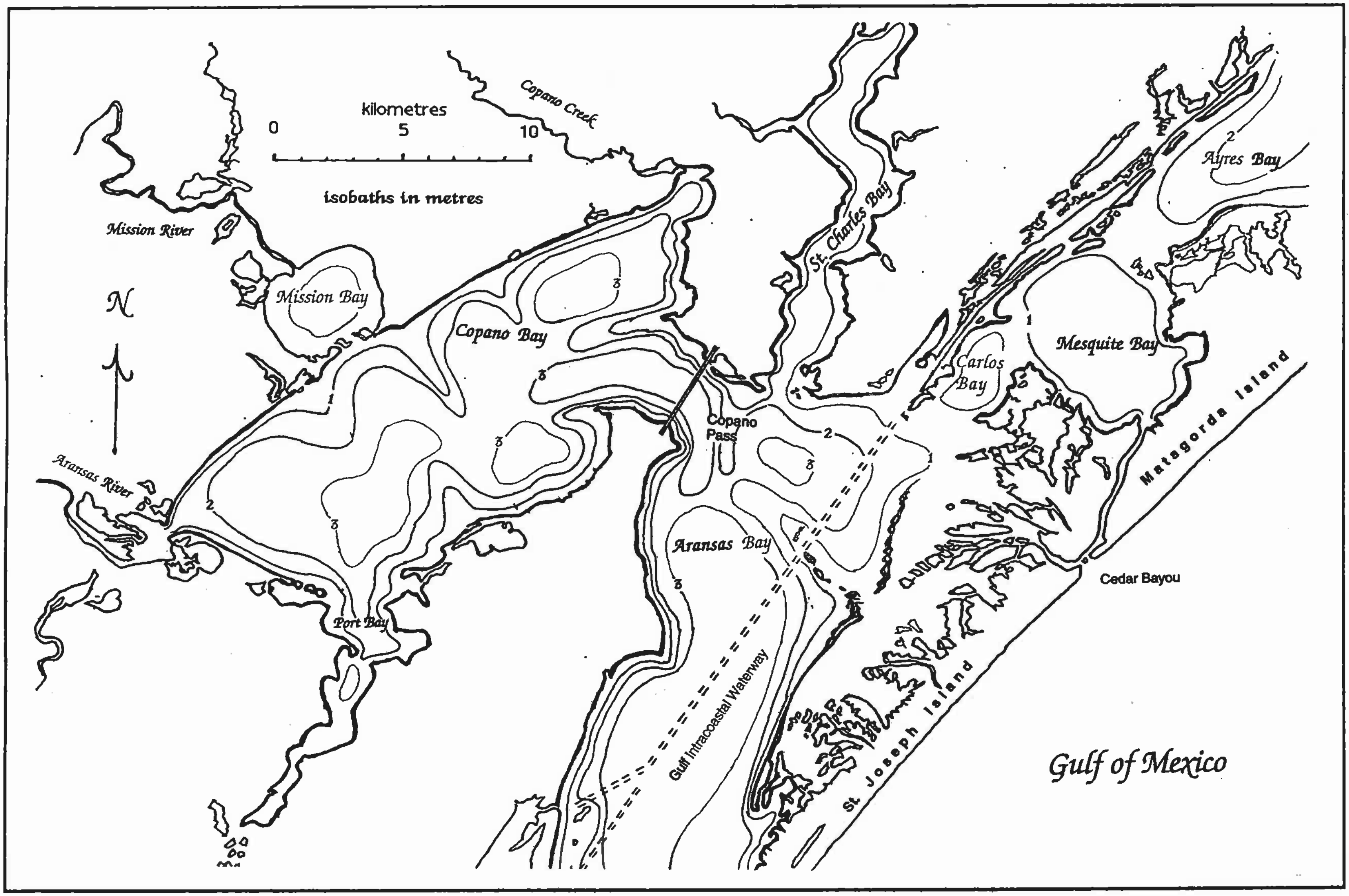


Figure 2-1. Aransas-Copano Bay

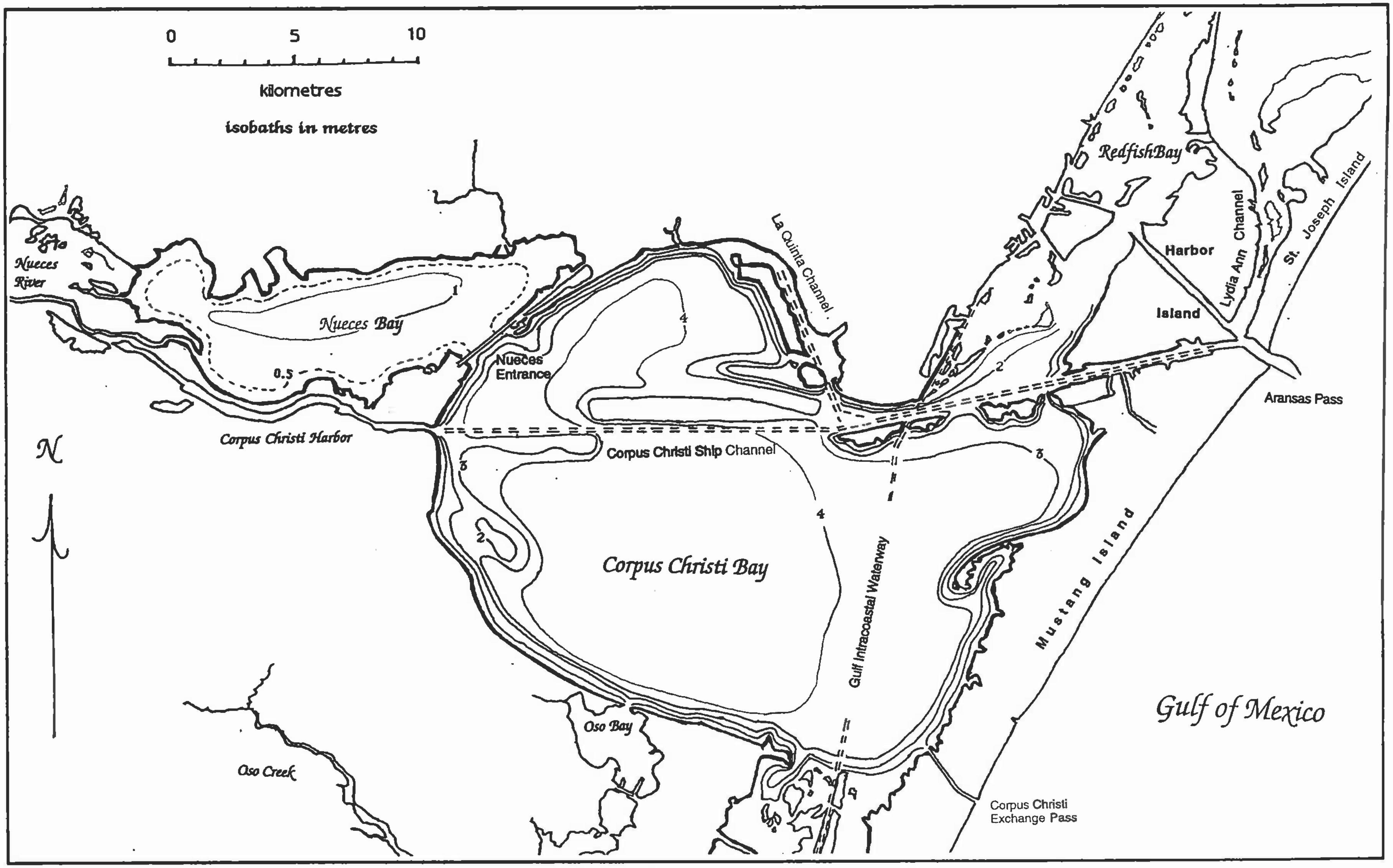


Figure 2-2. Corpus Christi Bay

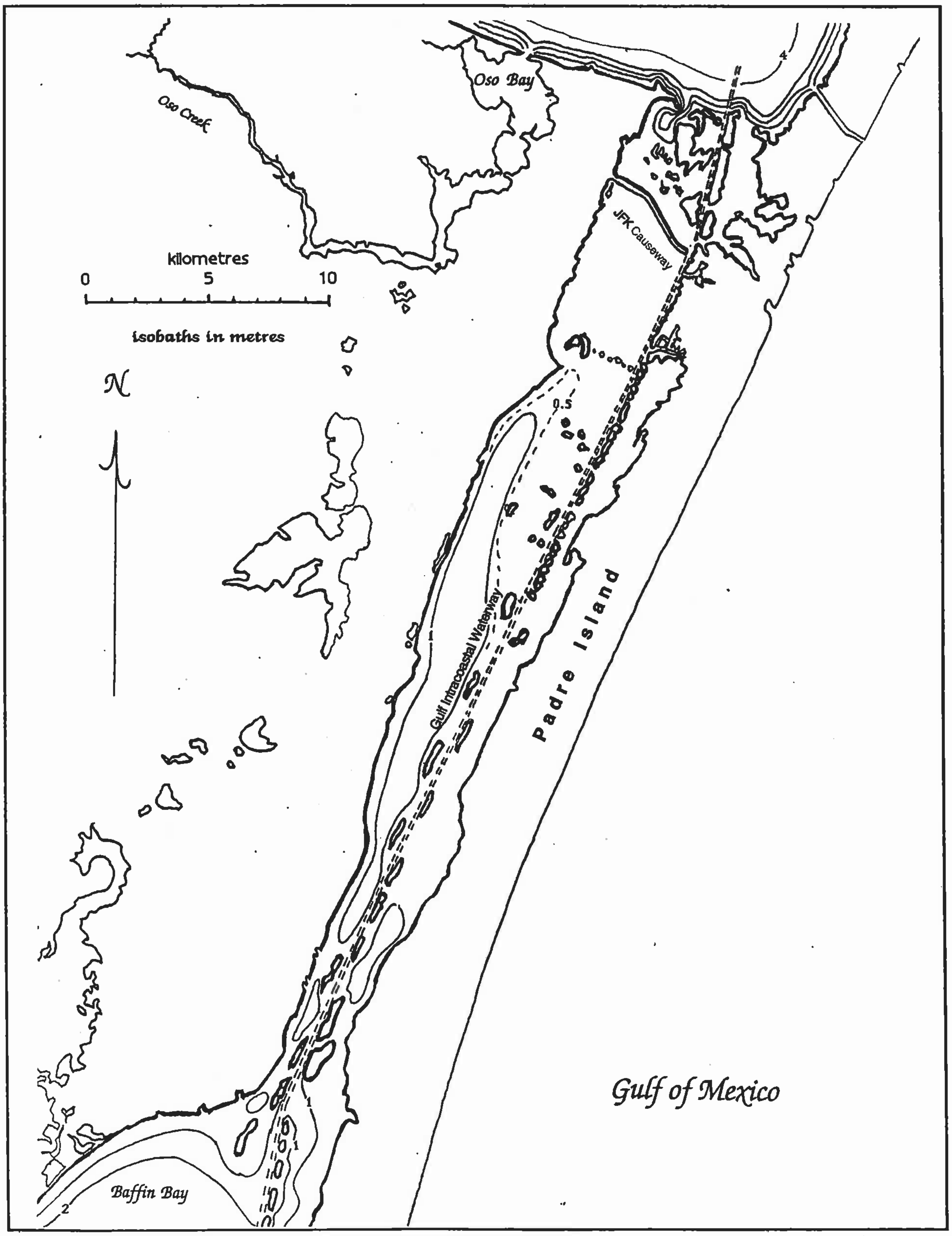


Figure 2-3. Upper Laguna Madre

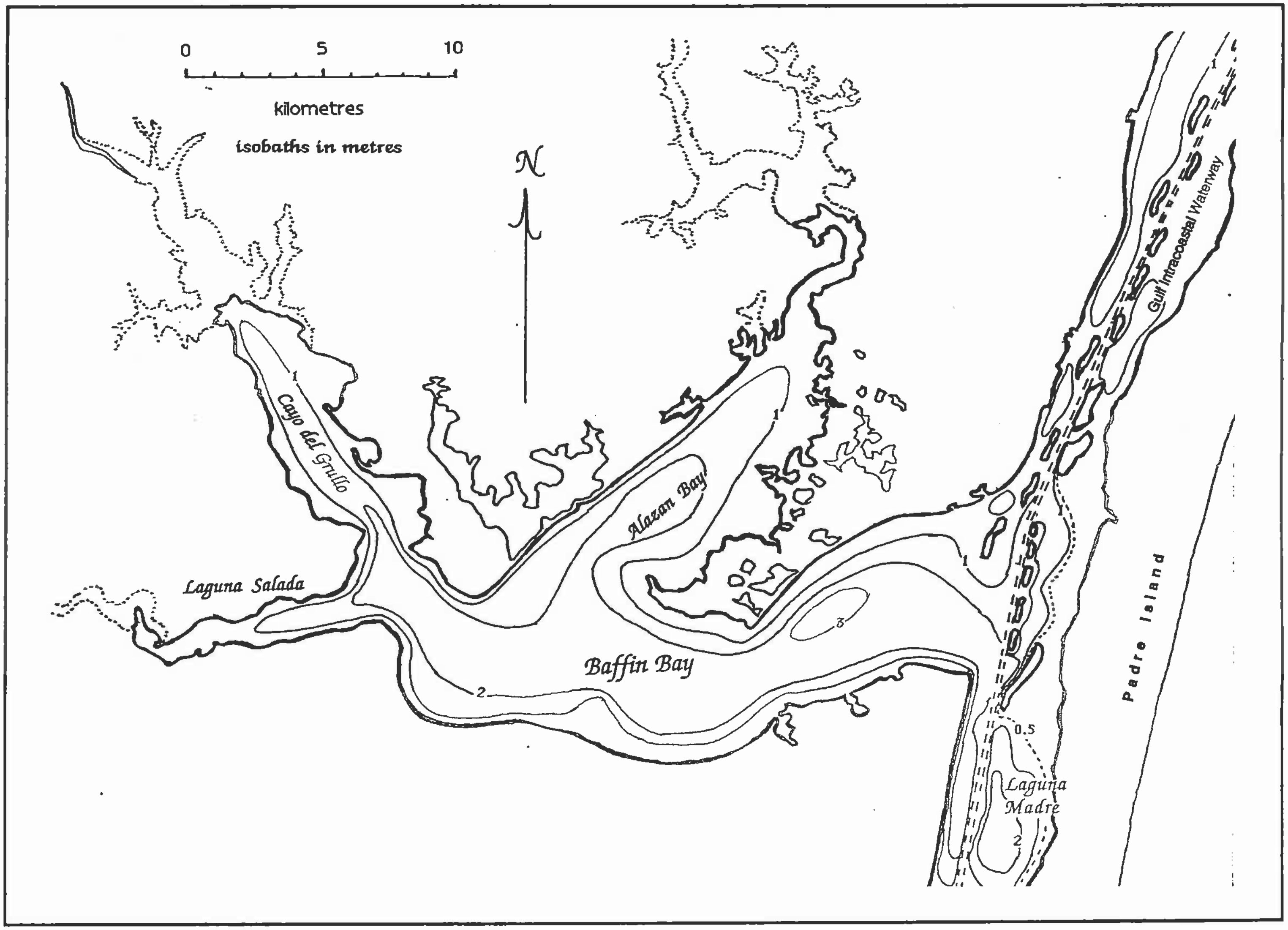


Figure 2-4. Baffin Bay

Table 2-1
Physical dimensions of component bays

Bay	*surface area (sq km)*		*mean depth (m)*	*volume ($10^6 m^3$)*
	EPA RRF	*CCBNEP WQ*		
Aransas	232	219	2.4	526
Copano	196	195	2.2	429
St. Charles	31	32	1.0	32
Mesquite*	71	62	1.2	74
Redfish	113	98		
Corpus Christi	434	435	3.6	1566
Inner Harbor	**	6.2	10.0	62
Aransas Pass inlet area	**	19		
Nueces	72	70	0.7	49
Oso Bay	17	17		
Upper Laguna (King Ranch)	158	155	0.2	26
Upper Laguna (Baffin)	284†	102	0.5	51
Baffin	258	241	1.8	434

*includes Ayres and Carlos Bays ** not resolved † includes Mudflats

physiographic details of: (1) dunes capping the barrier islands, (2) abrupt bluffs on arcuate bay shorelines, (3) extensive areas of urban development on the margins of the bays, (4) deeper slot-like channels crossing the bays.

There are of course other physiographic features that can be differentiated, such as shoals placed in the system by natural processes versus shoals created by man. Also, the shapes of the bays are influenced by a terrace-like ridge on the land paralleling the barrier island and lying about halfway inland athwart the bays, which follows and defines some of the peninsulas that constrain exchange between the bays. But those enumerated above are the physical features with which the flows and exchanges of water interact to produce the circulation of the system. How some of these features have evolved over time, and the consequent effects on circulation will be addressed later.

2.1.1 Component bays

The northernmost region of the study area, Fig. 2-1, is the upper bays, namely Aransas and Copano Bays, and the adjacent systems of Mesquite/Carlos/Ayres Bays, which are referred to here collectively as "Mesquite Bay." Both Aransas and Copano are shallow systems, and are connected by a narrow inlet, Copano

Pass. (This name was occasionally applied to this inlet in the early part of the century, e.g. Martin, ca. 1930, though usually it is shown unnamed.) The 1936 coastal pilot (USC&GS, 1936) describes these systems aptly, "St. Charles Bay is an arm of Aransas Bay extending northward. ... There is 2 to 3 feet (0.6 to 0.9 m) through the entrance and somewhat greater depths with numerous reefs inside. ... Copano Bay is a northwesterly extension of Aransas Bay. Extreme caution is required when navigating the bay on account of the numerous unmarked reefs extending across the bay." The bottom contours drop rather rapidly from the shoreline to the more uniform depths of the open bay. Collier and Hedgpeth (1950) compare the shape of Aransas Bay to a flat-bottomed vegetable bowl.

Corpus Christi Bay *per se*, Fig. 2-2, is one of the deeper bays on the Texas coast, averaging some 4 m in depth. Apart from the oyster/sand reefs and the dredged channels, its bathymetry is strikingly uniform. The bathymetry slopes steeply from the shore. To continue their culinary analogy, Collier and Hedgpeth (1950) liken Corpus Christi Bay to a frying pan. The bay is surrounded by eroded bluffs around most of its periphery, though a high proportion of this shoreline is now modified and stabilized by human development. Bed sediments have a high proportion of sand in a narrow apron around the bay periphery, while the deeper central sediments are fine silts and clays.

Nueces Bay, a shallow secondary bay of Corpus Christi, is connected to the larger body by a shallow, narrow pass, referred to in this report as Nueces Entrance. (There is no geographical precedent for this name. Nueces Pass or Rincon Pass would work as well.) Kennedy (1841) succinctly described the area, "Nueces Bay, a branch of Corpus Christi Bay, with which it is connected over a pass of four feet water, is formed by the *embouchure* of the Nueces river... ," though he was generous in assigning four feet to the inlet. It was choked with oysters and sand bars, and formed a convenient ford for crossing from Rincon Point on the south to Indian Point on the north. During the Nineteenth Century, this was an important route to Corpus Christi for riders and wagons, called the "Reef" or "el Rincón," see, e.g., Dunn (1932). Mrs. Sutherland (1916) states:

> This reef, dividing Corpus Christi Bay from the Bay of Nueces, cut quite a figure in the early days, being then about three miles north of the city, but now [1915] the town has gradually expanded until it has become a suburb. The San Antonio and Aransas Pass Railroad has a bridge there now, three miles long. The old wagon road, with its many twists and turns, following the apex of the reef of oyster shells, making distance to be traveled more than twice that distance as used many years. This road at one time was our only outlet northward, and was carefully staked to mark the safe path, as the road was under water, and if the traveler deviated from it, he was sure to get into trouble and deep mud at one and the same time, with an excellent chance of drowning his team. To passengers on outgoing or incoming trains, these road stakes looked like a puzzle, but to the traveler of early times they were carefully studied, and learned to a turn.

Nueces Bay itself is quite shallow, ranging 0.3-2 m and averaging about 0.5 m. The western upstream terminus of the bay is the delta of the Nueces River, an area of extensive marshes and tidal distributaries.

Extending south from Corpus Christi Bay lies the Upper Laguna Madre. This is the northern portion of the much larger system, the Laguna Madre, which extends nearly to the Rio Grande, terminating at South Padre Island and Brazos Santiago inlet. The Laguna Madre is divided into two quasi-autonomous bodies, the Upper and Lower Laguna, by the Mudflats (see Section 2.1.2 below). The Upper Laguna is extremely shallow throughout most of its area, its average depth being a strong function of season of the year as well as what areas one chooses to consider to be lagoon and include in the area. If Corpus Christi Bay is a frying pan, then the Laguna is a griddle. A generous estimate of average depth would be 0.3 m, if seasonally emergent shoals are excluded. Even the expansive Kennedy (1841) was equivocal about this region: "The Laguna del Madre is a long, shallow sound, formed by the mainland upon the west, and the Isla del Padré upon the east. ... Its shallowness renders it little available for navigation, having in many places not more than from eight to fourteen inches of water." The coastal pilot (USC&GS, 1936) tried to be downright discouraging, "Laguna Madre is a shallow body of water, scarcely more than a few inches deep in places, extending southward from Corpus Christi Bay for a distance of 100 miles, and separated from the Gulf by only a low and barren storm-swept strip of sand beach, known as Padre Island."

The Upper Laguna has no direct inlet to the Gulf of Mexico, despite the long efforts of the Texas Game, Fish and Oyster Commission to open Yarborough Pass (née Murdock Pass) across Padre Island. What little natural exchange there is occurs either through the Bulkhead Flats area with Corpus Christi Bay to the north, specifically through two inlets through the earthen JFK Causeway, or with the Lower Laguna Madre to the south, primarily through the GIWW cut across the Mudflats.

Baffin Bay, Fig. 2-4, would appear from a map of the area to have a fairly wide entrance, but this is deceiving. Extensive "rocks"—in fact massive serpulid worm secretions—and associated mud and sand accumulations partially block this entrance posing a serious hazard to navigation. The coastal pilot (USC&GS, 1949) is blunt, "Baffin Bay and its various tributaries should not be entered without local knowledge." The main axis of Baffin Bay exhibits average depths on the order of 2 m. The upper tributary bays of Baffin are indistinct, grading into extensive sand and silt flats, normally subaerial but seasonally inundated depending upon wind, Gulf water elevations and rare runoff events.

2.1.2 Inlets, barriers and reefs

There are three quasi-permanent inlets to the system. The main inlet is Aransas Pass, which has been stabilized by revetment and jettied, and is presently the only one of the three that is perennially open. Inside Aransas Pass lies Harbor Island, a portion of which is the natural flood bar of the inlet. Oyster reefs, sand bars and shoals provide a triangular system of shallows connecting Harbor Island to the mainland, and this area has been further modified by man, with numerous dredged channels, some now abandoned, well pads, spoiling areas, harbors and levees. This entire triangular area with base at the mainland and apex at Harbor Island is Redfish Bay. To further indulge Collier and Hedgpeth's likening to culinary *implementa*, if Corpus Christi Bay is a frying pan and the Upper Laguna a griddle, then Redfish Bay is a waffle iron.

The second pass to Corpus Christi Bay is Corpus Christi Pass, which has been closed during most of this century, but was usually open in the last century. Collins (1878) noted the convoluted, southward trending channel of Corpus Christi and judged that it was the older of the two. Howell (1879) stated in his report that Corpus Christi seemed to be gradually filling, that a "man of ordinary stature can now wade it at several points," and recommended closing the pass with a dam, thinking that would help maintain the passage between Laguna Madre and Corpus Christi Bay. The Texas Game, Fish and Oyster Commission made valiant attempts over several decades to open this pass (see Section 3.1.2) for water exchange and as a migratory route. The third inlet to the system is Cedar Bayou, which connects Mesquite Bay with the Gulf. It, too, has been closed for much of this century, but has been re-opened by hurricanes and by TGFOC (and successor agency) projects.

The upper bays, especially, have extensive oyster reefs. There seems to be little doubt that the form of large-scale elongate reefs is related to predominant current directions. Grave (1905) described the formation of linear reefs by growth into a passing current and elongation across the current, resulting in the reef lying transverse to the current. This seems to be the case for the reefs in Copano and Aransas Bays. (Price, 1954, observed that some oyster reefs form parallel to the main current, generally in pairs on opposite sides of the current trajectory.) In Copano Bay, Fig. 2-1, several extensive reef systems are evident in the distortions of the bathymetric contours extending from the shoreline into the center of the bay. An elongated nearly unbroken reef extends from St. Joseph Island and northward to St. Charles Bay (at Goose Island) practically bisecting Aransas Bay, Fig. 2-1. The geometry of these reefs seems to be governed more by sources of freshwater than by tidal currents (though in the case of Copano Bay, the two have similar trajectories.) No extensive reefs exist in Nueces Bay, but this was not always the case. Oysters were harvested from Nueces Bay for consumption by Corpus Christians since the last century, and were still being taken from beds along the south shore of the bay during Dr. Cline's tenure as Corpus Christi meteorologist during the first decade of this century (Cline, 1946). There are two primary regions of oyster reef deposits in Corpus Christi Bay, the Alta Vista Reef along the Corpus Christi shorefront, and Donnel and Long Reef in the northern segment of the bay near Ingleside.

Mud Island, a recurved spit extending from St. Joseph Island and constricting the entrance to Aransas Bay, has been asserted by several authors to have formed since 1833 (e.g., Price, 1947, Collier and Hedgpeth, 1950), apparently based on the fact that the 1833 chart of Monroe printed in Kennedy (1841) does not show this feature. Shamrock Island is a similar structure in lower Corpus Christi Bay.

Both of these in all likelihood antedate historic times.* The shoals of Bulkhead Flats separate Corpus Christi Bay from the Upper Laguna Madre, Fig. 2-3. These shallows are natural feature of the system, a complex structure of emergent bars, barely submerged flats, and narrow scoured channels, which has clearly received littoral sediments from the years when Corpus Christi Pass was open, as well as wind-blown sand and overwash, and is regularly inundated by north-wind setup. This description, as far as it goes, could have applied as well a century ago. However, this area has been further modified by man, including access channels to well pads, spoiling and hydraulic fill, boating channels, and, most notably, construction of the JFK Causeway and the dredging of the GIWW.

The lower boundary of the study area is the Mudflats of the Laguna Madre (a.k.a. Tidal Flats, Land Bridge, Landlock, Middle Ground, Landcut). These extremely shallow, frequently emergent flats are transected by the GIWW, which in fact is the "land cut." The Flats bridge the Laguna from the barrier island to the vast mainland aeolian sheet, referred to in the late Nineteenth Century as the "Sand" (e.g., Dunn, 1932).

2.2 Hydroclimatology

There is only a handful of meteorological factors that control the basic climatology of the Corpus Christi Bay area:

- synoptic-scale disturbances in the westerlies
- the trade winds blowing across the Gulf of Mexico
- tropical disturbances

The relative interaction of these factors, together with the physiography and surface of the land, in turn control the other elements of regional meteorology: cloud forms, receipt of solar radiation at the surface, air temperature and moisture, thunderstorms, precipitation, and so on.

Proceeding southward across Texas into Mexico, there is a geographical convergence of the North American Cordillera and its associated interior rainshadow from the west, with the principal source of atmospheric moisture to the continent—the Gulf of Mexico—from the east. This westward encroachment of the rainshadow, combined with the increasing influence of tropical meteorology, has important consequences for the coastal climate of Texas. From north to south along the Texas coast, rainfall diminishes, air temperature increases, and evaporation increases, all of which create a transformation in climate from humid to arid. The arid and semi-arid climate of the Corpus Christi

* The chart of Capt. Monroe is not to be trusted for morphology; its only purpose was to document soundings along the main channel (now the Lydia Ann Channel) into Copano Pass. The shoreline physiography was obviously sketched from the deck at a considerable distance. If we are to believe the absence of Mud Island in 1833, then we should also accept the even more remarkable re-orientation by 45° of the main axis of Copano Bay, as well as the formation of St. Charles Bay, which apparently did not exist in 1833 either.

Bay system and its watershed belies the high moisture content in the air flowing inland from the Gulf of Mexico. Moreover, the upper atmosphere over the watershed frequently has moisture-rich currents from the southern Pacific. The aridity of the region is not a consequence of a moisture-deficient atmosphere so much as of the infrequency of triggering mechanisms necessary to precipitate that moisture. The subsiding air in the lee of the mountains maintains dry, stable conditions, even in summer, to resist cloud formation and precipitation, and this stable atmosphere frequently expands eastward to the Corpus Christi region. Midlatitude frontal passages penetrate this far south only for the most energetic systems, usually a phenomenon of winter.

The climate of the Corpus Christi Bay area vacillates between temperate-midlatitudinal in winter and tropical in summer, according to whether it is dominated by either the continental airmasses brought to the area by midlatitude disturbances in the westerlies or by the warm, humid Gulf of Mexico airmass associated with the easterly trades. To a first approximation this is an annual cycle, tracking the retreat of westerlies to the north and expansion of circulation about the Bermuda High with the increased insolation of summer in the Northern Hemisphere. The relative importance of midwesterly and tropical systems can vary considerably within the year and from year to year about this general annual cycle, however. Generally, the region is dominated by onshore flow from the Gulf of Mexico, from the southeasterly quadrant, i.e., ranging from south to east. This brings warm marine air over the region. The effect of midlatitude disturbances, especially in winter, is to turn the wind to the north, from which quadrant the wind will be sustained as long as the midlatitude system is controlling, and replace the marine air with drier air of continental type. Once the disturbance weakens or migrates to the east, the marine influence reasserts itself and winds return to the prevailing southeasterly direction.

2.2.1 Precipitation

Figure 2-5 displays the annual sequence of monthly precipitation, averaged over the period 1950-1990, for some representative stations in the region. (In some cases, this period of record was not available. The periods used are indicated on the figure.) The Aransas Pass/Rockport data exemplifies the pattern of monthly precipitation at the coast. In the upper panel of Fig. 2-5 are plotted three stations, all lying approximately 50 km inland, extending from the northern limit (Refugio) to the southern limit (Kingsville) of the study area, and indicate the general sequence of precipitation in this coastal-zone area. The lower panel plots the same data for three stations moving inland in the Nueces Basin, from Alice (90 km inland) to Uvalde (300 km inland).

In the Corpus Christi Bay watershed, as in Texas in general, the dominant source of precipitation is deep convection, i.e. thunderstorms. The atmospheric processes giving rise to these are, in order of usual decreasing importance, synoptic-scale midlatitude disturbances, tropical storms, and instability in the lower atmosphere arising from heating at the surface. The first includes a

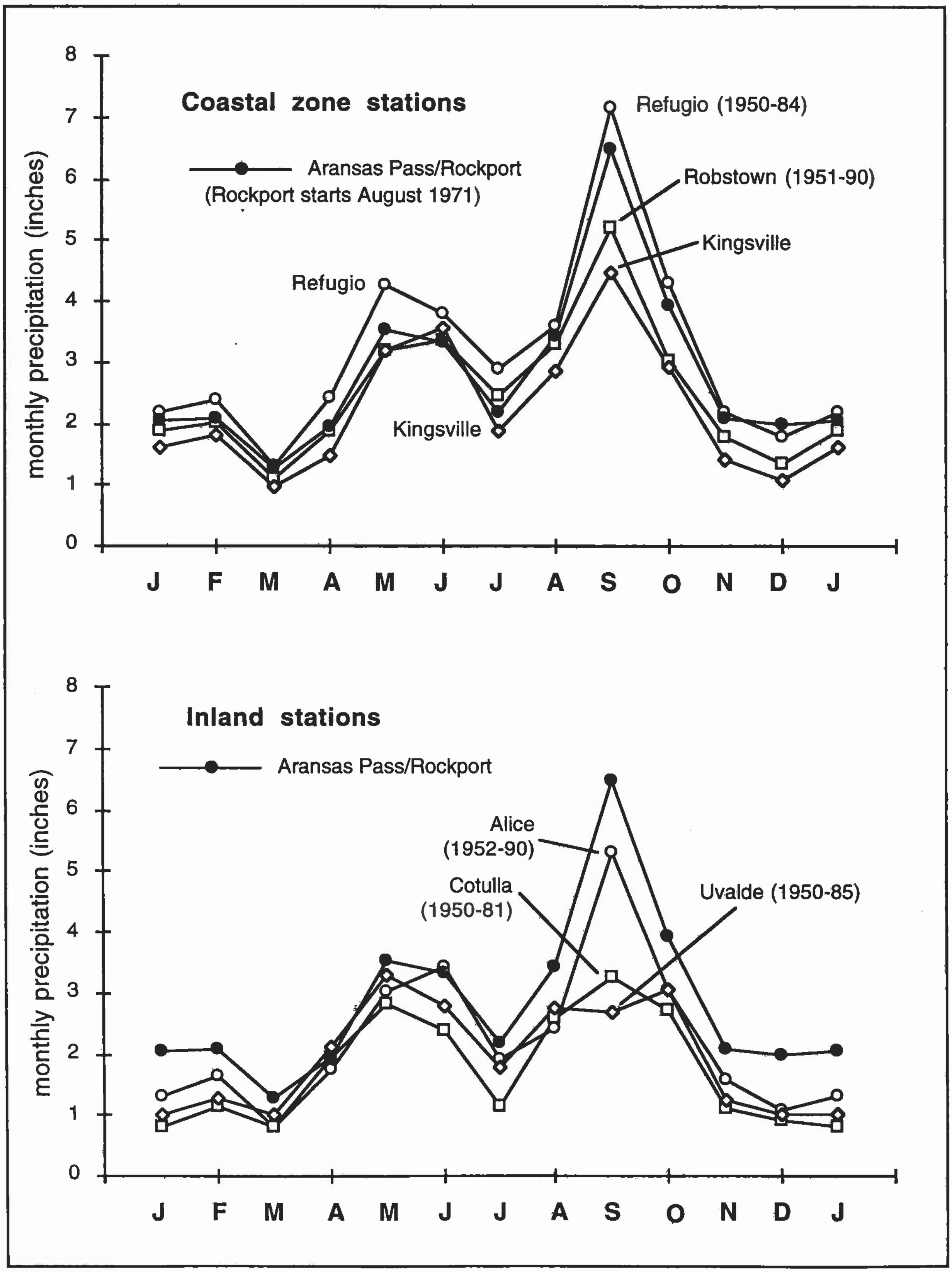


Figure 2-5. Monthly mean precipitation for 1950-90 (except where indicated otherwise) for selected stations in region.

variety of pressure disturbances developed in and carried by the westerlies, including near-surface convergence in advance of upper-level "short wave" systems, eastward migration of the "dry line" (yet another effect of the proximity of the Cordillera), and continental-scale pressure troughs and their associated frontal passages. The seasonal maxima in this type of activity occur when the relative influences of midlatitude westerlies and the circulation about the Bermuda High are about equal, *viz.* the equinoctial seasons. This is exemplified by the clear spring and fall maxima in monthly precipitation in all of the stations plotted in Fig. 2-5.

The second category of convective precipitation is due to tropical disturbances, almost entirely those systems carried in the easterlies and entering the Corpus Christi Bay region from the Gulf of Mexico. These systems have a seasonal maximum in late summer and early fall, and are primarily responsible for the enhanced fall precipitation maxima of the coastal zone stations of Fig. 2-5. Their occurrence in time is irregular, and may be separated in the data record by several or many years. However, they are such prolific rain-producers that they have a major effect on the long-term mean rainfall. Their influence diminishes with distance inland.

Both midlatitude storms and tropical disturbances diminish in rainfall amounts with distance south. The third category of precipitation process, convective thunderstorms produced by daytime heating, i.e. "airmass" thunderstorms, is primarily a summertime phenomenon, as would be expected from the rôle of heating in this process, as well as the instability of moist air in the summer. In this category is included the thunderstorms that frequently erupt along the seabreeze front, which is best-developed during summer. In terms of volume of rainfall produced, airmass thunderstorms are much less significant than frontal or tropical systems.

Long, uninterrupted periods of precipitation records are relatively rare in the Coastal Bend area. Two long-period stations are Sarita in the south part of the study area, where data are available back to the turn of the century, and George West in the upper watershed, where data extend back to about 1916. These precipitation time-series are plotted in Figs. 2-6 and 2-7, respectively, as cumulative departures from the period average. This perhaps curious means of displaying a long-term precipitation series in fact is quite revealing of long-term patterns of rainfall. A series of months with above-average rainfall is revealed as an upward trending segment on this sort of graph, and, similarly, a series of months of below-average rainfall appears as a downward trending segment. A region with no particular month-to-month systematic variation in rainfall plots as a line with wiggly excursions above and below zero. For Sarita and George West, the more typical shape of the curve is a sharp increase followed by an extended downtrending segment. The sharp increase corresponds to a high-rainfall month, as indicated on Fig. 2-6a, and the downward trending period to a drought. Two examples of drought are indicated on Fig. 2-6a. By inspection, we note the following features of rainfall climatology in the Corpus Christi Bay study area:

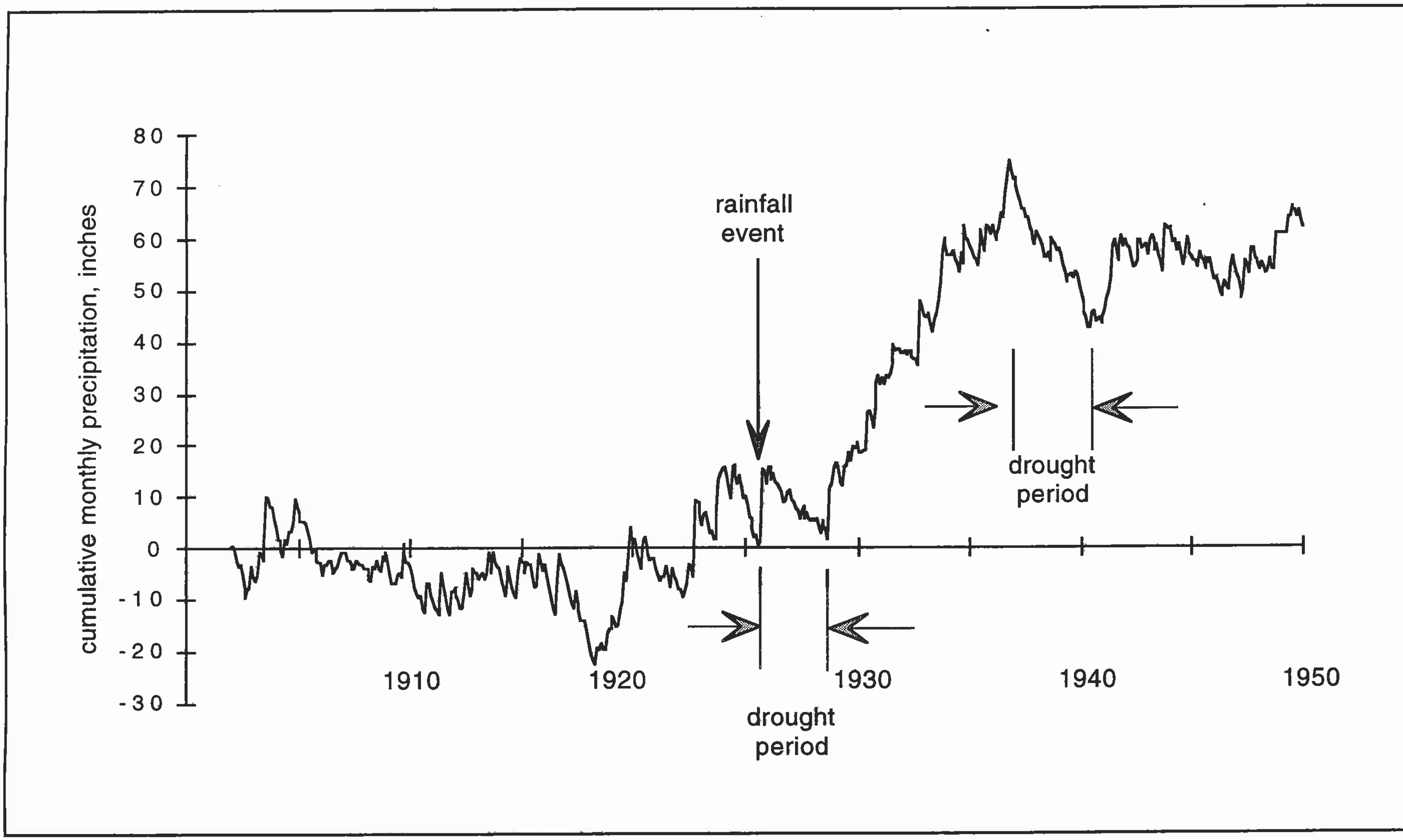


Figure 2-6a. Cumulative departure of monthly precipitation from mean, Sarita gauge 1900-50

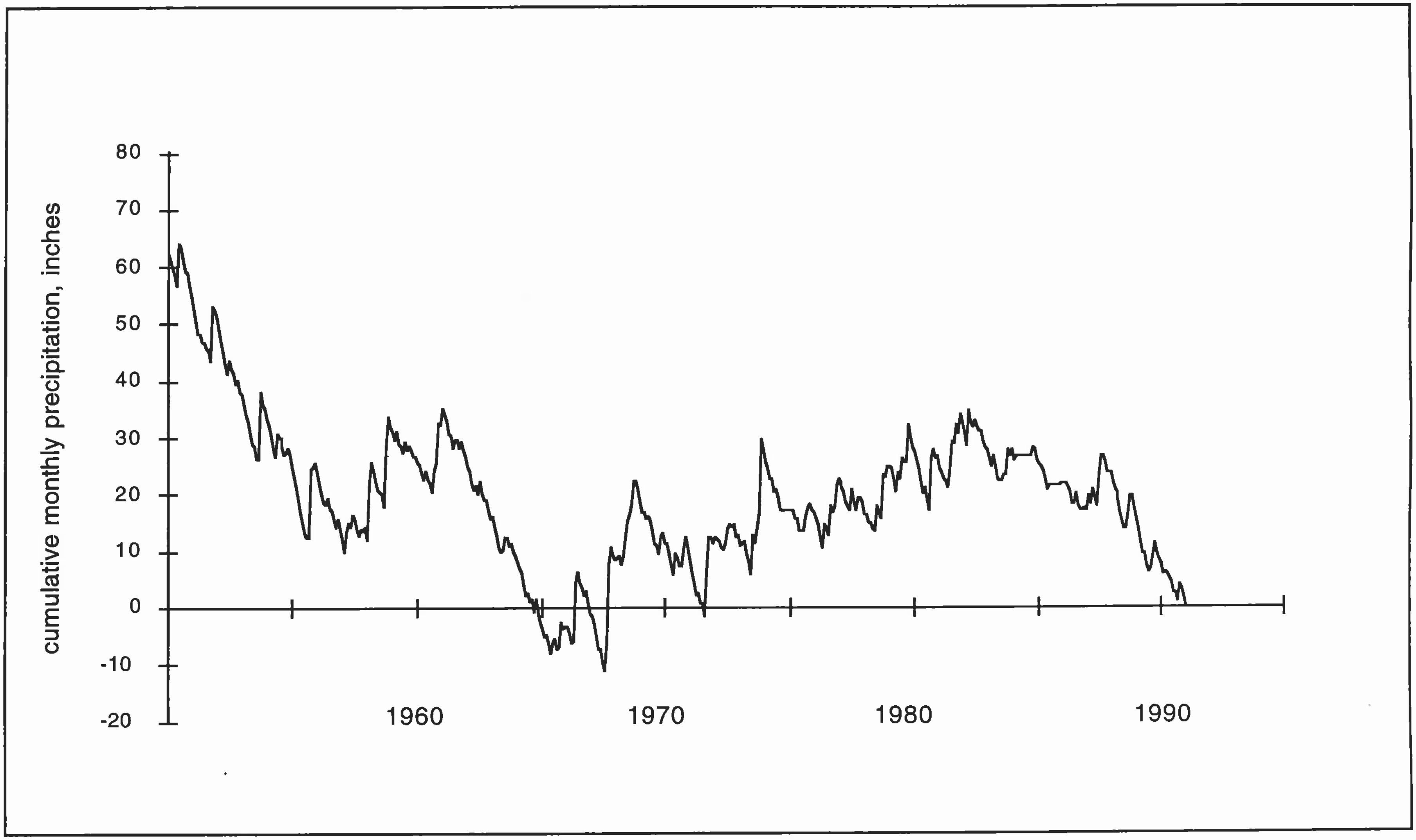


Figure 2-6b. Cumulative departure of monthly precipitation from mean, Sarita gauge 1950-91

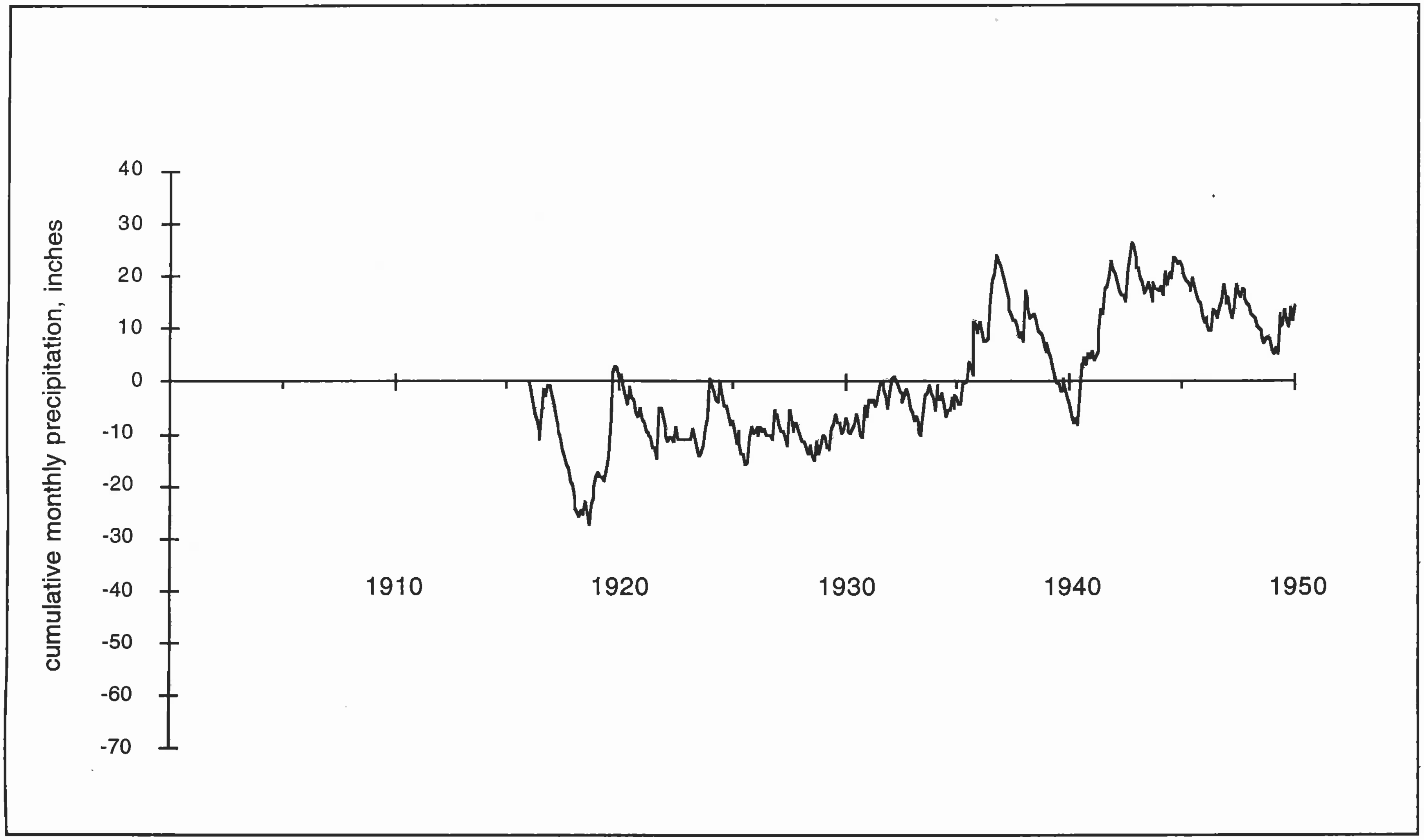


Figure 2-7a. Cumulative departure of monthly precipitation from mean, George West gauge 1916-50

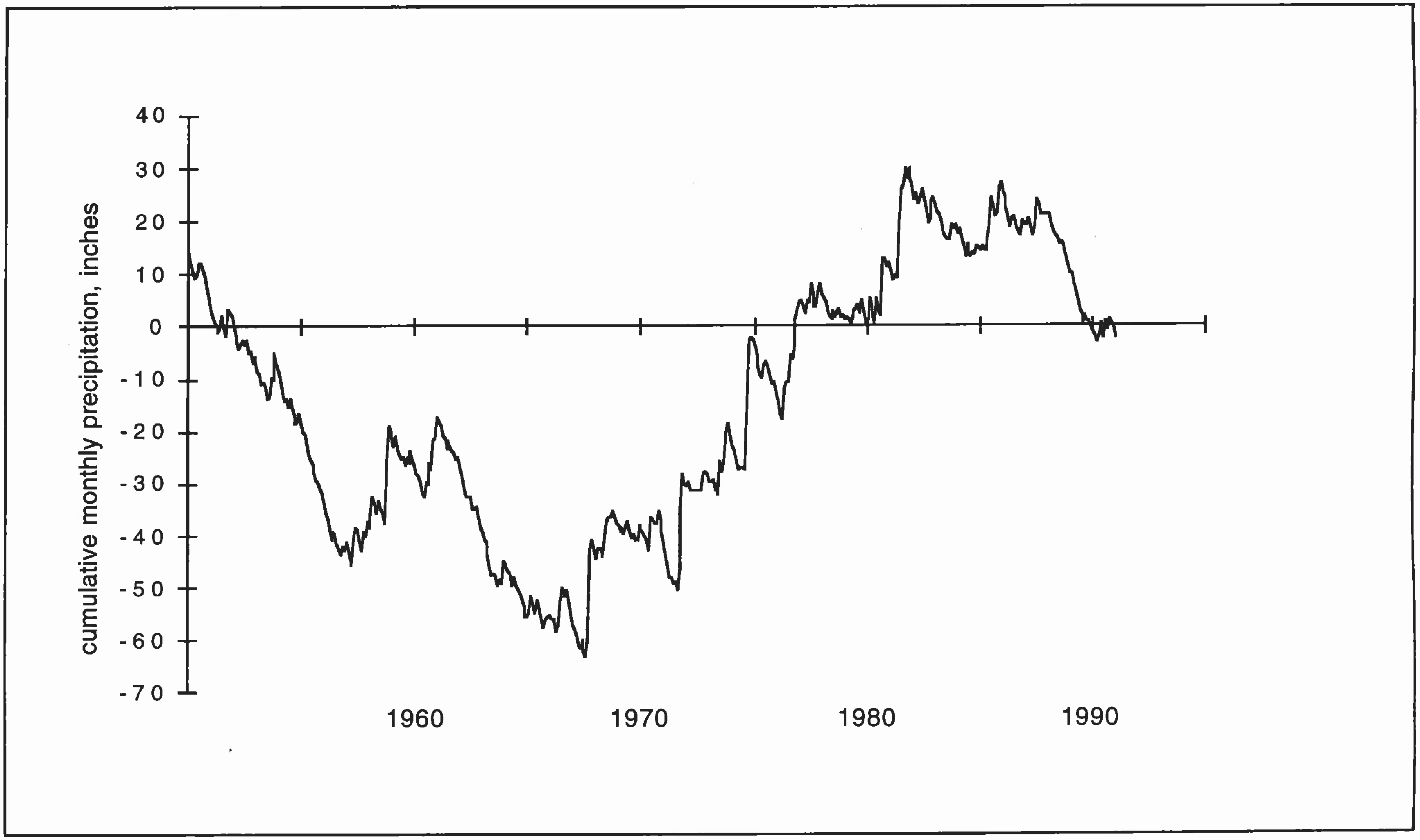


Figure 2-7b. Cumulative departure of monthly precipitation from mean, George West gauge 1950-91

- the region is drought-prone: generally cumulative rainfall is in a state of decline between widely spaced high-rainfall months
- the periods 1920-45 and 1968-85 were ones of overall abundant rainfall
- the periods 1950-68 and since 1985 are ones of relative drought.

The rate of decline of the cumulative rainfall curve is a measure of the intensity of the drought. By this measure, the most intense droughts in this record are in the late 1910's, the mid-1950's, the early 1960's and the late 1980's. The drought-prone nature of the area is indicated by the fact that about 65% of the monthly rainfalls are below average, since 1950 about 70%.

The problem of drought in the study area has been contended with since the first European settlements. In 1852 water became so scarce that for a time Col. Kinney had it hauled in barrels from the Nueces (Caller-Times, 1952). Military operations were hampered during the Civil War; according to Evans (1899), "The drought of 1863 and 1864 dried up the water and grass between the Nueces [Major Nolan] and Rio Grande [Col. Ford], so that the passage of the troops from one to the other was attended with much suffering to the men and teams." In Corpus Christi, the public artesian well drilled by Gen. Taylor helped during those times, but in 1871, when this area was in the throes of a "torturous drought", the well ceased to flow. A subscription fund was mounted and the well re-drilled, but did not survive for long. In 1872, the problem was temporarily solved by installation of a "Town Pump" (Allhands, 1931).

The drought of 1876-1879 was especially severe and had a major impact on cattle ranching in the region. The "great die-up" of 1878-79 ruined many small ranchers on the coastal prairie (Stephens, 1964). At this time, Collins (1878) made his survey of the passes through Mustang and Padre Islands. He noted overgrazing on these islands, the grass being fast destroyed and the cattle "which nearly starve on it." Further, he observed that the dunes were "...fast being carried inland by the destruction of the protective coating of grass by cattle." While his observations are indubitably accurate, the extreme state of the islands (and the cattle) was probably as much due to the intense drought underway at the time, of which Collins was probably unaware. Drought returned again in 1886, following an especially hard winter of 1885-86, and cattle shipments reduced to a standstill.

During the drought of the 1890's the Corpus area had a brief flirtation with rainmaking. In 1891, G.W. Fulton, Jr. observed a USDA experiment in El Paso in which dynamite was floated to cloud level in balloons and exploded, and appeared to produce rainfall. Based on his report, a group of ranchers, including George Fulton, Sr., Robert Kleberg and N.G. Collins, underwrote the costs to repeat the experiment in the Corpus Christi region. This was carried out on 26 September 1891 at Corpus Christi and produced heavy rain where no rain was falling before the explosion. Later, on 17 October, the most spectacular event yet was carried out at San Diego, involving massive explosions from balloons, mortars and cannons (sent from Ft. Bliss). Later in the evening 0.5-in of rain fell, and there were also reports of several inches in the desert region southwest of San Diego. But because a norther blew in during the climax of explosions, the association of rain with the explosions could not be unequivocally demonstrated. Supporters considered the experiment a success, and skeptics a failure, but no further rainmaking efforts were pursued in the Corpus Christi area. (See Stephens, 1964.)

The obverse face of the prevalent droughts in the region is the infrequent occurrence of excess rainfall events. The principal effect of these events on circulation in the bays is through the freshets that they produce through runoff into the river channels. These are treated later in Chapter 5 in the context of intertidal time scales of variability.

2.2.2 Evaporation

One consequence of the increasing aridity with distance southward along the Texas coast is that evaporation plays an increasingly important part in the surface water budget. On a long-term average basis, the zero crossover of *net* surface evaporation and precipitation falls in the vicinity of Matagorda Bay, so that the systems lying south of this point, including the entirety of the Corpus Christi Bay study area, have a net evaporative deficit. This is not the whole picture however. The region of zero deficit crossover migrates up and down the coast on a year-to-year basis, in response to the variations in meteorology, and the magnitude of the deficit is a strong function of season as well as location.

Estimation of evaporation for the Corpus Christi coastal area is problematic for three reasons: (1) there are major shortcomings in the use of pans as direct measurement; (2) the number of pan stations is small, and not well-situated for the coastal zone; (3) the periods of record available from the extant stations are limited, at best extending back to perhaps 1960. The fundamental problem with measuring evaporation by a pan is that the exposure and thermodynamics of a pan are fundamentally different from those of a large waterbody. This requires the use of an empirical, and uncertain, multiplier to convert pan evaporation to natural surface evaporation. Moreover, the sparsity of pan data in both space and time necessitates some rational means of extrapolation. In this study, a quantitative relation between pan evaporation and monthly mean air temperature was developed by adopting a Dalton-type form as a regression. The details are given in Appendix F. This relation could then be used to synthesize monthly evaporation wherever a record of air temperature is available.

The annual cycles of monthly pan evaporation at the upper and lower limits of the study area, based upon data from Rockport and Kingsville for the 1950-90 period, are shown in Fig. 2-8. (Air temperature data for 1953-58 were missing for Rockport and all of the other coastal stations in the upper bay area, so data from Beeville were substituted.) Clearly, there is a substantial seasonal variation through the year in mean evaporation, as well as a slight increase from north to south across the study area. There is also a decrease in precipitation from north to south (see Fig. 2-5), and the two combined create a significant geographical

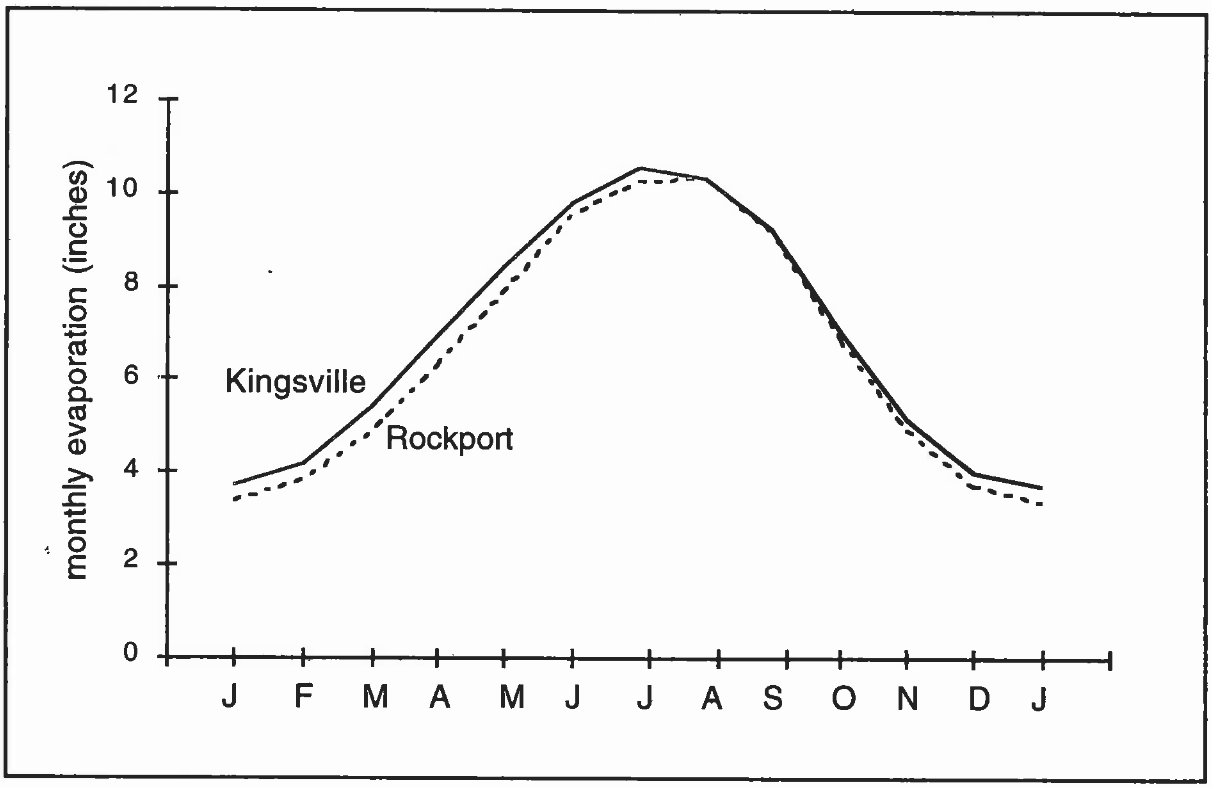


Figure 2-8. Mean monthly evaporation at northern and southern limits of study area, from 1950-90 temperature record

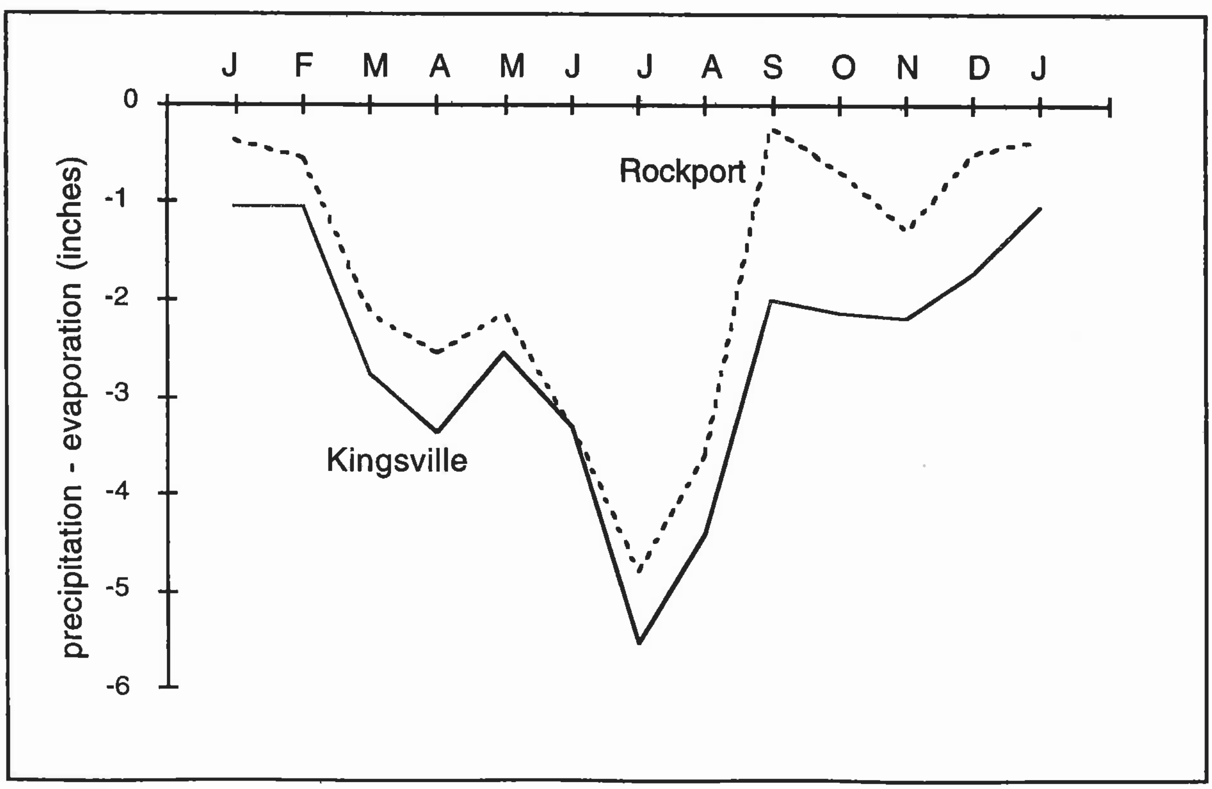


Figure 2-9. Mean monthly net precipitation (P-E) based upon rainfall record and data of Fig. 2-8.

range in the water budget at the surface of the Coastal Bend bays. Fig. 2-9 shows the 1950-90 average annual cycles of monthly surface *net* precipitation, computed from:

$$\text{Net precip} \equiv P - E = \text{precip} - C \times (\text{pan evap})$$

where C is the pan correction. For this study a value of 0.7 was used. This net precipitation is a measure of the evaporative stress on the bay itself, and when negative indicates an evaporative deficit, a net loss of water from the surface of the bay, the normal circumstance as evident from this graph.

The variation in P-E from year to year is also great, becoming particularly high during drought periods, when increased insolation and decreased precipitation combine. This is displayed in two ways. First, in Fig. 2-10 is shown the annual-mean net precipitation P-E for each of Rockport and Kingsville. Over this period, the evaporative deficit at Kingsville is 50% greater than that at Rockport. Moreover, this geographical difference was much greater during the drought period of 1950-70 than the relatively wet period of 1970-85. The large year-to-year variation in P-E should also be noted. In Fig. 2-11, the monthly P-E time series are displayed for Kingsville and Rockport, employing the same device as used for Fig. 2-6 of plotting the cumulative departure from the mean for each station. This better depicts the general trends in the variates.

2.2.3 Storms

Air-sea interaction is central to the circulation processes of the nearshore environment, and especially to systems like Corpus Christi Bay, which respond both directly and indirectly (via the Gulf of Mexico) to atmospheric forcing. Synoptic-scale storms could be expected therefore to have great potential for affecting bay circulations. While there is a variety of such disturbances, the two of greatest importance in the study area are midlatitude ("extratropical") cyclones and tropical hurricanes.

A characteristic feature of a developing cyclone is the formation of high gradients of atmospheric properties, usually associated with the convergence of two air masses. These high-gradient zones, which can become very well-differentiated at the surface, are the classical air-mass fronts, whose movement and evolution are a standard indicator of the life history of the cyclone. The formation, growth, intensity and trajectory of a North American cyclone are much more complex than the Atlantic storms that inspired the concept of frontal dynamics in the early part of this century. The strategic placement of the Rocky Mountains and, in their lee, the Great Plains, allows for entrainment of the dry, lee air at the surface into the circulation about the cyclone. This can lead to formation and movement of Pacific or dry-line fronts across Texas into the Coastal Bend area, or can bring dry colder air southward from northern latitudes. In combination with an upper-level ridge over the western tier of states, the flat, featureless Plains allow unhindered north-south excursions of polar air, so the frontal movement into

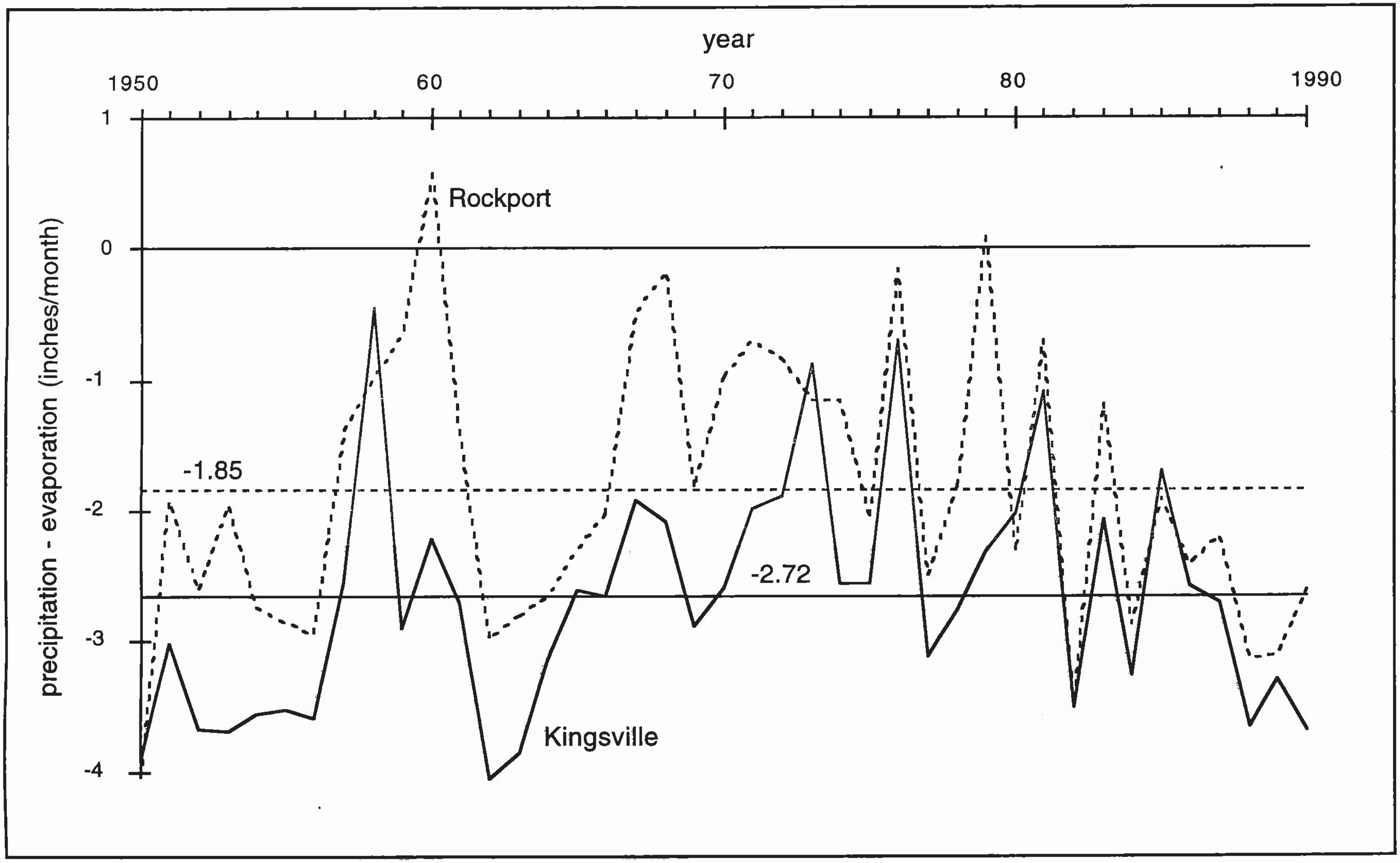


Figure 2-10. Annual-mean monthly precipitation - evaporation for 1950-90

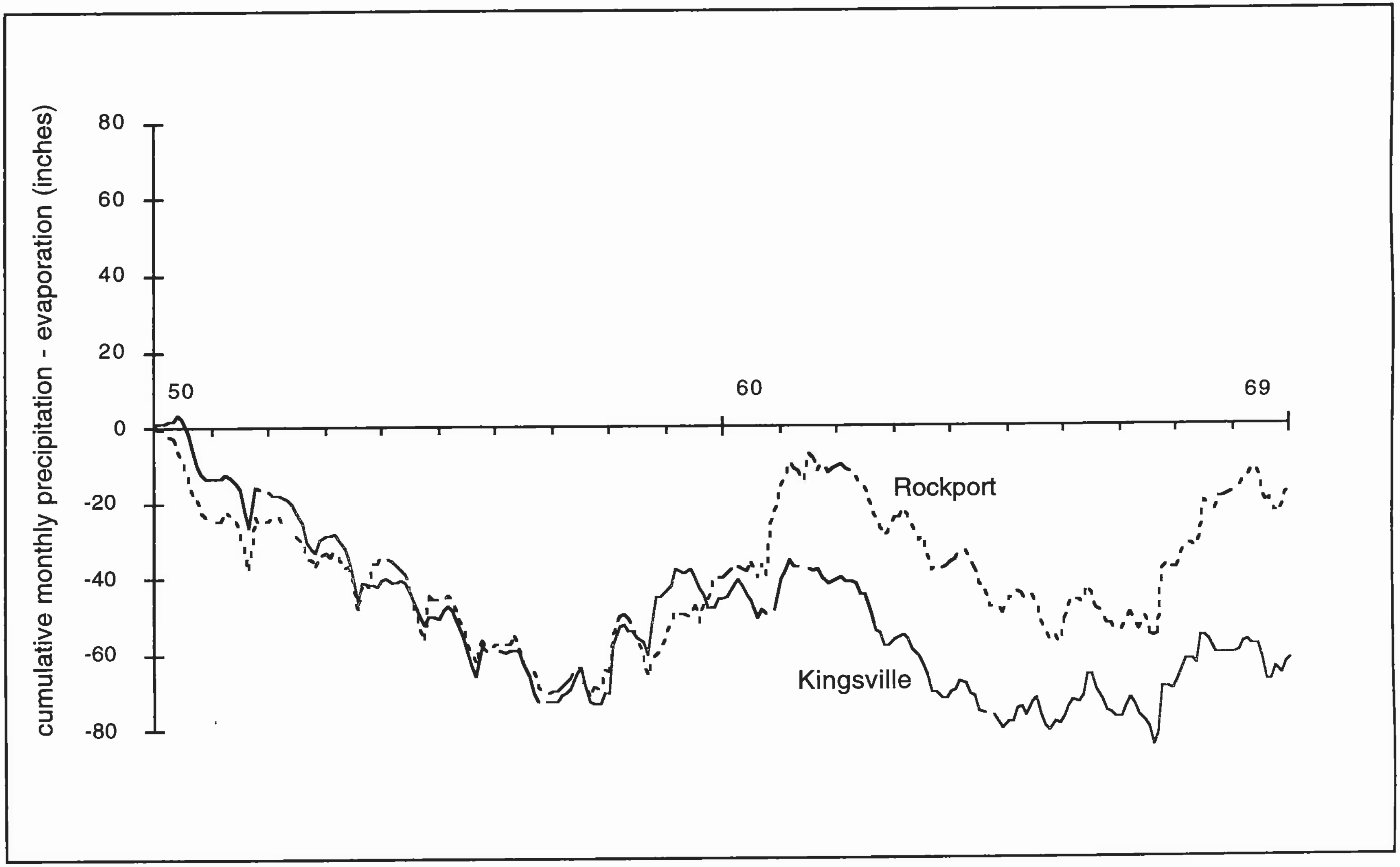


Figure 2-11a. Cumulative monthly net precipitation above mean, 1950-90

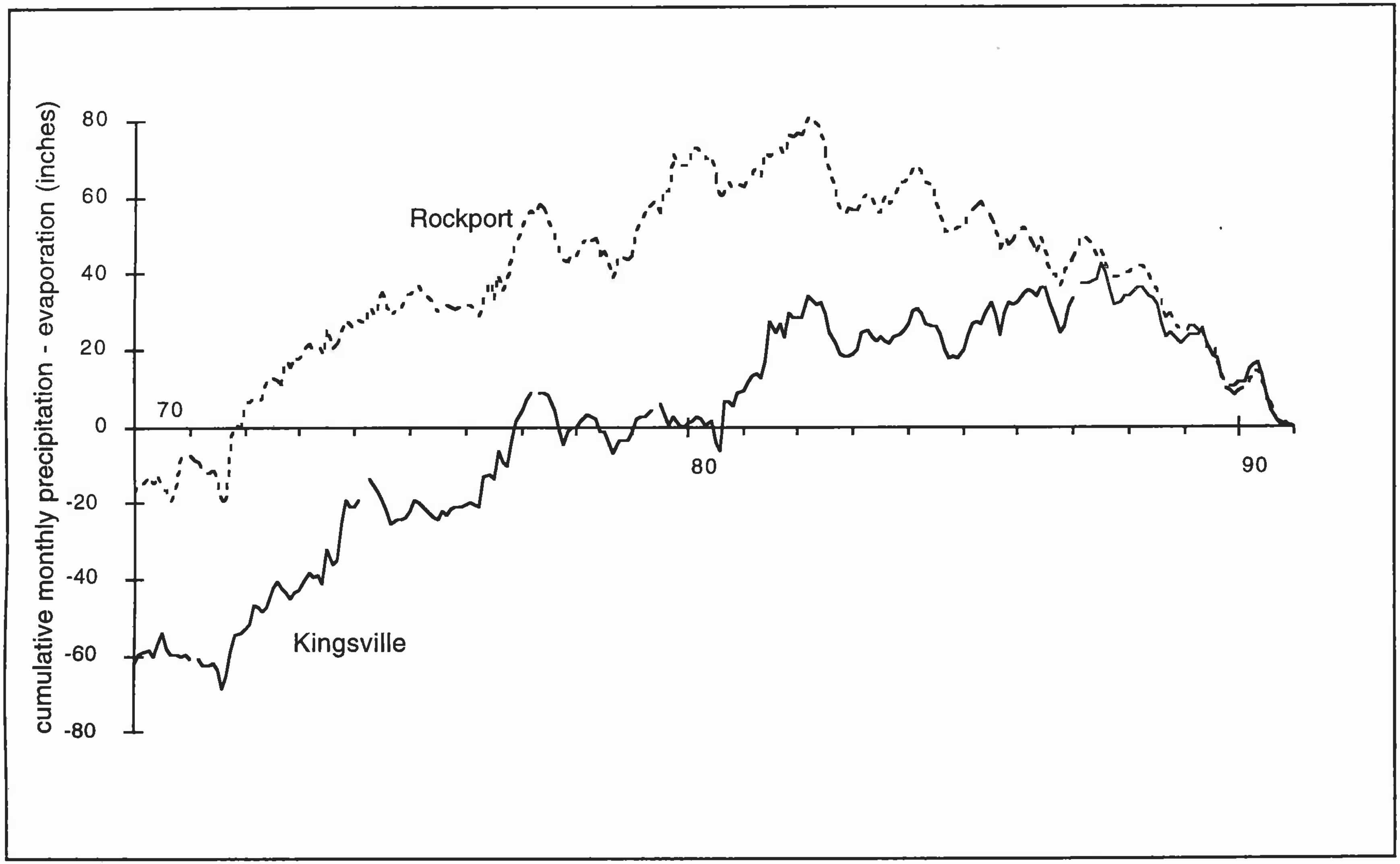


Figure 2-11b. Cumulative monthly net precipitation above mean, 1950-90 (continued)

Texas can attain considerable velocity, sometimes outrunning its upper-level support. As the cold airmass moves faster, the frontal gradient zone becomes almost interfacial. These are the legendary "northers" of Texas. The most extreme variety originates in winter when the cold airmass has remained over the Canadian snowfield long enough to lose considerable heat. This *arctic* airmass, now extremely cold and dense, is assisted by gravity as it spills down to the Gulf from higher elevations. (A review of meteorology is manifestly beyond the scope of this report as well as the patience of the reader. The polar-front theory of cyclone development, mainly applicable to North Atlantic systems, is summarized in many introductory textbooks on meteorology, and is described in some detail in Palmén and Newton, 1969. North American cyclones are discussed in Wallace and Hobbs, 1977, see especially Chapter 3. Bomar, 1983, is recommended for information about meteorology in general and Texas weather in particular.)

From the standpoint of the response of Corpus Christi Bay, what is important is that a norther, or, more generally, a frontal passage, consists of a relatively abrupt shift in wind from the southeast to the north quadrants, accompanied by replacement of marine air with drier (and probably colder) air at the surface. Figure 2-12 depicts a generic frontal passage across Texas, showing successive stages of the frontal position. The front (and associated pressure trough) is a zone of low-level convergence. As it enters the state from the northwest, Position A in Fig. 2-12, the normal onshore flow along the Texas coast is enhanced. As the front draws closer, Position B say, these onshore wind speeds increase. Then, as the front passes the coast, Position C, the actual windshift takes place, winds turning to the north. Depending upon the season of year and characteristics of the front, there may be a calming of the winds prior to their turning to north, or the wind shift can be sudden. Sometimes, the synoptic system may have insufficient energy to force the frontal boundary entirely through the state. The front can stall before reaching the coast or even retreat as a warm front, typically dissipating into a zone of convection and precipitation. Often, it stalls out along the coast. However, when the synoptic system has sufficient energy, the airmass and the leading front cross the coast and race out over the Gulf of Mexico, Position D in Fig. 2-12. Intense winter systems can penetrate as far south as Central America and spread over the Gulf to Florida. Such an incursion of cold air over the Gulf is referred to as an "outbreak" and, as will be seen, produces a dramatic response in the Gulf and bays.

The abruptness of northers in Texas was unexpected to new arrivals from the northeast in the last century. Olmsted (1857) in recording his travels in Texas in 1854 made special note of the plummeting temperatures after passage of a norther. There is almost a tone of awe in his remark of a 15°F fall in temperature in 15 minutes, accompanied by a "furious wind." While the temperature can drop 40-80° in 24 hours with a frontal passage, the more significant feature with respect to circulation is the abruptness of the windshift.

There are three primary climatological hazards to the organisms in the bay: freezes, freshets and droughts. With respect to the first, the occasional episodes of arctic outbreaks and associated freezing temperatures represent to Corpus

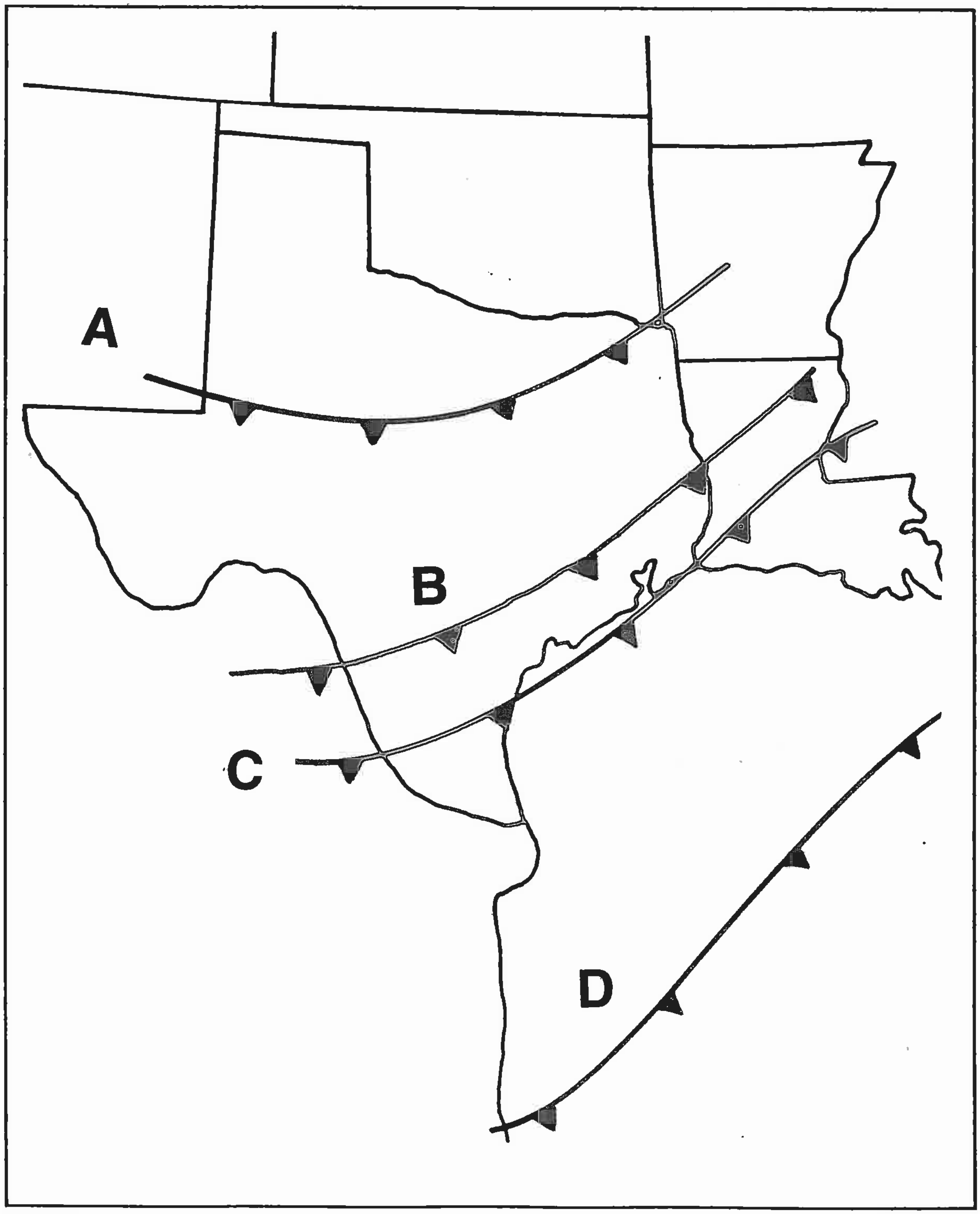


Figure 2-12. Schematic of stages in frontal passage across Texas coast

Christi Bay what the "jubilees" are to Mobile Bay. The history of the system is replete with episodes of decimation of the biological communities by freezes, after which the residents of the area enjoy a bounty of seafood from the simple effort of going on the water—and sometime merely to the water's edge—to collect it. Gen. Taylor's men found numerous half-frozen fish and sea-turtles in the bay in 1845, during that unusually cold winter (Caller-Times, 1952). From oldtimers in the area, Mrs. Sutherland (1916) learned of such events: "Some time in the '50's, on the 17th of March, St. Patrick's Day, the bay froze over near the shore, and the whole population was treated unlimited fish, the men going up the reef in carts, and picking up all that they cared to haul home, the fish being torpid from the unusual cold." She quotes from a newspaper clipping, "In December, 1871, Captain H. Hawley, of the schooner Bessie, brings in a fine lot of green turtles and distributes them among his friends. Fish are torpid from cold and many picked up in shoal water, particularly pompanos." These events continue to the present (Collier and Hedgpeth, 1950), one of the more severe recent episodes being the 1983 freeze, which was devastating because of its earliness in the season (19 December) and the two-week prolongation of freezing temperatures (McEachron et al., 1984).

The record was established on 12 February 1899, "The Big Freeze" (Huson, 1955, p. 276). Temperature fell to 6° F inland, around 10°F on the coast. 40,000 cattle were killed, and several ranchers wiped out. Mrs. Sutherland (who incorrectly gave the year as 1900) recalls, "Thousand of birds flying over Nueces Bay, north of town, were frozen, and falling into the bay, were swept to the southern shore by the fierce Norther raging, where they lay in a long windrow, in some places several feet deep." Dr. Cline* (1946) was in Galveston at the time, and personally logged the record temperature at that city of 7.5°F and observed extensive shore ice on Galveston Bay. From Port Arthur to Brownsville, fish perished by the tons. In Corpus Christi, dead fish along the shore had to be hauled off because the stench was unendurable (Cline, 1946). (At the time Corpus Christi was the largest cabbage mart in the world. Sutherland states that because the cabbage crop was lost to the freeze, a later crop was sought, and cotton was tried, being planted in alternate rows between the cabbage. Actually, the cabbage recovered, but cotton succeeded also, starting the cotton crop in the Corpus area.)

* The Cline brothers, Isaac ("Ike") and Joseph ("Joe"), were early meteorologists in Texas. Ike was chief of the Galveston bureau and Joe his assistant at the turn of the century. Joe sent the last report from the island just before the last telephone line to Houston went down on 8 September 1900, while Ike was evacuating people from the beachfront to the center of the island. Ike later became president of the American Meteorological Society and a world authority on tropical cyclones. His analytical and dispassionate description of the Galveston hurricane (Cline, 1926) gives no intimation to the fact that his wife perished in that storm. From 1903 until 1913, Joe was meteorologist at Corpus Christi. While at Corpus, Joe may have been personally responsible for the land boom of the early 1900's since he started to buy properties in the city, the first such purchases since the collapse of the Ropes boom. He was also the first to cultivate a winter crop of truck vegetables. Joe later became meteorologist at Dallas, where as "maligned, cussed, discussed and much beloved Texas weather man," he had a reputation for the uncanny accuracy of his forecasts.

Fronts are essentially midlatitude systems, more dramatically evidenced in winter. At the opposite end of the seasonal spectrum are the tropical vortices developed in the trade winds during summer. The most extreme form is, of course, the hurricane. The historical hurricanes which have significantly affected the Corpus Christi Bay system since 1900 are listed in Table 2-2. For those that actually made landfall in the Corpus Christi Bay study area, the approximate landfall location is given. We note that this catalog is limited to hurricanes only: tropical storms and minor depressions are excluded. Two immediate conclusions are inferred from Table 2-2. First, the occurrence of a hurricane landfall within the study area has had a relative frequency this century of about 1 in 12 years. Second, there have been over twice as many hurricanes affecting the study area but with landfall elsewhere, as there have been hurricanes making direct landfall in the area. One might also observe that the frequency of hurricanes making landfall in the study area is substantially less in the second half of the century compared to those in the first half. The most recent hurricane listed, Gilbert, deserves special mention. This storm achieved Category 5 status and record low pressure while offshore in the Gulf of Mexico. It miraculously weakened just before making landfall farther south than expected (200 km south of Brownsville), and most of the damage in Texas was in the South Padre Island area.

Hurricanes affect circulation of a coastal bay in three ways:

(1) Production of intense rainfall, and associated runoff
(2) Direct wind effects, especially setup on the bay, and generation of wind waves
(3) Indirect wind effects, through production of a storm surge

The relative importance of these mechanisms vary with the storm. Infrequently, one may completely dominate the other two. For example, Beulah (1967), which actually made landfall below Brownsville, was a diluvial storm, bringing heavy rainfall and widespread flooding to the Corpus area. Celia (1970) was a small, intense vortex with high winds but relatively little precipitation or surge. The 1919 storm, the third deadliest in the U.S. since 1900, wreaked its damage primarily through the storm surge. Generally, however, all three factors can be presumed to operate. Table 2-2 demonstrates that while direct landfalls in the area have been much lower after 1950 than before, the frequency of hurricane effects has not changed. Suarez and Ward (1978) found the upper Texas coast, above Matagorda Bay, to have roughly twice the likelihood of sustaining a hurricane landfall as the lower coast. This was based upon hurricane data for the period 1871-1978. Data through the present would not modify this conclusion materially. If one broadens the category of storm to include tropical storms, and includes effects of a storm on an area, independent of the landfall location, then one finds a much more homogeneous distribution of probability along the Texas coast (e.g., Henry et al., 1982).

Table 2-2 is limited to the Twentieth Century partly for convenience, partly because hurricane data becomes increasingly qualitative with age. There is some

Table 2-2
Hurricanes affecting Corpus Christi Bay study area 1900-96
Compiled from Neumann et al. (1978) and Henry et al. (1982)
and updated from records of the National Hurricane Center

date		*landfall*	*names*
Jun	1902	*	
Aug	1909	*	
Sep	1910	*	
Oct	1912	Baffin Bay	
Jun	1913	Baffin Bay	
Aug	1916	Baffin Bay	
Sep	1919	Baffin Bay	
Aug	1921	*	
Sep	1929	*	
Jul	1933	*	
Sep	1933	*	
Jul	1934	Rockport	
Aug	1934	*	
Jun	1936	Aransas Pass	
Aug	1942	*	
Aug	1945	*	
Sep	1958	Corpus Christi	Ella
Sep	1961	*	Carla
Sep	1963	*	Cindy
Sep	1967	*	Beulah
Aug	1970	Corpus Christi	Celia
Sep	1971	*	Fern
Oct	1971	*	Ginger
Sep	1973	*	Delia
Aug	1977	*	Anita
Aug	1979	*	Elena
Aug	1980	*	Allen
Aug	1983	*	Alicia
Aug	1983	*	Barry
Sep	1988	*	Gilbert

* landfall outside of the study area.

indication that the great storms in the Nineteenth Century exceeded the worst of the present century. The monster storms of 1875 and 1886, which obliterated Indianola, inflicted enormous damage on the Coastal Bend Bays, as did the hurricane of 1837. The Great Storm of 1816 must have pegged the scale. Information on these older storms is provided by Frazier (1921), Geiser (1944), Neumann et al. (1977), and Henry et al. (1982).

2.3 Tides

The quasi-regular rise and fall of water in the adjacent Gulf of Mexico is the most obvious, continuous and ubiquitous influence of the marine environment on the Coastal Bend bays. A significant component of this rise and fall in water level originates in the differential gravitational attraction of the earth-moon-sun system. This is what is meant by "tide" or, to avoid confusion with other sources of water-level variation, the "astronomical tide." The interested reader is referred to standard references in oceanography and marine piloting for descriptions of the mechanics of tides, such as Van Dorn (1974), Beer (1983) and Brown (1989) for general discussions, and Defant (1961), Neumann and Pierson (1966), Bowden (1983) and Pugh (1987) for advanced treatments.

2.3.1 Tidal analysis

As a starting point, an idealized problem is addressed of the response of a layer of homogeneous water on a uniform, frictionless globe in equilibrium with the impressed gravitational force of a distant astronomical body, considered to be the sun or the moon. The principal results of this "equilibrium tidal theory" are:

(1) two bulges are produced in the water surface, on opposite sides of the globe and along the line joining the centers of the globe and the distant body;
(2) rotation of the globe on its axis *with respect to the position of the distant body* creates an apparent motion of the tidal bulges relative to a fixed point on the globe's surface, so that a periodic water-level variation is experienced at half the period (twice the frequency) of rotation;
(3) additional long-term variations in the range or elevation of the distant body appear as modulators of the fundamental periodic variation;
(4) the effects of two distant bodies on the apparent water-level variation are simply superposed;
(5) parameters appropriate to the earth and sun imply a tidal period of 12 hours and a tidal range of 0.48 m;
(6) parameters appropriate to the earth and moon imply a tidal period of 12.4 hours and a tidal range of 1.1 m.

This rather spartan theory in fact allows inference of many aspects of tidal behavior. Coupled with orbital parameters determined by astronomy, (2), (3) and (4) allow identification of the periodicities to be expected in tidal variations. While great astronomical precision can require as many as several hundred such constituents, the basic behavior of tides can be determined with a relatively small number, notably the diurnal periods of 24 (solar) and 24.8 (lunar) hours and their first harmonics (12 hrs solar, 12.4 hrs lunar), the fortnightly variation of lunar declination (27.2 days, or 13.6 days in the absolute value of declination, hence the term "fortnightly"), variations of earth-sun and earth-moon distance, the period of rotation of the lunar orbital plane with respect to the ecliptic, and a few others. The declination (i.e., angular elevation) of the distant body above the equatorial plane (the plane of rotation) can be seen to induce a diurnal inequality in the highs and lows. For lunar tides, this is the basis for equatorial and tropical tides. When the sun and moon are considered together, (4) implies that the maximum tidal elevation—spring tide—will occur when they align with the center of the earth so their respective tidal bulges coincide, and the minimum elevation—neap tide—will occur when their lines to the earth's center lie perpendicular. Also, the effect of the moon is indicated to be much greater than that of the sun, over a factor of two, due to the moon's proximity to the earth.

That this cannot be a complete theory of tidal behavior is apparent from (5) and (6), since this theory predicts a relatively modest tidal range of a little over a metre. The deficiencies of the theory lie in the original assumptions. In fact, the real earth is not uniform, but has bathymetric variations of rises and deeps, and continental barriers to flow. The water surface is not free to follow the movement of sun and moon. Moreover, the real ocean is not frictionless, nor is it homogeneous. Substantial drag and inertia greatly affect the response of the ocean. While the complete mathematical problem cannot be solved, it does indicate that the real ocean will lag behind the orbital forcing, the tidal response will be greatly modified by bathymetry and physiography, and new periodicities will be generated by nonlinearities and higher-order interactions. The real ocean will act like a filter, selectively amplifying certain components of the tide, while reducing or eliminating others, and sometimes supplying frequencies of its own. The practice of tidal analysis is based upon long-term measurement of water levels at a given site which are then subjected to mathematical analysis to extract the frequencies present. Once these are quantified, they can be used in conjunction with long-term orbital predictions to predict tidal behavior at that site.

One must realize that this analysis procedure will quantify the energy present in a particular frequency derived from astronomical considerations, but cannot distinguish between the energy supplied by gravitational effects and that from non-gravitational processes. For example, a 24-hour periodicity is induced by the changing position of the sun in the sky that is truly tidal. The same periodicity is created by the nontidal processes of heating and cooling of the water. A "tidal" analysis will include both effects in the 24-hour constituent. Therefore, nontidal effects will be reflected in the constituent amplitudes determined by a tidal analysis.

2.3.2 Tides in the Gulf of Mexico

As oceans go, the Gulf of Mexico is bush-league: a minor, shallow indentation on the west shoreline of the Atlantic, whose exchange with the sea is hampered by a near blockage of its opening (by Cuba and the Yucatan peninsula). This blockage, in itself, could be expected to act as a filter for some of the tidal frequencies even before the tide traverses the length of the Gulf. Figure 2-13 shows the measured tide on the seafront at Bob Hall Pier for a period relatively free of atmospheric disturbances, so that the variation is close to being a pure astronomical tide.

To a first approximation, the Gulf seafront tide is a superposition of a 12.4-hour semidiurnal and 24.8-hour diurnal tide, the latter modulated by a 27.2-day period arising from the declination of the moon, all of which is superposed on a long-term "secular" semi-annual rise and fall. In the upper panel of Fig. 2-14 is shown the same record as Fig. 2-13 (with a compressed vertical scale), and in the lower panel is the synthetic record using only the three periodicities of 12.4 hrs, 24.8 hrs and 27.2 da. While the agreement can be made even better by addition of a few more frequencies, it is clear that these three alone account very well for the observed variation. (Those familiar with spectral analyses of coastal tides in Texas will realize that a 24-hr component is also present, and in some analyses appears as prominent as the 24.8-hr component. They may puzzle over why Fig. 2-14 indicates that the 24-hr component is unimportant in accounting for the major tidal variation in the Gulf. The 24-hr component is artificially enhanced if the analysis is limited to a short period of record, e.g. 1 year, or if the record is noisy due to meteorological effects, and the spectral procedure does not adequately account for these corruptions. The reason for the enhancement is that one of the sidebands resulting from the 27.4 day modulation of the 24.8-hr signal turns out to be close to 24 hours, so that noise in the signal "leaks" into the 24-hr component.)

Since only 30 days are shown in Figs. 2-13 and 2-14, the longer secular variation is not apparent. Figure 2-15 displays a full year of such data, for 1995, averaged by a 14-day sliding average to remove most of the diurnal and fortnightly fluctuation, and expose the longer-term pattern. The semi-annual variation of 1995 would generally be regarded as "normal" with clear maxima in spring and fall, and clear minima in winter and summer. However, a plot of the last five (complete) years of data, similarly averaged, shown in the lower panel of Fig. 2-15, demonstrates that the regular variation of 1995 is in fact rather anomalistic, and this semi-annual variation exhibits considerable year-to-year differences. (This is, indeed, why the label "secular" is demanded.)

The semi-annual variation is generally considered to be dominated by the winter minimum and fall maximum (e.g., Chew, 1964). With respect to the extremes of elevation, this is correct, the fall maximum being usually the highest water level attained, and the winter minimum being the lowest. In terms of consistency in the calendar, however, the summer minimum and fall maximum would be considered dominant, the former occurring regularly in July and the latter in October. The winter minimum, in contrast, can occur any time from December to March, and the spring maximum any time from April through June. There are some years when there are multiple maxima in winter and/or spring.

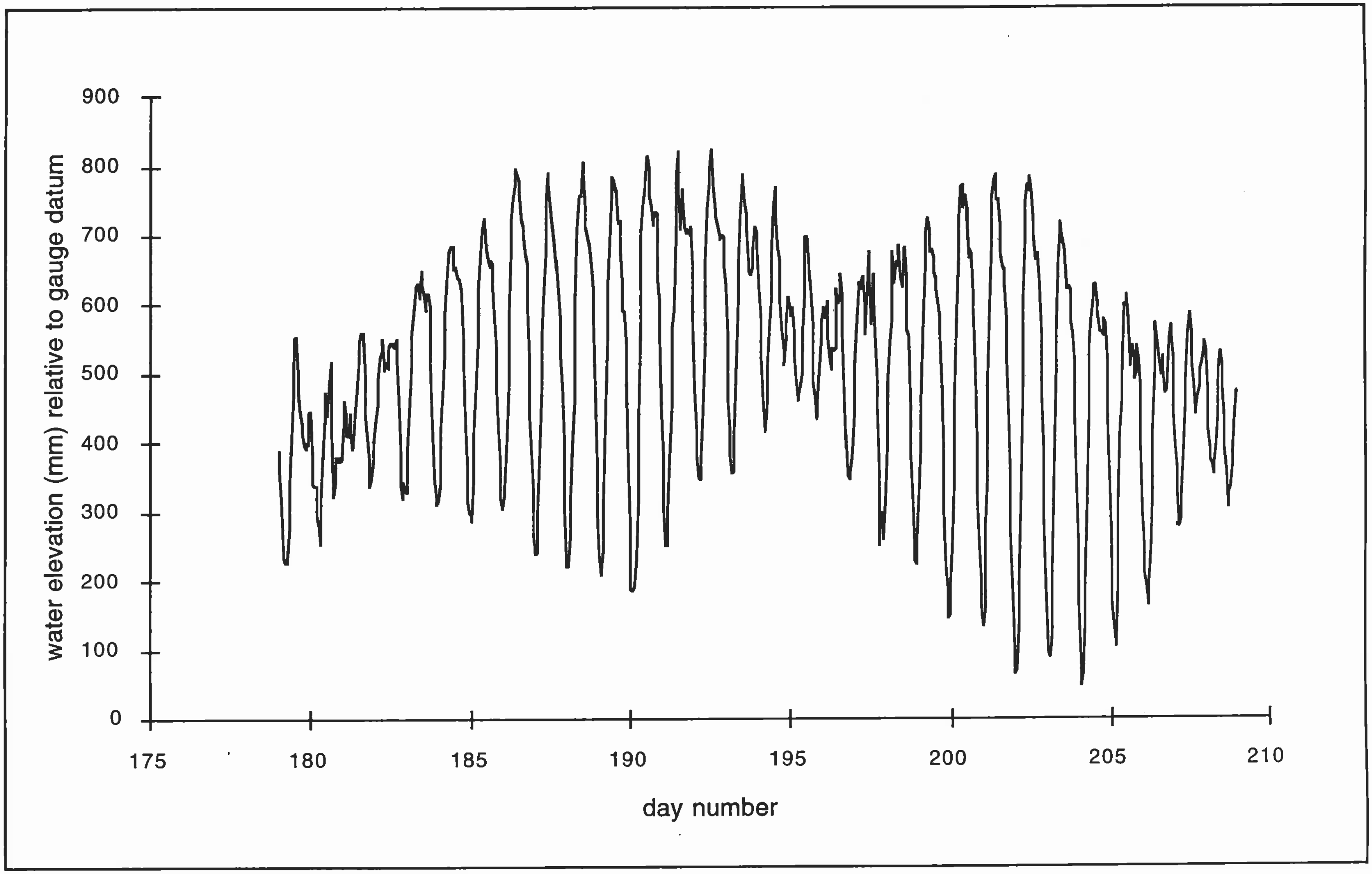


Figure 2-13. Observed hourly water levels at Bob Hall Pier, July 1994.

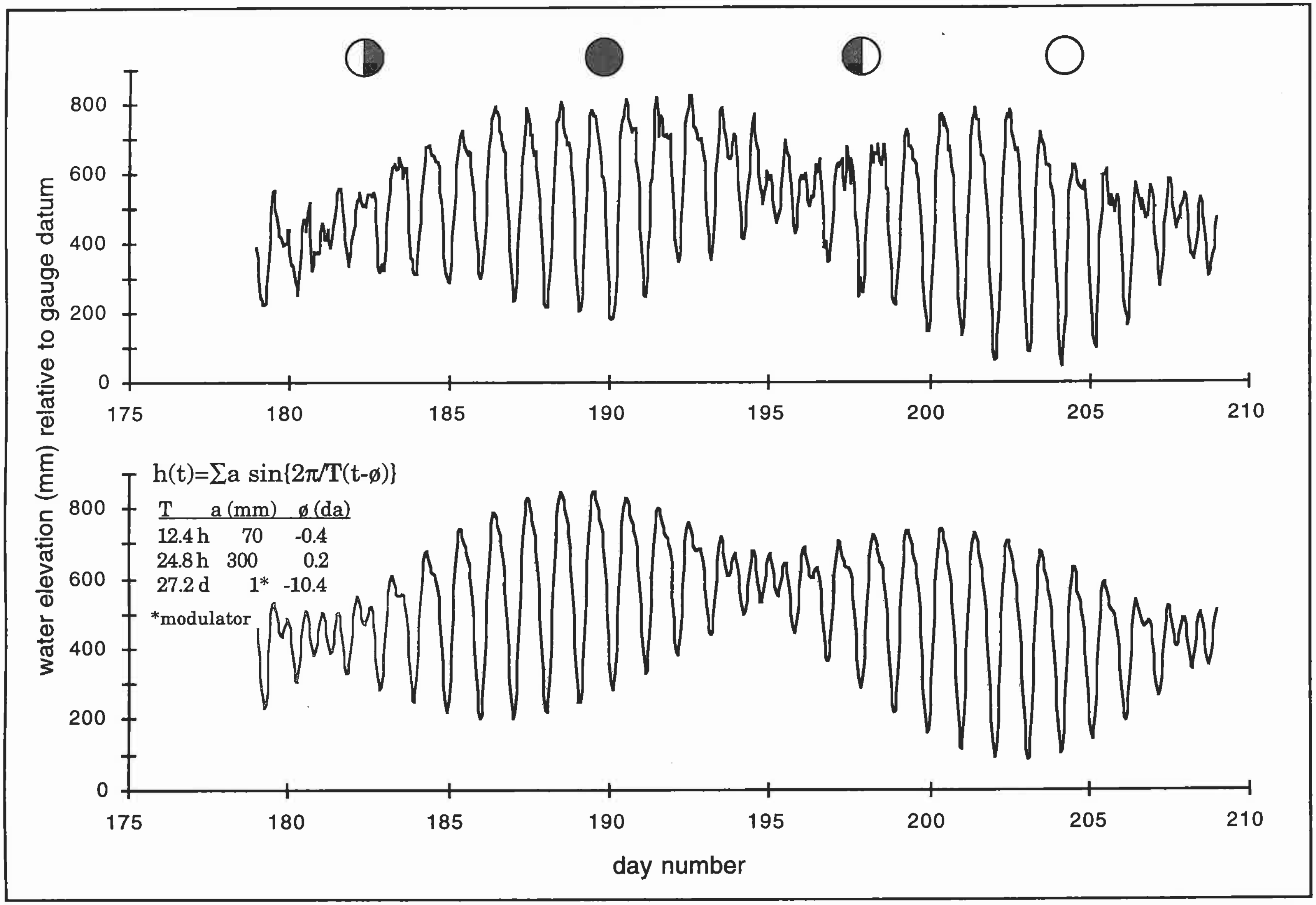


Figure 2-14. Observed (above) and computed hourly water levels at Bob Hall Pier, July 1994.

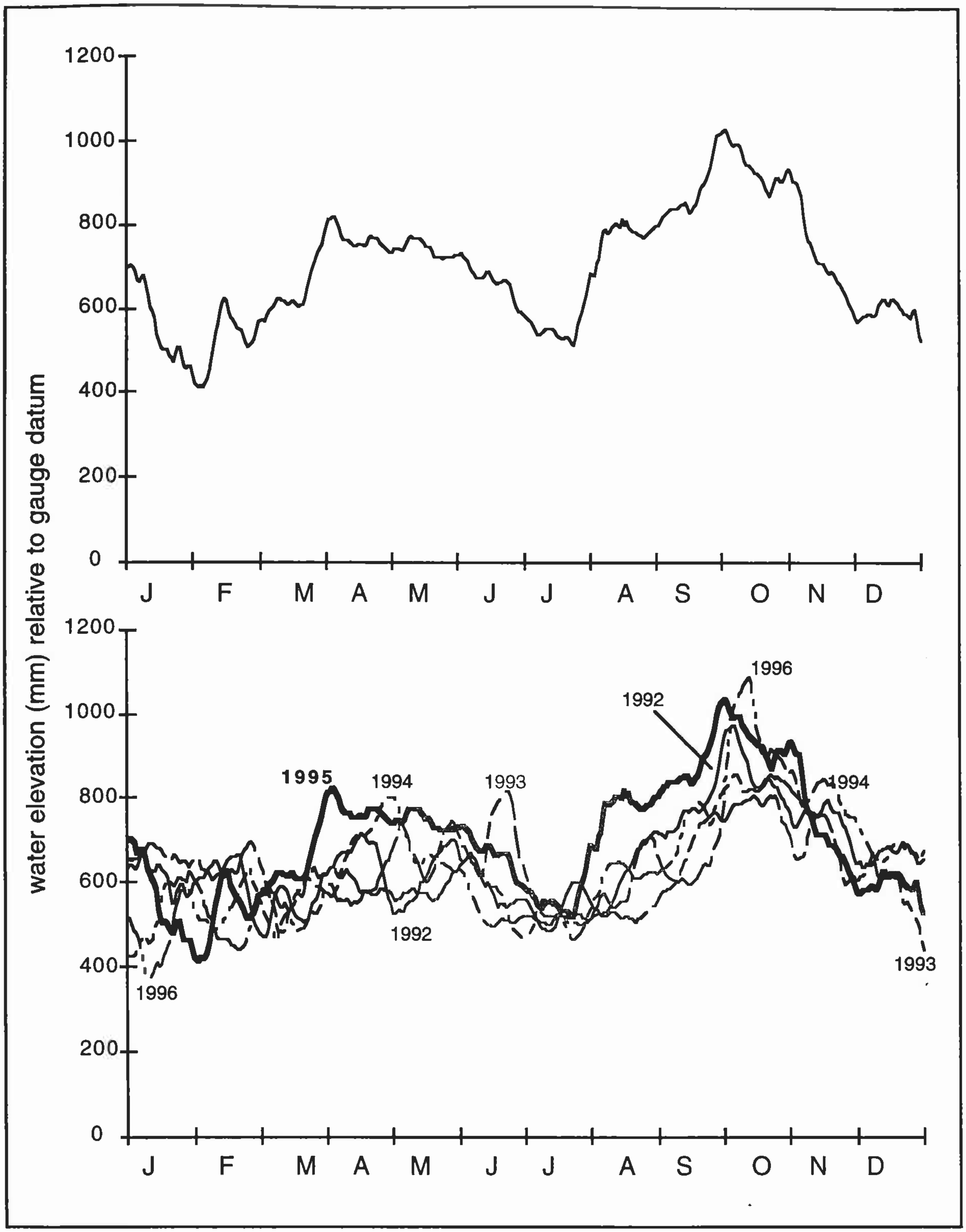


Figure 2-15. Secular mean water level variation at Bob Hall Pier: above, 1995 data; below, 1992-1996 data.

The physical cause of the secular semi-annual variation is not well understood. The winter minimum is thought to be a combined result of frequent frontal passages and a steric decrease in water level due to the colder temperatures. With respect to the latter, about a 0.15 m change in water level from summer to winter would be expected based upon the normal seasonal variation in water temperature. But the actual correlations of low water levels with temperature are not very convincing. The spring and fall maxima are considered to be the result of increasing south wind set-up in conjunction with the onshore flow from the Gulf. The sharpness and regularity of the fall maximum, however, do not seem to be well-associated with frequency of onshore winds. The summer minimum, which is most pronounced along the south Texas and northern Mexico coast (Blaha and Sturges, 1981), remains a total mystery. (Proposed mechanisms include Ekman convergence, see Chew, 1964, and development and detachment of a western boundary current, Sturges and Blaha, 1976.)

3. EVOLUTION OF THE CORPUS CHRISTI BAY SYSTEM

> The entrance to Aransas Pass is obstructed by a bar, which has been improved by the construction of two jetties extending over a mile into the Gulf, and by dredging. ... Port Aransas, inside the entrance on the southwest side, is the headquarters of the construction force employed upon the improvement of the pass. ... In approaching Aransas Pass in daytime the first object sighted is a water tower 145 feet high located on Harbor Island opposite the inner end of the pass. Smoke from the dredges used in improvement of the pass may also be seen.
>
> — United States Coast Pilot, 1916

During the Pleistocene, from approximately 1600 x 10^3 yr BP to 18 x 10^3 yr BP, the earth was subjected to four great periods of glacial advance. The vacillating climate that produced these glaciations is now considered to be driven by long-term changes in the geometry of the earth's orbit, dominated by a 100,000-yr periodicity (Hays et al., 1976). Sea level in the Gulf of Mexico tracked the advance and retreat of the glaciers, lowering during the glacial advances and rising during their retreats ("interglacials") on the order of 100 m. Each period of glaciation and deglaciation actually consisted of a series of minor fluctuations in advance and retreat of the ice cover (perhaps indicating a bistable nature of global climate), see Hays et al. (1976) and Broecker (1975). Interpretation of the geological record indicates that the most recent glaciation, the Wisconsin, consisted of two advances separated by an interglacial. The first glacial maximum, the "Early Wisconsin," was about 90,000 yrs BP and the second, "Late Wisconsin," about 18,000 yrs BP, see, e.g. Morton and McGowen (1980). More recent inferences based on detailed cores from lakes, ice sheets, and the sea bottom, especially during the CLIMAP project, now indicate that the Wisconsin was a period of highly variable ice cover superposed on a increasing trend of glacial advance over about a 120,000-year period.

During the Late Wisconsin, great continuous ice sheets 3000-4000 m thick extended over the higher latitudes of the northern hemisphere continents, locking up 50 x 10^6 km^3 of water and lowering sea level by about 120 m relative to present (see Denton and Hughes, 1981). Insofar as the Texas coast is concerned, there is no doubt that sea level reached a minimum during the Pleistocene 18,000 yrs BP, and that this was preceded by an brief interglacial maximum in sea level perhaps 65,000 yrs BP that was somewhat lower than present sea level. The chronology and elevations of earlier sea level maxima during the Wisconsin advance are less certain (e.g., Shackleton, 1988). During the sea-level minimum of 18,000 BP, mean air temperature was obviously cooler. Extensive lakes developed in the Great Basin, indicating a moister climate in the southwest U.S. (though how much of this can be attributed to precipitation increase, versus suppressed evaporation and increased meltwater, is unknown). Prevailing winds in the Great Plains were more northwesterly (Wells, 1983) and wind speeds were substantially greater (say, 50%) than present; these conditions can be presumed to translate to a greater frequency and higher speeds of northerlies in the Texas coastal zone. (Wells, 1983, reported analysis of relict dune features in the study area that indicated a prevailing northeasterly wind, compared to modern features which indicate southeasterly winds.) Simulations of the 18,000 BP climate using GCM's (Kutzbach and Wright, 1985, Kutzbach, 1987) depict a prominent jet stream over the North American southwest and southern states, demarcating the locus of a zone of enhanced precipitation (ca. 30%). Whether such a zone of enhanced precipitation would have applied to the Texas coast is conjectural (and the cautions of Ward and Proesmans, 1996, regarding the application of GCM's to precipitation simulation should be borne in mind), but it seems likely that the variability of precipitation, and occurrence of extreme precipitation events would have been greater than in the present climate.

For the Texas coast during the 18,000 BP sea-level minimum, there are several implications. The present coastline lay 100 km inland (i.e., the 18,000-BP Texas coast lay 100 km farther out than the present, e.g. Winker, 1979, Morton and Price, 1987), and was dominated by fluvial processes, *viz*. the channels and floodplains of the rivers. These rivers, in turn, were actively incising their channels and scouring their floodplains, perhaps assisted by an enhanced frequency and intensity of diluvial storms. (Blum et al., 1995 suggest that the Texas rivers carried a higher discharge but with a smaller variance, so that out-of-bank flood events were less frequent than characteristic of the last 5,000 years.) Moreover, the increased erosion meant that the riverine sediment load would have been greater and probably coarser than present, much of which was deposited in what is now the nearshore and coastal zone (see Morton and Suter, 1996). The general physiography of the modern coastal zone is considered by geologists to be an expression of depositional features established during the Pleistocene, *viz*. the divides between the principal river channels, the riverine deltas, and strandplains (see McGowen et al., 1977).

After 18,000 BP, the climate changed dramatically. Most of the glaciers vanished rather abruptly (on a geological time scale) from about 14,000-6,000 BP accompanied by a rapid increase in sea level of 100 m in the same time interval (e.g., Ruddiman, 1987, Fairbanks, 1989). During the early stages of glacial retreat, until about 11,000 BP, glacial meltwater discharged primarily down the Mississippi into the Gulf of Mexico. Once the St. Lawrence drainageways cleared of ice, around 11,000 BP, much of the meltwater was shunted to the North Atlantic (Ruddiman, 1987). There is evidence that global mean temperatures were in fact warmer at this time (a warm "pulse"), and cooled during the Holocene. During this same interval, the enhanced runoff of the glacial climate was apparently sustained (and the lakes of the Great Basin were maintained). As the sea encroached over the ancestral Texas coastal plain, the locus and character of deposition changed from fluvial to deltaic, with increasing littoral influences. The floodplains and river valleys inundated by the rising sea were to become the modern coastal bays. The periphery of the drowned floodplains was exposed to wind waves, driven by the increasingly prevalent trade winds, which eroded and sculpted the lee shorelines. Sediments from both riverine and marine origins were trapped and deposited within the river estuaries.

By 5,000 BP, the atmospheric and oceanic circulations had acquired more-or-less their present configurations, and the climate became somewhat cooler and drier than characteristic of the early Holocene. The general view is that sea level continued to rise but at a much slower rate than during the previous 10,000 years, to its modern level, which is practically a "stillstand," see Brown et al. (1976). There is some evidence from archaeological excavations (Prewitt et al., 1987) that a highstand was acquired perhaps 4,000 BP about 1.5 m above the present level, and that sea level has been declining for the past 2,000 years to its present levels. Morton (pers. comm., 1997) notes that this fall in sea level probably occurred shortly after the highstand, rather than gradually. The wide barrier islands are thought to date from about the close of the Holocene, 5,000 BP, developing from precursor barrier islands formed during the rising sea level (Morton and Price, 1987). The eolian sand sheet and the associated Mudflats of the Laguna Madre are generally considered to be a more recent feature, but still prehistoric.

While this brief summary clearly indicates that the morphology of Corpus Christi Bay on a time scale of millennia is indeed mutable and evolving, on a time scale of the historical presence of man, this natural morphology has been practically static, the exception being the short-term responses to coastal sedimentary processes and to major hydrometeorological events. On this shorter time frame, man himself has become the primary agent for physical change to the system, and the historical evolution of Corpus Christi Bay is driven by human settlement and development of the system. Many of these alterations have had consequences in modifying circulation in the system.

3.1 Inlet projects

Like all of the bays of Texas, the prime driver for modification of the Corpus Christi Bay system was the requirements of navigation, and the prime requirement for navigation was access between the bay and the sea. Therefore, the navigation evolution of Corpus Christi Bay, like its hydrography, begins with the inlets. Throughout the Nineteenth Century, there were two natural, quasi-permanent inlets to the study area affording navigational access, Aransas Pass and Corpus Christi Pass. Aransas Pass, the deeper of the two, was the main navigational entrance to the bay from the time of the Spanish. In many respects, the history of navigational improvements in the bay tracks the engineering projects to improve Aransas Pass. Alterations have also been implemented in the minor inlets, not for navigation, but to improve biological exchange.

3.1.1 Aransas Pass

In their natural state, all of the inlets of the Texas coast were surmounted by bars on either end. The outer, or ebb, bar, where the tidal current flowing out from the bay to sea diverges and, losing velocity, deposits much of its sediment load, was an arc of shallow sand, over which an entering vessel had to pass. This was frequently the most hazardous part of a voyage. In the Nineteenth Century, the controlling depth over the outer bar of Aransas Pass was generally 8-12 ft. Certainly for the early Nineteenth Century, 12 ft was adequate to allow passage of most ships, provided the channel of greatest depths through the bar could be located. (Linn, 1883, describes his crossing of the Aransas Pass bar in April 1834.

Table 3-1
Summary of least depths in principal coastal inlets along Texas coast ca. 1840 compiled by Muir (1943)

Inlet	*controlling depth (ft)*	*comment*
Sabine Pass	8	soft mud
Bolivar Pass	12	hard sand
West Pass *	10	
Paso Cavallo	11	
Espíritu Santo Inlet *	4	
Aransas Pass	8	
Corpus Christi Pass *	4-5	

* see text

His schooner ran aground on the bar to port, and was lifted by a roller onto the shallows where it permanently stranded. The following day, while Linn was still aboard his immobilized ship, two more vessels attempted entry. The first, steering toward Linn's schooner, grounded on the bar and was broken up by the surf. The second ran into the breakers on the starboard bar but managed to struggle through the pass only to be grounded permanently on a mud bank.)

Muir (1943) compiled observations on the controlling depths of the Texas inlets around 1840 summarized in Table 3-1. These were based upon reports by E. W. Moore, who was commanding officer of the survey party of the Texas Navy assigned to survey the coast, and (marked with asterisks in Table 3-1) an 1847 map of Texas compiled by S. Hunt and J. Randel from surveys at the Texas General Land Office. (West Pass probably refers to San Luis Pass, and Espíritu Santo to Cedar Bayou.) Col. Fulton (1880) reported that in the period 1837-39, during which he was the collector of taxes for the Republic, vessels drawing 12-14 ft passed easily over the Aransas Pass outer bar.

The disparity in these values of the controlling depth at Aransas is because the outer bar varied greatly depending upon waves, tides, and recent hydrometeorological history. This is well illustrated by the report of Capt. George B. McClellan to the Chief of Engineers of January 1853, on his survey of the Texas coast (quoted in USCE, 1880). Within a week, he reports, the bar channel shifted all the way over from the north to the south breakers, showing 9 ft in the new channel and shoaling to 4 ft in the old channel, "three vessels being wrecked in as many days before the change was discovered."

With a return to normalcy after the cessation of Civil War hostilities, activity was renewed in establishing a harbor in the Coastal Bend bays. The natural depths in the Lydia Ann Islands Channel continued to favor the ports on the Copano-

Aransas bay system. In fact, Collins (1878) noted that the Lydia Ann Channel was increasing in depth due to currents, especially dramatic during northers. The greatest depth he sounded in 1878 in Lydia Ann was 36 ft just inside the Harbor Island passage. In the 1890's depths of 42 ft were sounded in this same area. Ocean-going vessels could easily attain Rockport and Fulton, if they could cross the Aransas Pass bar. This shifting, shoaling bar continuously frustrated shipping, so became the focus of attention for navigation of the bay.

In 1869, Col. Fulton, whose ranch shipped cattle products, and later cattle, from its wharf at Rockport, contracted with one Mr. Halliday to improve the pass (Cameron, 1898). Halliday constructed a crib-work jetty extending out from St. Joseph's Island about 600 ft into the surf zone. The cribs were standard construction for those years, in this case triangular in section, made from 4x6-in yellow-pine or live-oak scantlings and ballasted with sand and stone. For a short while 12 ft over the bar was attained, a net gain in depth of 2 ft (though one can wonder whether the jetty had anything to do with this), but by 1871 no trace of the work could be found (Howell, 1879). Collins (1878) believed the failure of the jetty to be due to the southward migration of the pass, which averaged 184 ft/yr from 1861 to 1887 (Ripley, 1898).

Then in the late 1870's, the nuisance became a calamity when the outer bar shoaled to the point that shipping was locked out of the bay: in effect, when the controlling depth reach 8 ft, the pass was closed to ocean-going vessels (according to Mercer, 1880, who was the Branch Pilot Aransas Bar). Figure 3-1 shows the monthly controlling depth over the bar throughout this period. In 1878, when the bar reached a least depth of 8 ft, most of the commerce was routed to Indianola or Galveston. Also, at this point, the Morgan Line, which had lost a steamship, the *Mary*, on the Aransas Pass bar in 1876, terminated service. At that time, Morgan steamers called at St. Mary's, Rockport and Fulton (Guthrie, 1991), and this service was essential to their economies. Moreover, the Coleman-Fulton Pasture Company was entirely dependent upon the Morgan line for shipping its cattle (Fulton, 1880, Stephens, 1964). The citizens appealed to the government, and in the Rivers and Harbors Acts of 1879 and 1880, work at Aransas Pass was authorized and appropriated.

As noted above, for the previous several decades, for which surveys had been performed, Aransas Pass had migrated south, Fig. 3-2. It was apparent that the deposition of littoral drift into the inlet had to be controlled, either by blocking the drift or by focusing the current so as to maintain a channel over the bar against the drift. A jetty, which would accomplish both, was the preferred solution. At this point in time, there was relatively little experience with jetty construction on the Texas coast, basically limited to the above jetty on St. Joseph's Island, and a gabion jetty at Galveston, neither of which proved to be permanent. The Galveston office of the Corps of Engineers was established in 1880 under Maj. S.M. Mansfield (Alperin, 1977), who brought ideas about jetty engineering from experiences on other coasts and a penchant for action, but was hampered throughout his tenure in Texas by inadequate financing, as well as inadequate understanding of Texas coastal processes. He saw the two primary problems at

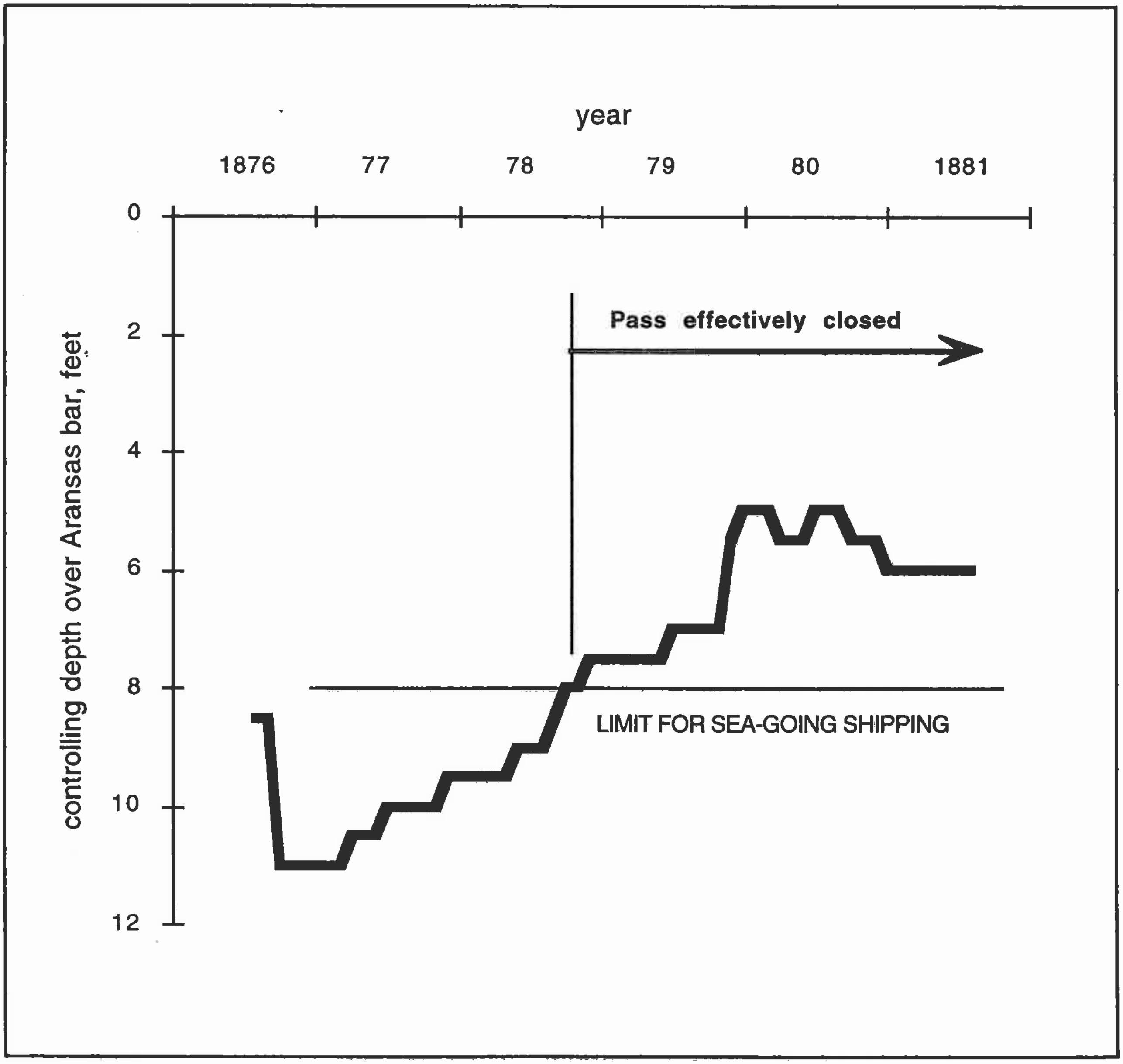


Figure 3-1. Observations of least-depth over Aransas Pass bar during 1870's shoaling episode (data from Fulton, 1880)

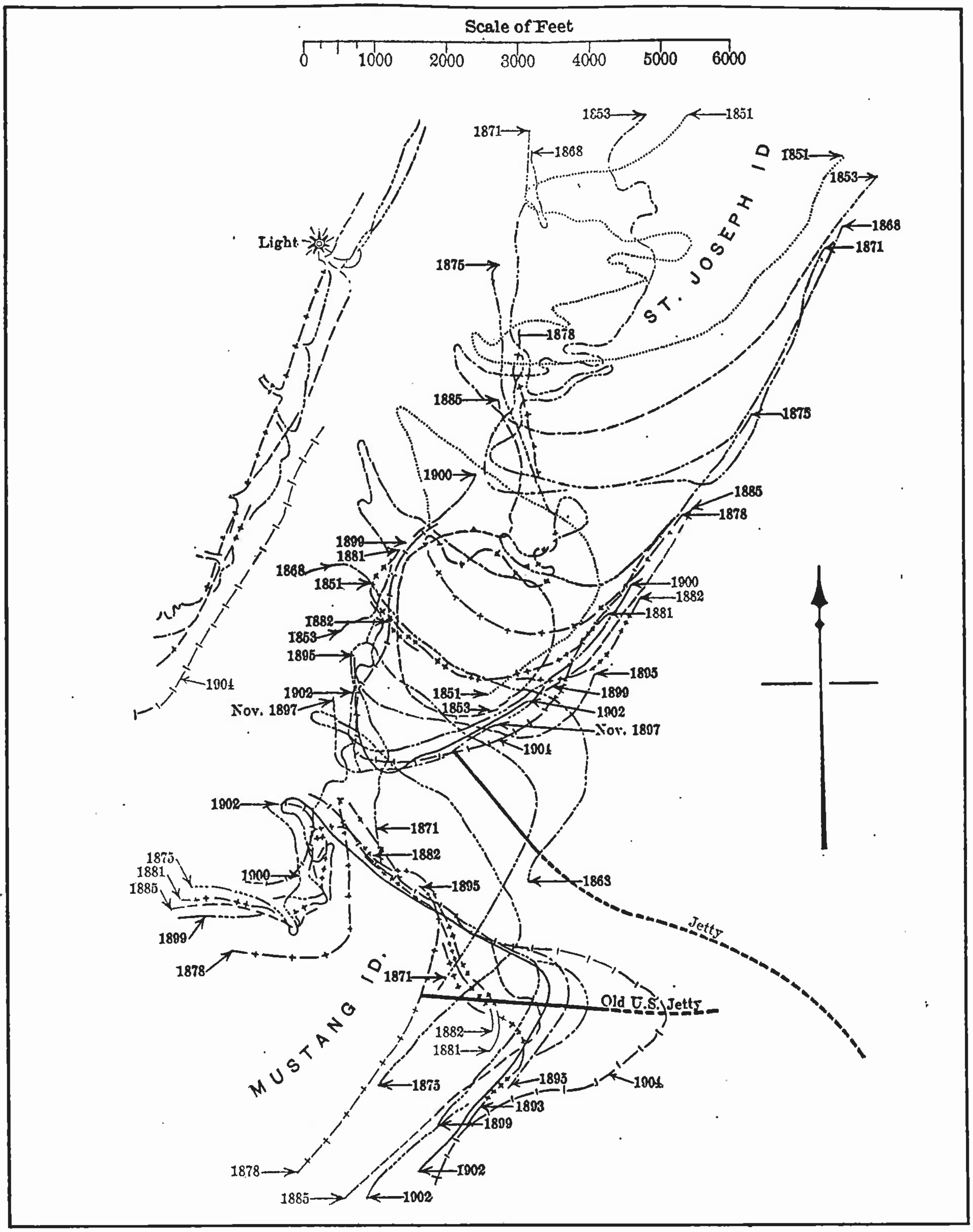


Figure 3-2. Superposed surveys of the location of Aransas Pass before stabilization, 1851-1904, from Gillette (1904b)

Aransas as the erosion of the north end of Mustang Island and the littoral sediment load into the inlet. His project work began in 1881. The south face of the pass was stabilized with stone/mattress revetment and a system of seven short groins. Under the presumption that the waves driven by the prevailing wind and hence the littoral drift of sand were from the south, a single 5500-ft jetty was constructed east out into the surf from Mustang Island, out to the wreck of the *Mary*, which was still there, and turning to northeast. Like the jetty construction underway then at Galveston, this jetty was constructed of brush mattresses and stone to save money. Known as the "government jetty" or the "Mansfield jetty", it was completed in a couple of years, but proved to be shortlived. By 1885, it had become submerged, "being buried under the sand by the cross-currents, the channel having crossed the jetty" (Haupt, 1904). The fundamental problem was thought to be the compression of the mattress material (Gillette, 1904b). After an 1888 survey failed to locate the jetty, it was declared by the Corps to have disappeared.

In 1887-89, the Corps reinforced the protection on the north end of Mustang Island with 1.5-ft riprap. However, this was the last work to be done by the Corps in the Nineteenth Century. Attention at the Galveston office had now been diverted to the work in the Galveston entrance channel, and the growing conflict with Eads (see Merrill, 1886, Haupt, 1899, Alperin, 1977). Improvements to Port Aransas once again fell to the locals. In 1890, the Aransas Port Harbor Company was incorporated, and given exclusive permission by the government for port improvements, contingent upon a ruling depth of 20 ft over the bar being attained by 1899 (Stephens, 1964, Alperin, 1977). In 1892, the Company constructed a south jetty, from its wharf on the Mustang Island side of the Pass extending east-southeastward along the shoreface and out toward the wreck of the *Mary*, which was still there. This jetty, known as the "Nelson jetty," really more of an extended shore revetment, was constructed of 7-ft diameter wooden caissons sunk in the sand and filled with sand and rock, and the structure carried out "some distance" from the island (Pitts, 1899, Haupt, 1899). A large part of this jetty had disappeared by summer of 1895 (Pitts, 1899). Then, in 1895, through the offices of Brewster Cameron, the Harbor Company solicited a proposal from two consulting engineers, Haupt and Ripley, for a north jetty, which ignited a controversy that was to last 40 years.

L.M. Haupt, Professor of Civil Engineering at the University of Pennsylvania, was involved on several major canal projects (e.g., Engineer in Charge for the Canal Commission of Philadelphia), and had a wheelbarrow-load of honors, including the Magellanic Premium of the American Philosophical Society, being one of only two such conferees in a half century. He had written widely on harbor entrances and inlet mechanics (e.g. Haupt, 1888, 1899), and held a patent on a Reaction Breakwater, a curved jetty designed to take maximal advantage of tidal currents. A West Point graduate, he had served as Engineer Officer in Texas during Reconstruction. H.C. Ripley had worked for the Corps of Engineers in Texas for over two decades, and had recently entered private practice in Galveston. (He would later be co-designer of the Galveston seawall and grade-raising project.) He had long been a proponent of curved jetties, and one of his last projects in the Corps was the design of a detached, curved north jetty for the inlet at Galveston

(Ripley, 1899), which was approved but not built (probably because of the publicity attending Eads' proposal for Galveston, see Merrill, 1888). Therefore, it should not be surprising that the two proposed a radical design:

> In plan it will differ from the usual form of jetty or breakwater, being detached from the shore and located on the bar to the "windward" of the channel. Its axis will be curved (compound and reverse) to produce reactions similar to those found in the concavities of streams, and having radii sufficient to maintain channels of the requisite depths... .
>
> The work will be executed in two parts. The first will consist of 1 250 feet of completed breakwater and 2 500 feet of foundation extension; the second of 5 950 feet of completed breakwater and 250 feet of foundation extension. It is to be covered with a substantial apron of heavy blocks, weighing from two to five tons, carefully placed so as to produce a permanent and substantial structure.
>
> The construction of the proposed breakwater, as designed, will unquestionably result in securing navigable depths over the bar of 15 feet for the first part of the work and 20 feet for the second. (Haupt and Ripley, 1895).

Two important features of the design were the assumption that the important littoral drift direction was from north to south (i.e., the north side of the pass would be "windward"), and the utilization of heavy stonework in the construction. The unconventional elements were that there was only a single jetty (not two), the shoreward terminus was to be 1700 ft from the beach (i.e., "detached"), and the jetty itself was to be strongly curved in a long "S" shape. Indeed, the Corps had a plan for a pair of straight jetties on the books since 1887, approved but not yet built. (Actually, some experiments with jetties having one of these three features had been carried out, primarily on the east and west coasts of the U.S., but the results were mixed, and there was much debate about their success, e.g., Harts, 1901a. McKinstry, 1901, commented about the Aransas Pass design, "While there are no novel elements in the reaction breakwater, the combination of these elements is unique, and the reaction breakwater at Aransas Pass is the first concave [i.e., toward the channel] windward jetty built at a tidal entrance in this country." On the other hand, Symons, 1899, made the amazing statement, "In fact, officers of the Corps of Engineers, U.S.A., have designed and have been building just such structures for years, and some of the most successful works of the Corps have been accomplished by adopting in the main the principles enunciated by Professor Haupt.")

The Harbor Company decided to build the first part of the project, which, as noted above, was predicted to result in a controlling depth over the bar of 15 ft. Work began in August, 1895, and appeared to be going well. A 1250 ft seaward length was completed starting with its seaward point at the 15 ft contour outside the bar, and the foundation mattresses were installed 1000 ft further seaward and 1500 ft landward from the completed section. The immediate response of the bar was described by Haupt (1896) as "phenomenal." Within a few months after the first mattress was placed, the bar crest had reduced by 3 ft. The channel depths continued to increase as the work progressed, to 13 ft. However, the foundations of the old Mansfield jetty were unexpectedly encountered (Pitts, 1899, who served as Assistant Engineer on the project for two years). The jetty had been marked as "disappeared" on the Corps charts (Haupt, 1899), and an 1895 survey by Ripley (see Gillette, 1904b) apparently failed to detect it. The engineers urged the Harbor Company to contract to remove these foundations because they lay across the channel and prevented any further scour, see Fig. 3-3.

In winter the controlling depth over the bar shoaled to 5.5 - 6 ft. The reasons proffered by Pitts (1899) are significant: "The condition of the jetty in the spring of 1896 was such that it caught and caused to be deposited on the bar the sand carried along the shore by the northerly current which prevails at that season. This current was of unusual strength and duration that year." Construction on the jetty was continued, building up the landward foundation segment to high water, and further extending the foundations landward to the projected end point of the jetty (Pitts, 1899). In late summer of 1896, the jetty was built up over this section, but to less than full section, leaving a gap toward the landward terminus. Depths over the bar had slowly increased during this period. In winter of 1896, C.P. Goodyear began blasting the Mansfield jetty. After going through over 10 tons of dynamite, a 500-ft breach had been made, but Goodyear had to stop, having exhausted his funds (Haupt, 1899). Much of the old jetty remained, "still a serious obstruction and menace in the navigable channel." Pitts (1899) reported a continuous increase in depth over the bar after the old jetty was breached, but with seasonal variation. He also noted that measured surface currents in the channel were as high as 7 fps (and that probably not the maximum attained).

The status of the jetty constructions as of 1897 is shown in Fig. 3-4. Subsequent performance of the reaction breakwater is murky, because of the complexity of the coastal environment, inadequate surveys to properly evaluate the inlet channel, the interfering effects of other physical structures, and the conflicting interests among coastal engineers of the time. Almost immediately, in 1897 the Board of Engineers of the Corps declared it worthless (Haupt, 1901a, Alperin, 1977), but this was in part a political move, involving valuation of the works of the Harbor Company to the U.S. government, in anticipation of the government taking over the project. Haupt (1899) stated that at Aransas Pass, "with an incompleted reaction breakwater, having large gaps at both extremities, a feeble tide (only 14 ins.), and a serious submerged obstruction almost completely blocking the channel, the depths have progressively increased from about 6 ft. to an average of over 18 ft. in a few years... ." However, the requisite 20 ft was not achieved by 1899, and Aransas Port Harbor Company, its resources depleted, relinquished its rights to the government.

The Corps revised its existing two-jetty plan to incorporate the Haupt breakwater into a north jetty, while adding a straight south jetty. But in 1902 Congress intervened and authorized completion of the Haupt jetty as originally designed by Haupt and Ripley. It was necessary to first remove the old Mansfield jetty from its

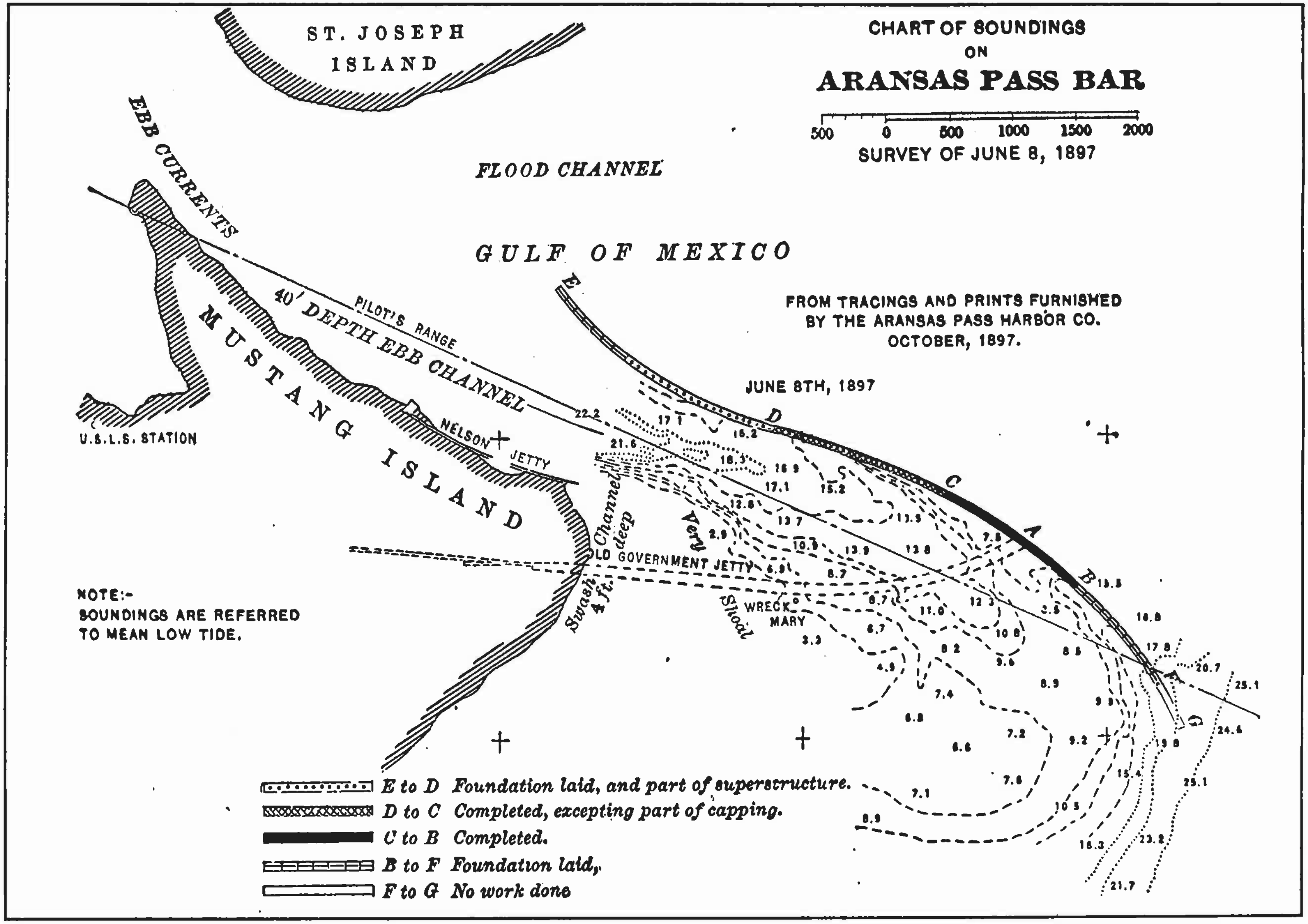


Figure 3-3. Jetty constructions in Aransas Pass as of 1897, from Haupt (1898). Note location of Old Government (Mansfield) Jetty relative to channel talweg.

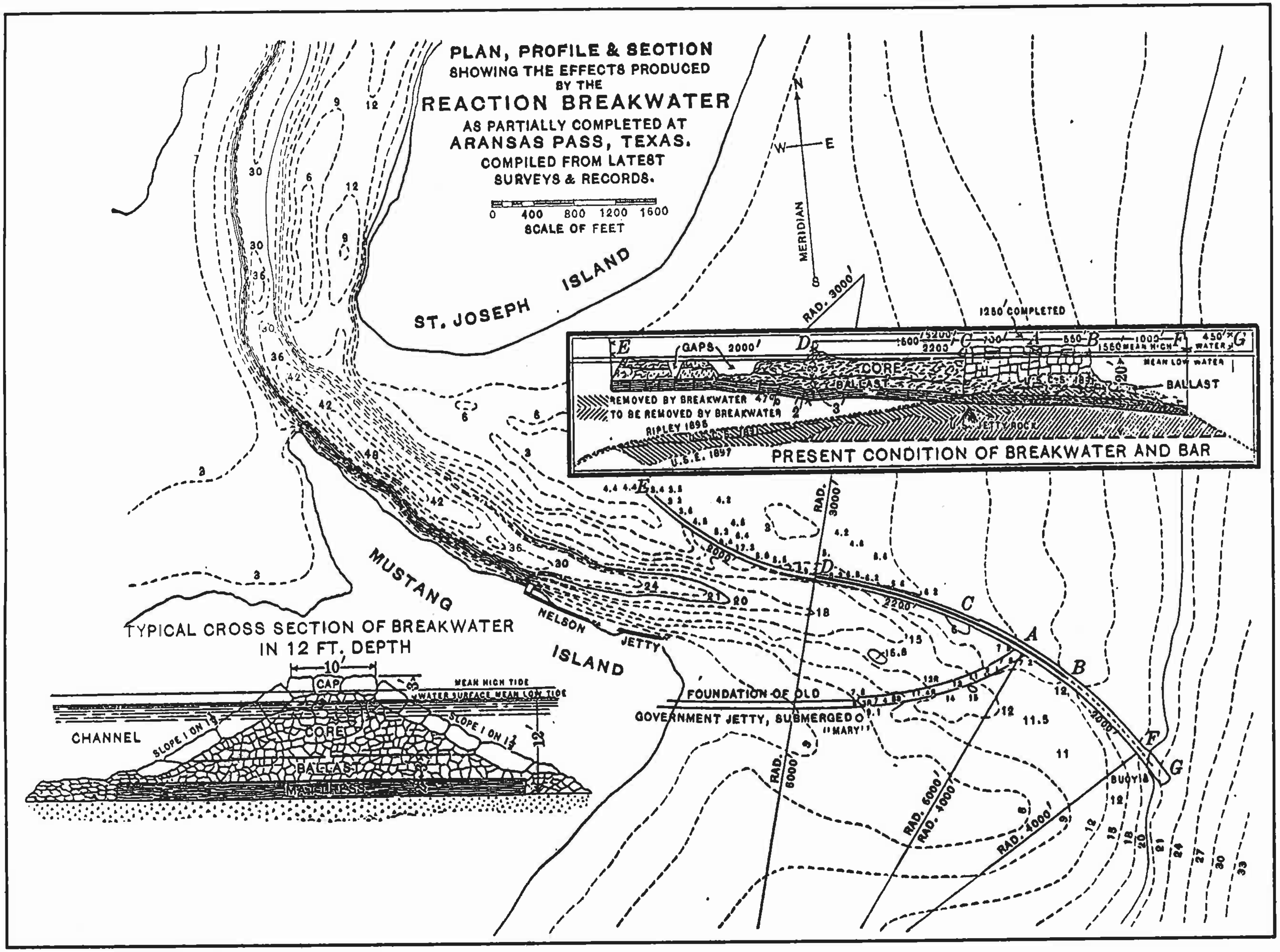


Figure 3-4. Status of jetty project in Aransas Pass as of 1897, from Haupt (1898).

seaward end to the wreck of the *Mary*, which was still there. About 1000 ft was considered removed by 1904. The construction of the reaction jetty to original specifications was completed in 1906. Almost immediately, in 1907, the Corps declared the channel to be deteriorating (Haupt, 1910), noting that "a secondary channel, 600 feet wide and 6 feet deep, broke through the gap between jetty and shore with the result that for all practical purposes the channel was on the north side of the jetty instead of the south side, as intended... " (USCE, 1912). Work was begun to extend the jetty to St. Joseph's Island and tie it to the shore, extending a dike along this axis across the end of the island to the Lydia Ann Channel, this work being completed in 1909 (Ripley, 1924). At the same time, a south jetty was begun, its axis to run southeast from Mustang Island to the south of the *Mary*, which was still there. Figure 3-5 shows the status of Aransas Pass in 1909. After this south jetty was completed, the depth of the bar *reduced* to 13 ft over the bar (Haupt, 1927). However, scattered stone remained from the Mansfield jetty, which the engineers believed was armoring the tidal channel against scour. Work resumed on removing this stone, piece by agonizing piece, from 1911 to 1915. Construction was also begun to extend the jetties further into the sea. By 1919, both jetties had been constructed to their present project lengths (9241 ft on the north, 7385 ft on the south, Alperin, 1977). In 1936, the coastal pilot (USC&GS, 1936) reported that the *Mary* was still there, baring 5 ft at low water.

Was the reaction breakwater successful? Engineering evaluations at the time ranged from expansive to vitriolic. But these judgments were rendered in an engineering culture that was experiential rather than analytical, and politically charged by a long-running conflict between civilian consulting engineers and public military engineers. An essay addressing this question is provided in Appendix E for the amusement of the reader. In summary, the breakwater design was never fairly tested, because at no point in its existence, for a period of time sufficient to unequivocally determine the response of the channel contours to the breakwater, was the breakwater free of the influences of other constructions in the pass. The Mustang Island revetments, the Mansfield jetty and the Nelson jetty all antedated the Haupt jetty, and significantly affected the currents in the Pass. When the Haupt jetty was built up to specification, the foundation stones of the Government jetty remained affecting scour in the tidal channel. Before these stones were finally removed, construction had already begun on the modern south jetty, and the Haupt jetty had been tied to the shoreline. A deep channel did form adhering to the concave face of the jetty. This was probably due to deflection of the ebb current by the Mustang Island revetment onto the north jetty, rather than the "reaction principle," but in any event it was too close to the stonework to be safely navigated.

After the north jetty was tied to St. Joseph's Island in 1909, four spur jetties (actually groins) were constructed extending south from the jetty to discourage the formation of a scoured channel along the jetty face. The construction work on the north and south jetties was basically complete in 1916, but since then the jetties have been repaired many times. A major rehabilitation project was undertaken in 1962, motivated in part by damage sustained during Carla the previous year.

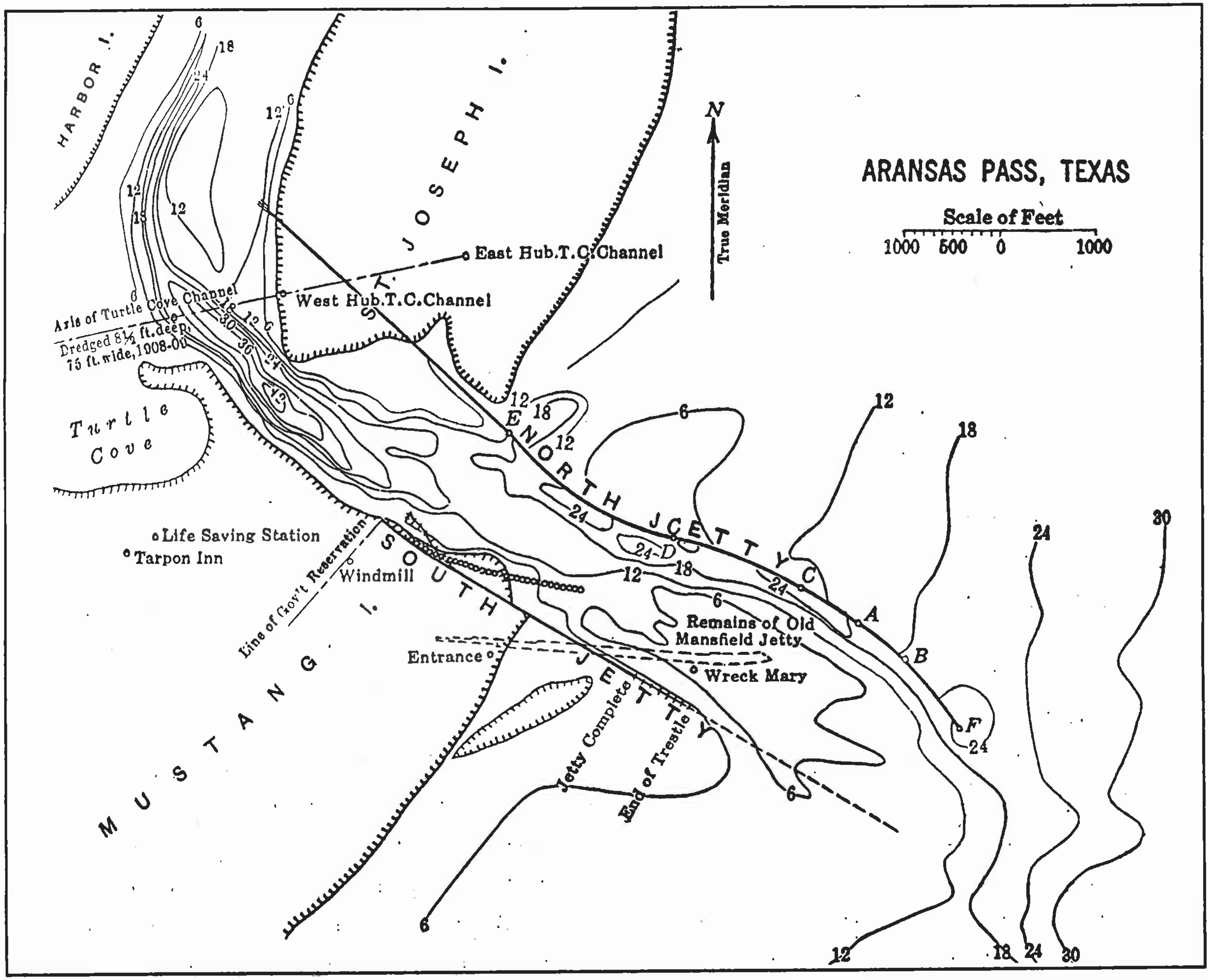


Figure 3-5. Status of jetty project in Aransas Pass as of 1909, from Ripley (1924).

The effect of the Aransas Pass improvements on the hydrography of the Corpus Christi Bay system was probably not manifested until the extension of the jetties and the maintenance of a 20 ft navigation channel. This effect most likely included an increase in the tidal prism for the inlet, hence the bays. No data survive to quantify this change, however. In the Galveston system, the increase in tidal prism after the late-Nineteenth Century jetty project was reported to be as much as 20% (see Ward, 1993), but because none of the supporting data at the Corps have survived, the reliability of this estimate cannot be determined either. For Aransas Pass, the small cross section of the inlet and the frictional resistance to tidal influx are proportionately greater, so even a modest increase in inlet section would have a significant influence on the tidal prism. It is prudent to judge an increase in tidal prism on the order of 10%.

3.1.2 The minor inlets

The other natural inlet to Corpus Christi Bay, Corpus Christi Pass, seems to have always been secondary to Aransas. The ca. 1840 outer-bar soundings of Table 3-1 show the controlling depth at Corpus Christi to be half that of Aransas. McClellan's 1853 report on the shifting bar at Aransas reported with respect to Corpus Christi Pass, "Corpus Christi bar opened at the same time to 9 feet, having but 5 feet in it before. This channel is probably closed by this time, or soon will be." Nevertheless, the inlet was open a decade later during the War of Secession, and served as a Union camp until Aransas Pass was captured. Mrs. Sutherland (1916) states, "To Corpus Pass, to run the bar for the United States Government, as Pilot, came one Captain Grant, and with him his family. After the war he remained on the Island and became a cattle raiser. His house became a landmark to all Bay folks, hunting parties and sight-seers, for its unbounded hospitality. The Captain and his good wife have gone to their reward, the children have founded homes nearer the haunts of men, and the old home, like the shallow Pass, is deserted." Features of the Grant ranch house at Corpus Christi Pass were used as triangulation reference points in the USC&GS surveys of 1877 and 1905, and the house was still standing in 1912 (Mourhess, 1913).

After the close of the War, Corpus Christi Pass appeared to be shoaling. Collins (1878) said that this pass had decreased in size by half since 1846, and commented, "Corpus Christi Pass is now very shoal and narrow–too narrow for vessels to beat anywhere in the pass–and it has at its head less than three ft of water over a large quicksand bar." He noted much greater windblown sand here than at St. Joseph Island, and suggested that this might be the reason for the inlet's shoaling. He added that in the brief time he was in the inlet, sand accumulated on his schooner to 1/8 inch depth. In the Twentieth Century, Corpus Christi Pass has opened and closed numerous times, but its more "normal" state has been closed. The 1916 coastal pilot (USC&GS, 1916) reports that the Pass is "seldom used," and, "sometimes the pass is entirely closed." This was while the initial dredging work at Aransas Pass was just underway. The TGFOC (1934) noted that it had closed in 1926, but was re-opened by the September 1933 storm. The coastal pilot (USC&GS, 1936) reported it closed in 1935. Fig. 3-6 shows the general configuration of this inlet complex as of the mid-1960's.

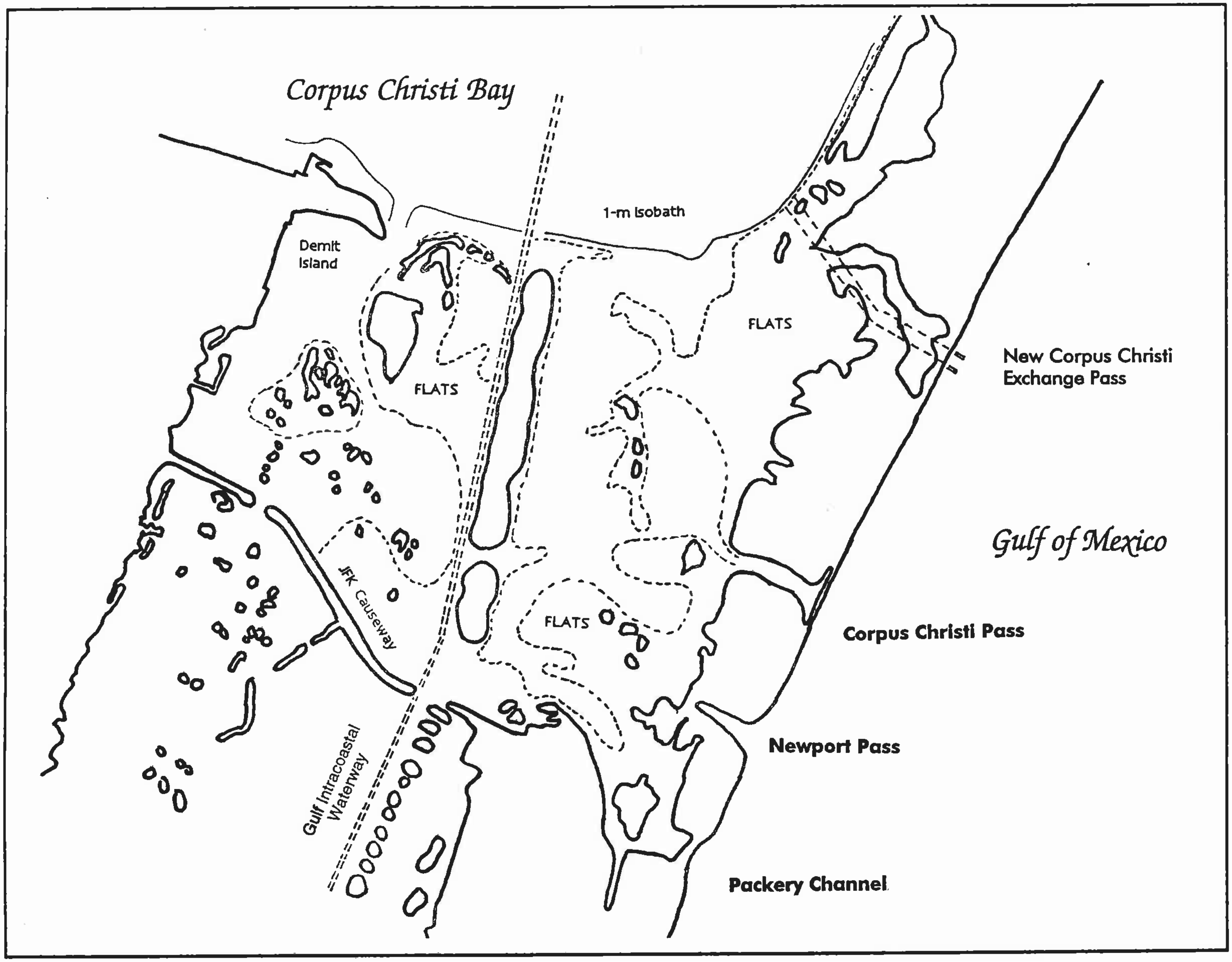


Figure 3-6. Bulkhead Flats area ca. 1960 showing Corpus Christi Pass inlet structure. In Nineteenth Century, main axis of inlet passed through "Packery Channel." New Corpus Christi Pass was completed in 1972.

Only one other inlet to the system has exhibited any degree of permanence, *viz.* Cedar Bayou which connects Mesquite Bay to the Gulf. This inlet was open during the Civil War (figuring in the tactics of some of the skirmishes on the barrier islands), but was chronically closed early in the Twentieth Century. The coastal pilot (USC&GS, 1936) states that it was closed in 1935.

As noted in Chapter 2, the Coastal Bend bays clearly are poorly connected with the Gulf of Mexico, being virtually landlocked, except for Aransas Pass. The Laguna Madre, in particular, is only remotely influenced by the sea, through whatever exchange filters down from Aransas Pass and across Bulkhead Flats. An early realization of fishing interests, as well as the TGFOC, was that the fishery could be materially improved by openings through the barrier island chain that would permit exchange, thereby moderating high salinities, allowing organisms to escape to the Gulf during freshets or freezes, and—most importantly—offering alternative routes for migration of diadromous species between the bays and the sea. As early as 1927, the annual report of TGFOC notes the importance of these passes and a call for state appropriations was made to "cut one or more channels through Padre Island near its center to admit water from the gulf, which it is claimed would relieve the salinity and stagnation of the Laguna and prevent the high mortality of fish." This was the modest beginnings of a theme that would become an *idée fixe* for TGFOC up to the present.

However, TGFOC was not the first agency to consider a direct channel across the barrier island. One of the earliest was the Corpus Christi Navigation Company in the early 1870's. Frustrated with the shallow passage through Turtle Cove, the CCNC contemplated a canal to be excavated through Mustang Island. The CCNC also considered enlarging Corpus Christi Pass. It was also authorized to construct an embankment across the mouth of Laguna Madre, in order to prevent the waters of Corpus Christi Bay from passing into Laguna Madre instead of out Corpus Christi Pass (Allhands, 1931). The Company proceeded instead with a channel through Harbor Island, the Morris and Cummings Cut, so nothing else came of these plans for Mustang Island.

The first real attempt to cut a pass through the barrier island was due to the promoter Col. Elihu Ropes, who exemplified the adage of Thinking Big. Ropes planned a 30-ft channel to the sea across Mustang Island. He formed the Ropes Port Company, bought a dredge boat, the *Josephine*, and began work in June 1890. The dredge had a 750 cu yd/da capacity and worked a 22-hr day. According to Allhands (1931), "Ahead of this machine a large force of teams and scrapers were engaged in cutting down the hills or mounds, some of which rose to a height of twenty-two feet above sea level. By the middle of the following March this dredge had gnawed out about 100,000 cu yds, and it was estimated that the first cut, about fifteen feet wide by ten feet deep, and involving the movement of 145,000 cu yds of material, was two-thirds finished." The work abruptly stopped with the financial panic and collapse of Ropes' empire. "Storms drifted the sand high into this new channel, engulfing man's puny dredge, the 'Johephine' [*sic*], in her self-dug grave, and today her decaying skeleton is about all that is left to mark the site of this one-time famous 'Ropes Pass.'"

In 1928, the first inlet experiment of the TGFOC was undertaken, namely the opening of Blind Pass on Mustang Island (*sic*, TGFOC, 1928) with a 3 x 25 ft channel. This channel was completed in August 1928 (TGFOC, 1928), but "failure to get a strong flow from the bay to scour the pass made it impossible to keep the entrance open, which continually closed with bars on the Gulf side." TGFOC installed a temporary bulkhead on the seaward end "to keep back the Gulf waters until stronger tides should set in from the bay." This attempt was abandoned, but the experiment demonstrated to TGFOC that a larger-scale and continuous effort would be necessary to succeed.

Passes were cut through the island during the 1933 storm, and soon shoaled closed. The area lapsed into drought and salinities climbed. Then the massive freshet of 1935, which was actually a series of freshets over the period 1935-36, decimated fish populations. "Countless tons" were reported killed (TGFOC, 1936), with "the brunt of the fresh water deluge ... felt more strongly along Mustang and Padre Islands." TGFOC was therefore motivated to renew the inlet work in 1938, and raised the ante by purchasing a small dredge with an 8-in suction pipeline powered by a diesel electric motor, to be dedicated to inlet maintenance. This dredge, named the "AE" after TGFOC Chairman A. E. Wood, worked continuously (except when down for maintenance or in transit between locations), operated on three eight-hour shifts by an eight-man crew: captain, two levermen, four helpers and a cook. The *AE* was tended by several small boats and a former laboratory boat converted to a houseboat. The dredge was to begin its operations in the Corpus Christi Bay system, starting with Corpus Christi Pass. As matters developed, it never left the system, ranging between Murdock's Pass in the Laguna to Cedar Bayou in Aransas Bay. The chronology of the dredging project is summarized in Table 3-2, extracted from the annual reports of the TGFOC, and reflects the frustration of trying to maintain these passes. According to Collier and Hedgpeth (1950), the project was abandoned due to the failure to achieve adequate circulation between the Laguna and the Gulf through Murdock Cut even when it was opened. Gunter determined from salinity measurements that "the pass did not permit influence of the Laguna waters by the Gulf for a greater distance than one-fourth of a mile from its mouth. As a result of his report to the Commission the effort was abandoned and the dredge was sold." It would appear that the decision was more one of inability to achieve a permanent inlet in any of these locations.

This, of course, was not the end of it. Nor is the sense of *déjà vu* an illusion in the description of the Murdock Pass work in the guidebook to Corpus Christi, published first by the WPA in 1942, then revised by the Caller-Times in 1952. In WPA (1942, p. 193), the reader is told, "During 1940 the fishing grounds were again extended into the Laguna Madre, when the Texas Game, Fish and Oyster Commission placed a dredge at Murdock's Landing and cut a pass, or 'fish channel' through from the land-locked lagoon to the Gulf of Mexico. The opening of such a pass at this point had been requested by sportsmen who held that the Laguna would always have had fish had there been such an outlet." Ten years later, the Caller-Times (1952, p. 130) states, "Late in 1951 the Texas Game & Fish Commission started cutting a pass, or 'fish channel' at Murdock's landing

Table 3-2
Chronology of operations of TGFOC dredge *AE* 1938-1945,
compiled from annual reports of the TGFOC

June 1938	Began Corpus Christi Pass
January 1939	Completed Corpus Christi Pass; moved to Cedar Bayou
March May	Work at Cedar Bayou
April 1939	Corpus Christi Pass shoaled
May 1939	Returned to Corpus Christi Pass, began re-opening
July 1939	Completed Corpus Christi Pass; returned to Cedar Bayou
November 1939	Cedar Bayou complete, opening assisted by strong norther
ca. January 1940	Corpus Christi Pass shoaled
ca. April 1940	Returned to Corpus Christi Pass, began re-opening, this time cutting the channel in a straight line, thereby eliminating the "double bend"
summer 1940	Cut 1-mi channel from Corpus Christi Pass to Kate's Hole in the Laguna Madre
ca. October 1940	Completed Corpus Christi Pass; installed south shore bulkhead; moved to Murdock's Landing Pass in Laguna
December, 1940	Began Murdock's Pass, after much trouble moving boats over shallows
April, 1941	Completed Murdock's Pass to 5.5 x 80 ft; began cutting way out of Laguna Madre (through shallows)
August, 1941	Murdock's and Corpus Christi Pass failing
November 1941	Completed cutting way out of Laguna, *AE* sent to Rockport for overhaul
ca. February 1942	Murdock's Pass closed
spring 1942	Returned to Murdock's Pass
August 1942	Murdock's Pass dredged to within 700 ft of Gulf when Hurricane of 29 August struck, refilling pass; dredge began re-opening pass
November 1942	Completed Murdock's Pass; dredge returned to Corpus for overhaul
ca. February 1943	Murdock's Pass closed
ca. April 1943	Corpus Christi Pass closed
June 1943	Began cutting way through Laguna shallows below Pita Island to make way back to Murdock's Pass
ca. August 1943	Began re-opening Murdock's Pass
November 1944	Completed Murdock's Pass; began cutting way out of Laguna Madre
March 1945	Arrived Corpus Christi for overhaul
March 1945	Murdock's Pass closed
July 1945	All three passes closed (as they were in June 1938).

through the land-locked lagoon to the open Gulf. This is designed to increase the flow of fresh sea water into Laguna Madre and increase the supply of fish there. It was completed in February, 1952." It was open six weeks (Simmons, 1957).

Cedar Bayou was reported (still) closed in 1948 by the coastal pilot (USC&GS, 1949). (This is in contradiction to Collier and Hedgpeth, 1950, who state that Cedar Bayou remained "more or less" open after its initial dredging by TGFOC in 1939-40.) In 1949 it was open, but closed in 1955. Cedar Bayou was again dredged in 1959, and functioned satisfactorily for the next two years. It was enlarged by Carla in 1961 (which also re-opened other passes along the coast) and seems to have remained open throughout the 1960's (being enlarged by Beulah in 1967). It was deliberately closed by bulldozing in 1979 to protect Mesquite Bay from oil contamination, when the Ixtoc I oil-spill plume was entrained in the Gulf of Mexico coastal circulation and drawn north to the Texas coast. Hurricane Allen re-opened the pass in 1980, and it shoaled closed in 1985 (see Gough, 1989). A joint private-state-federal dredging project for fisheries restoration was completed in October 1988 of a 6 x 100 ft channel re-opening the pass (Gough, 1989).

The coastal pilot (USC&GS, 1949) reported Corpus Christi Pass closed once again in 1948. Except for brief openings by tropical storms, such as Beulah in 1967 and Delia in 1973, the pass was closed for the next twenty years. (According to McGowen et al., 1970, it was not opened by Celia in 1970.) In 1971, TPWD raised the ante again on Corpus Christi Pass, introducing a new and grander tactic. Instead of keeping the natural pass open, a new "water exchange pass" was begun in a natural overwash across Mustang Island about 2 km north of the natural inlet. This pass, a three-million-dollar project designed by Lockwood, Andrews and Newnam after an extensive study (Carothers et al., 1959), entailed major construction efforts, including a highway bridge and a pair of 1400-ft jetties, and was completed in August 1972. It was placed up the island away from the shoals of Bulkhead Flats, with the intention to improve exchange with the deeper waters of the open bay. The pass itself is a 10,000 ft (3 km) channel originally dredged to 8 x 200 ft dimensions (approximately) with a 23° dogleg 3200 ft (1 km) in from the Gulf, and the jetties extended 875 ft into the Gulf. The pass is shown superposed on the map of Fig. 3-6.

As a completely new inlet based on engineering design and equipped with structures for stabilization, the experiment attracted the interest of the Corps, and studies were funded to monitor and evaluate its performance, *viz*. Defehr and Sorensen (1973), Watson and Behrens (1976), and Behrens et al. (1977). Deposition in the inlet proceeded from the seaward (jettied) end (Watson and Behrens, 1976). By March 1973, shoals had begun to form between the jetties and inside the bay mouth, and the depth in the inlet had shoaled to 5 ft. The minimum inlet cross section developed between the jetties in the shoal areas, and this minimum area varied sporadically but generally declined from about 900 ft^2 to less than 300 ft^2 in early summer 1975 (Watson and Behrens, 1976). This declining cross section, and associated decreasing channel volumes and tidal currents, led Behrens and Watson (1977) to declare the inlet unstable and to predict that it would close in 1980. The actual closure occurred in the early 1980's, in agreement with the prediction, the event being delayed some by Hurricane Allen. (Paul Carangelo, pers. comm., 1997, observed it to be shoaled in 1980, before Allen.)

3.2 Dredge and fill projects

3.2.1 Channelization: the Corpus Christi Ship Channel

The real problem at Aransas Pass in the early Nineteenth Century, insofar as shipping to Corpus Christi was concerned, was confronted on the interior side of the inlet, namely the sand/mud shoal complex of Harbor Island, which in part was maintained by deposition of littoral sediments by the flooding current. The principal tidal distributary was the channel leading northward into Aransas Bay, what would later be called the Lydia Ann Islands Channel. The "distributary" leading southward into Corpus Christi Bay was through Turtle Cove, and was extremely shallow, as evidenced on the Frontispiece, from the Coast Survey 1887 navigation chart. This meant that Aransas and Copano Bays were more favorable sites for ports than Corpus Christi Bay.

One of the oldest operating ports on the bay complex was located on Copano Bay east of Mission Bay, called El Cópano (Guthrie, 1988). Almonte (1835) filed a report on the Department of Texas in which he identified Cópano as the deepest port on the coast. It was reported to him that it had fifteen to eighteen feet of water "on the bar." In contrast "ships with a draught of not more than six feet can arrive safely at Corpus Christi...," the difference evidently being the lack of a deep channel through Redfish Bay or Turtle Cove. (The outer bar depth would of course have been the same for either bay, so "on the bar" undoubtedly meant the inner bar. The reference to Corpus Christi is to a landing somewhere on the bay; it may have been McGloin's Bluff, but was almost certainly not the site of the present city.) Kennedy (1841) commented, "Any vessel that has crossed the bay of Aransas can enter Copano Bay." Of Corpus Christi Bay, "It is accessible from the gulf by a narrow pass over the bar, on which there is from five to six feet water." Again, the inner bar is meant.

This general area, Turtle Cove and Harbor Island, was referred to as the "mud flats" by the residents on the bay in the mid-Nineteenth Century. It was the Turtle Cove mud flats that frustrated the transfer of Gen. Taylor's troops from St. Joseph's Island to H.L. Kinney's trading post in 1845 (McCampbell, 1952). The lighter, drawing 4 ft, ran aground, and the troops had to be lightered by even shoaler fishing boats (in the process of which a young officer, one U.S. Grant, fell into the bay). Col. Kinney operated one dredge in the late 1840's to keep this passage clear; there may have been others (e.g., Caller-Times, 1952). Around 1850, a group of Corpus Christi businessmen contracted to dredge a 5-ft channel through the mud flats, the project being assumed by the Corpus Christi Navigation Company in 1852 (Allhands, 1931). It did not go well (in 1854, Sommers Kinney wrecked his "dredge machine" in the process, Allhands, 1931) and was re-subscribed and re-organized several times. In 1857, a 10 x 44 ft channel through the outer bar and the Turtle Cove mud flats was completed, the first vessel to enter being the three-masted schooner *Union* (Riley, 1951). The channel was further widened to 63 ft by the end of the year and re-dredged during 1857-59. The contract was evidently with a dredge owner named Hawley, who brought a new dredge to Corpus Christi for this work, which was operated by his son (Sutherland, 1916). The dredge was anchored on Shell Bank at the beginning of hostilities in the Civil War, and was burned to the waterline by the North. (Capt. Hawley fought with the South as a member of the Hobby regiment, though the elder Hawley was "a staunch Union man," and remained on the bay after the war. Mrs. Sutherland, writing in 1915, described him as "an old Bay Captain." She also notes that Hawley did not receive a cent for the loss of the dredge or the work performed prior to the war.)

As might be expected, in the late Nineteenth Century most of the shipping was concentrated in ports on the Copano-Aransas system, notably St. Mary's (especially for lumber) on Copano Bay, Lamar on Lookout Point, Rockport and Fulton on Aransas Bay (especially for hides and tallow and later for cattle). Commerce to Corpus Christi had to be lightered in order to cross the mud flats. The most significant improvement in seagoing access to Corpus Christi in these years was the dredging of an 8 ft channel by the Morris and Cummings Company of New York. This channel was placed to follow the route of Corpus Christi Bayou, a shallow, natural channel crossing the north segment of Redfish Bar. (See the Frontispiece.) Progress on this channel, according to Allhands (1931), "...was distressingly slow and unsatisfactory. Their old machinery was constantly breaking down, and they lost a schooner-load of coal at sea." This channel was finally completed in 1874. While it enabled seagoing vessels to enter Corpus Christi Bay without being lightered, the route was convoluted, first going up Lydia Ann Channel then traversing Redfish Bay on almost a due south course. The first vessel to use it was a Morgan steam ship *Gussie* (McCampbell, ca. 1934). The Morris and Cummings Cut, as it became known, was operated as a toll channel, under charter from the state (Howell, 1879, Guthrie, 1991). In 1884 Morgan Line began operating a regular fleet of steamships in the Corpus Christi service, which continued for about 5 years, using the Morris and Cummings Cut for access.

A major project in the region around the turn of the century was the construction of the railroad to Brownsville. The construction required 700,000 ties, most of which were supplied by the John H. Kirby Lumber Co. of Houston. Allhands (1931), who was heavily involved, recalls, "The shipments for the first part of the line and up until late February, 1904, were towed in slow-moving barges from Port Arthur to Corpus Christi, thence transferred to the Tex-Mex Railroad for delivery to Robstown. ... After clearing Aransas Pass, the first barge load, containing six thousand ties, went aground on a reef, whereupon it was lightened [*sic*] by taking off several hundred ties, only to go aground again. Finally arriving at Corpus Christi, the barge had great difficulty in getting to the wharf. Such annoying delays were never overcome, and those shipments became so uncertain that Johnston Brothers [the contractors] finally prevailed on the Kirby Company to send the ties all rail." This pretty well exemplifies the state of navigational access to Corpus Christi at the turn of the century.

The Rivers and Harbors Act of 1902, which authorized completion of the north jetty and removal of the old Government jetty, also included provision for a survey of a planned Turtle Cove Channel. In 1907 the Corps contracted with Bowers Southern Dredging Company for the first phase of the Turtle Cove Project, to be dredged to 8.5 x 75 ft. This was not so much a channel to Corpus Christi as it was really the initial work on the GIWW. The Turtle Cove Channel (see Fig. 3-5) reduced the distance from Aransas Pass to Corpus Christi from 32 to 22 mi, by eliminating the leg up Lydia Ann and back down through the Morris and Cummings Cut.

Both Rockport and Corpus Christi had been lobbying the federal government for a deepwater channel. In 1910, the Board of Engineers re-evaluated the deep port question, and concluded that the best location was neither Corpus Christi nor Rockport, but Harbor Island (Riley, 1951). However, legislation was enacted to enlarge the channel to Corpus Christi to 12 x 100 ft, to extend the channel across the bay to Corpus Christi, and to create a turning basin at the city. Of course, since the open waters of Corpus Christi Bay generally exceeded 12 ft, no dredging was necessary, except in the Turtle Cove area and in the approaches to the Corpus Christi port facilities. The small turning basin and channel entrance to that turning basin, located on the bayfront, were dredged in 1912. Meantime, commercial activity began to develop on Harbor Island, mainly supporting transport of oil from Mexico.

Turtle Cove was, as might be expected, prone to shoaling. From 1910-1913 it had shoaled to the point that vessels exceeding 5 ft draft were closed out (Riley, 1951). In 1915, the Atlantic, Gulf and Pacific Co. began re-dredging the Turtle Cove Channel with their dredge *Pensacola* between miles 4 and 5 (measured from Port Aransas). This work increased the ruling depth to 10.5 ft, removing 45,000 cu yds, but in the next year, the channel had shoaled to 9.5 ft. After the 1916 hurricane, the channel had shoaled to a least depth of 4.5 ft. In November 1916 re-dredging began by the U.S. dredge *Colonel A.M. Miller*, which removed 380,000 cu yds to bring the channel back to project dimensions by 1917. Within six months, it shoaled to 9.5 ft, and by June 1919 to 9.0 ft.

The historical turning point in port development for Corpus Christi, and the attendant channelization, was also its worst disaster, the great hurricane of 1919. This was a Category 4 storm that moved swiftly from the Windward Islands across the Caribbean and drew a bead on Baffin Bay (see Neumann et al., 1978). Corpus Christi lay on the right front quadrant of the storm. The newspaper reported a "tidal wave" 10-ft high, but this was an underestimate: the surge measured 8 ft at Brighton, 11.5 ft at Aransas Pass, 12 ft at Ingleside and 16 ft at Corpus Christi (Cline, 1926). The storm caused 20 million dollars in damage and 600 deaths. This storm destroyed the old port facilities on the downtown waterfront on Corpus Christi Bay, which were clustered around the municipal wharf on the bayshore, and basically all shipping facilities and most structures on Mustang Island, Harbor Island, and St. Joseph Island, including Aransas Pass.

The great hurricane re-focused the citizens of Corpus Christi on the construction of a protected harbor. For the Board of Engineers, it also re-opened the issue of selection of a deep water site in South Texas. Favored by business interests in San Antonio and by the railroads, Corpus Christi became the front-running choice. In 1921, in order to aid the city in construction of a seawall and breakwater, the Texas Legislature passed a bill returning *ad valorem* taxes to the city collected from seven South Texas counties in the region. In 1922 the Board of Army Engineers selected Corpus Christi as the site of a deepwater port, and the 1922 River and Harbors Act provided for a 1200 x 3000 x 25 ft turning basin, extension of city breakwater in front of the exposed face of the harbor, a levee between the harbor and Nueces Bay, and a 25 x 200 ft channel connecting Port Aransas and Corpus Christi. The turning basin was to be dredged across Rincon Peninsula north of the city in the lowlands of Halls Bayou into Nueces Bay. (See Riley, 1951, Mitchell, 1959, and Alperin, 1977.) Figure 3-7, reproduced from a boat-sheet of the Corps of Engineers, maps Corpus Christi and its harbor in 1921, and shows the proposed route of the new ship channel.

Dredging began 16 January 1925 from Aransas Pass across Turtle Cove. No maintenance had been done since the great hurricane. After the storm, the Turtle Cove channel had a least depth of 7 ft, and by 1921 had shoaled to a ruling depth of 5 ft, and an *average* depth over the eleven miles of dredged channel between Aransas Pass and McGloin's Bluff of 7 ft (USHR, 1922). Two dredges, the *John Jacobson* and *Matagorda*, carried out this work on the channel. The turning basin and associated work were completed in January 1926, and the channel itself was completed in July 1926. The last leg of the channel was excavated by the dredge *Texas* under Capt. W.W. Williamson from Atlantic, Gulf, and Pacific Company (Riley, 1951). Seven years to the day after the great hurricane, on 14 September 1926 the channel was officially opened when the destroyer flagship *Borie* steamed out of the turning basin under the bascule bridge. This marks the real beginning of industrial development of Corpus Christi Bay. At the grand banquet on 15 September, there was talk of a 35-ft project and a naval base on the bay, and it is reported that Sen. Morris Sheppard virtually committed himself to these projects (Riley, 1951).

The Rivers and Harbors Act of 1930 authorized a 30-ft project to Corpus Christi. Dredging contracts were awarded in January 1931. Five years later, motivated by the needs to accommodate the growing petroleum industry, Congress increased the project dimensions to 32 x 200 ft, the actual work being completed in 1937. The motivation for these incremental increases was the increasing size of ocean-going vessels, especially tankers. At the end of World War II, the T-2 tanker at 17,000 DWT with a laden draft of 30 ft, was the work horse of the world fleet, and channels were generally sized to this vessel. The location of the Corpus Christi Ship Channel, as well as the other main channels in the bay, at the end of the war and at present, is shown in Fig. 3-8.

Following the war, larger tankers, at 30,000 DWT appeared in the fleet (referred to then as "supertankers"), driving upward the necessary dimensions for ship channels. The project dimensions of the Port Aransas to Corpus Christi Ship Channel were increased to 36 x 400 ft, being completed to 34 ft by 1946 and to 36 ft

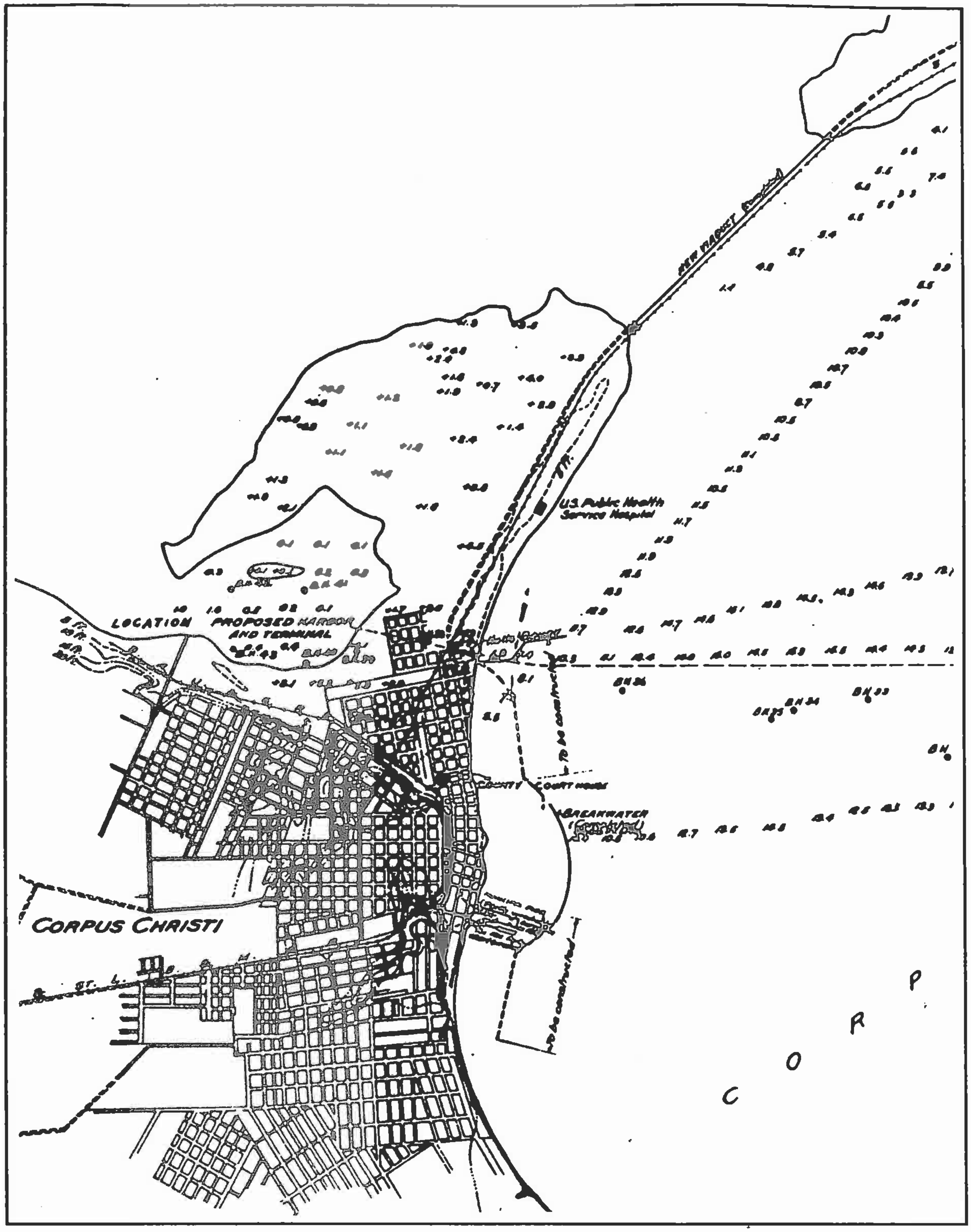
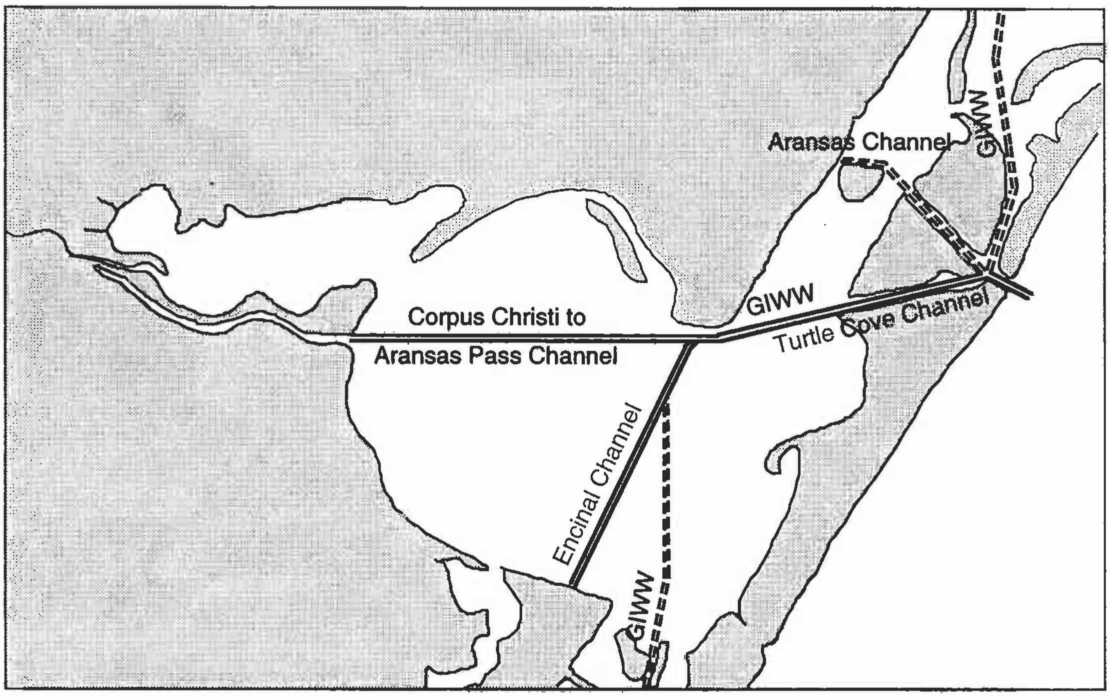
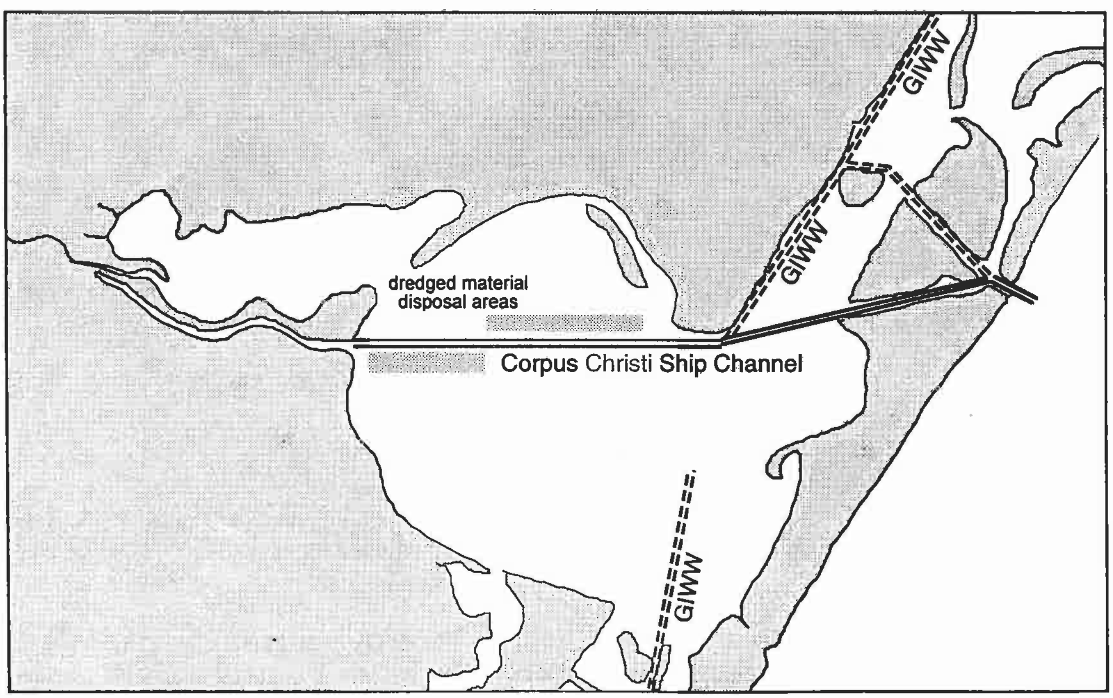


Figure 3-7. Portion of boat sheet showing Corpus Christi harbor configuration in 1921. Route of planned ship channel shown as broken line.



(a) ca. 1945



(b) present

Figure 3-8. Principal ship channels in Corpus Christi Bay
(shallow draft shown as broken lines)

in 1958. The next increment authorized in 1963 was to 40 ft, which was completed by 1966. (At that time, 100,000 DWT tankers were in service and vessels up to 300,000 DWT were under construction.) The Corpus Christi Ship Channel project depth was increased to 45 ft (47 ft in the outer bar and jetty channels) in the Rivers and Harbors Act of 1968 (modified by the Water Resources Development Act of 1976), which would be large enough to accommodate the laden draft of 41 ft of a 60,000 DWT tanker. The 45-ft channel was completed to within one mile of the entrance to the Inner Harbor by 1979. Dredging of the last reach, *viz.* the Inner Harbor, was delayed due to concerns about disposal of the dredged material, the present plan calling for disposal in 1200-ac leveed area along the south shore of Nueces Bay, as well as in disposal areas on the west side of Rincon Point.

3.2.2 Channelization: the GIWW and branch channels to the CCSC

The possibility of an inland waterway on the Gulf and Atlantic coasts was contemplated in the Nineteenth Century. In Texas, the prospects were particularly appealing because of the long reaches crossing the bays behind the cordon of barrier islands. Gov. Roberts (1881) made the case:

> The line of bays upon our coast could easily be connected by canals, so as to have an inland channel of navigation from the mouth of the Rio Grande to that of the Sabine; which, indeed, might be extended to New Orleans and Mobile, and perhaps further. The saving in the diminished loss of coasting vessels, and in insurance, apart from the great advantage in time of war, would certainly be a large item in the commerce of this state. This project of an inland channel of navigation upon our coast has long been spoken of in Texas as desirable and practicable, but too large to be undertaken by Texas.

In 1905 local business groups in Victoria formed the Intracoastal Canal League. They were able to instigate the construction of a 5 x 40 ft canal from the Mississippi River to the Sabine, and from Houston to Corpus Christi. As noted above, the first leg was dredged in 1907 to 8.5 x 75 ft as the Turtle Cove channel.

Under a 1910 authorization, the federal government began dredging a 5 x 40 channel from Galveston Bay/Oyster Bay to Aransas Pass. The government in 1925 purchased the private canals making up the route between Sabine Lake and the Mississippi. A canal project to 9 x 100 ft dimensions connecting Corpus Christi to Mississippi was authorized in 1927, however the Galveston to Corpus Christi reach was not completed until 1941. In the meantime, the 5 x 40 channel was not maintained and gradually deteriorated. Its status in 1935 is described by the coastal pilot (USC&GS, 1936), "The old dredged channel of the original 5 feet (1.5 m) by 40 feet inland waterway extends from San Antonio Bay, through Mesquite Bay to deep water in Aransas Bay. In 1935 there was a controlling depth of about 3 feet (0.9 m), and there was a sufficient number of the old beacons in place to indicate the channel."

The submarine threat in WWII renewed federal interest in the GIWW.* This led to authorization of a 12 x 125 canal from Carrabelle (Florida) to Brownsville in 1942. In 1945, the Sabine River to Corpus Christi reach was completed. The reach from Corpus Christi to Brownsville through the Laguna Madre was non-existent at that time. In November work turned to this reach. Figure 3-8(a) shows the GIWW channels in Corpus Christi Bay at this point in time. Work on the Laguna Madre reach of the GIWW continued for the next several years. In June of 1949, the dredges *Caribbean* and *Miami* cut through the Mudflats toward each other, and the connection was opened, along with a ribbon-cutting ceremony, on 18 June 1949 (USCE, 1949, Mitchell, 1959).

For a time, the dredged section where the Corpus Christi Ship Channel, Aransas Pass Channel, Lydia Ann Channel, and Jetty Channel conflow was called the Inner Harbor (e.g., USC&GS, 1949). The currents in this region were swift, unpredictable and particularly hazardous for barge tows travelling along the GIWW. In 1960, the GIWW was re-routed near Rockport to follow the mainland shoreline through Redfish Bay, rather than the Lydia Ann Channel. Since then, the Lydia Ann Channel has been maintained as an alternate route.

During the war years, the Naval Air Station was established on Flour Bluff, beginning operations in 1941. A 30 x 200 ft channel was dredged on a north-northeasterly line connecting the NAS turning basin to the main ship channel near McGloin's Bluff, see Fig. 3-8(a). This channel, the Encinal Channel, served its wartime function and has not been maintained since. In 1949, the coastal pilot reported controlling depths of 17 ft (USC&GS, 1949). More recently, it is reported to have shoaled to natural depths (USCE, 1968).

Reynolds constructed the $42M Sherwin Alumina plant on the north shore near Ingleside in 1953, dredging a 12 x 100 ft channel to the plant site (later abandoned). A reduction plant was located at Ingleside to produce aluminum ingots from the finish alumina, completed in 1952 (Mitchell, 1959). The north shore facility required deepdraft access: two of Reynolds' fleet of ore-transport ships were the largest in the world. The La Quinta Channel to the Reynolds facility on the north shore was planned to be part of a major industrial development for the area, and was to follow a route along the Ingleside Peninsula, so that the excavated material could be deposited just to the west of the channel, providing protection for the mooring and harbor facilities and the channel. A 32 x 150 ft project was authorized in 1954, but not appropriated, so local interests took the initiative and dredged the channel to 32 x 125 ft dimensions. The Rivers and Harbors Bill of 1958 authorized deepening of all channels in the project area to 36 ft, including the La Quinta Channel. Since then, the project depths in the La Quinta Channel have been increased along with the main ship channel.

Development of what is now known as the Inner Harbor of Corpus Christi took place over a period of years by construction of successive turning basins and

* Exemplified by the wreck of the Esso tanker *S.S. John Worthington* stranded on the east side of the Lydia Ann Channel, where she was towed after being torpedoed. According to USC&GS (1949) she was attacked off the Texas coast, but there is conflicting information that she was torpedoed off Brazil and returned to Texas under her own power.

connecting canals. Figure 3-9 shows stages in the development of the Inner Harbor, and the associated modification of the south shore of Nueces Bay. Prior to 1925, the main harbor was located at the present T-heads on the Corpus Christi bayfront. As noted above, these facilities were heavily damaged during the 1919 storm, demonstrating the desirability of a protected harbor. In 1925 the Nueces County Navigation District began development of the harbor, which evolved over the years as a series of turning basins linked by canals. The main turning basin was completed in 1926, as a part of the CCSC channel project.

The next important year for the Inner Harbor was 1934. During this year, the federal government assumed responsibility for the channel and turning basins inside the breakwater. Also in this year, the Southern Alkali Corporation Chemical (later Columbia Southern Chemical) plant was completed on the south shore of Nueces Bay at Avery Point. A joint operation of American Cyanamid Co. and Pittsburg Plate Glass Co., this plant produced chlorine, soda ash, caustic soda, dry ice, drilling mud chemicals and several caustics, and was the first major manufacturing plant to locate in Nueces County after construction of the deep port (Mitchell, 1959). Plans for the plant included a 30 x 150 ft channel of 7,500 ft length from the turning basin to the plant site. Dredging of this channel by the dredge *Orleans* began in January 1934 and was completed later in the year (Riley, 1951). This was the first leg of the Industrial Canal. One factor leading to this situation of this plant was abundance of oyster shells from Nueces Bay, for which purpose Southern Alkali dredged a small barge channel from its docks into Nueces Bay, see Fig. 3-9.

At the close of the war, the Tule Canal extension and a turning basin were on the books of the House Rivers and Harbors Committee, being authorized in 1931 and 1945, but no construction had yet taken place. The Navigation District built a small 18 x 100 canal 3.5 mis to service the new Corn Products Refining Co. grain refining plant (Riley, 1951). The federal government began dredging to project dimensions shortly thereafter. The channel itself was located in the waters of Nueces Bay, and the excavated material was used to build up a protective dike on the bay side of the channel. The extent of the Inner Harbor in 1950 is shown in Fig. 3-9(c). In 1958, the Inner Harbor was extended to Tule Lake Turning Basin, and in this same year work was begun on the Viola Channel and Turning Basin. Since 1960, the Inner Harbor has had the same basic configuration as shown in Fig. 3-9(e), the project dimensions being increased with those of the main ship channel. The present configuration of the entirety of Nueces Bay is shown in Fig. 3-10, including the tidal reach of the Nueces and the adjacent deltaic marsh. In these figures the actual shorelines of the Inner Harbor are shown, traced from vintage maps of the Navigation District. The channels and turning basins themselves are dredged to rectilinear plan, but the banks of the channels are subject to erosion by prop wash and bank caving. This, in fact, is thought to be the principal reason for maintenance in the Inner Harbor. Based on interviews with Port personnel, Mitchell (1959) stated, "Constant dredging is required to maintain the 36-ft depth along the industrial canal and shipping channel as slide-ins and the churning action of propellers on large tankers are responsible for intensified channel deposition." Table H-1 in Appendix H includes a chronology of dredged volumes for each of the extensions of the Inner Harbor project.

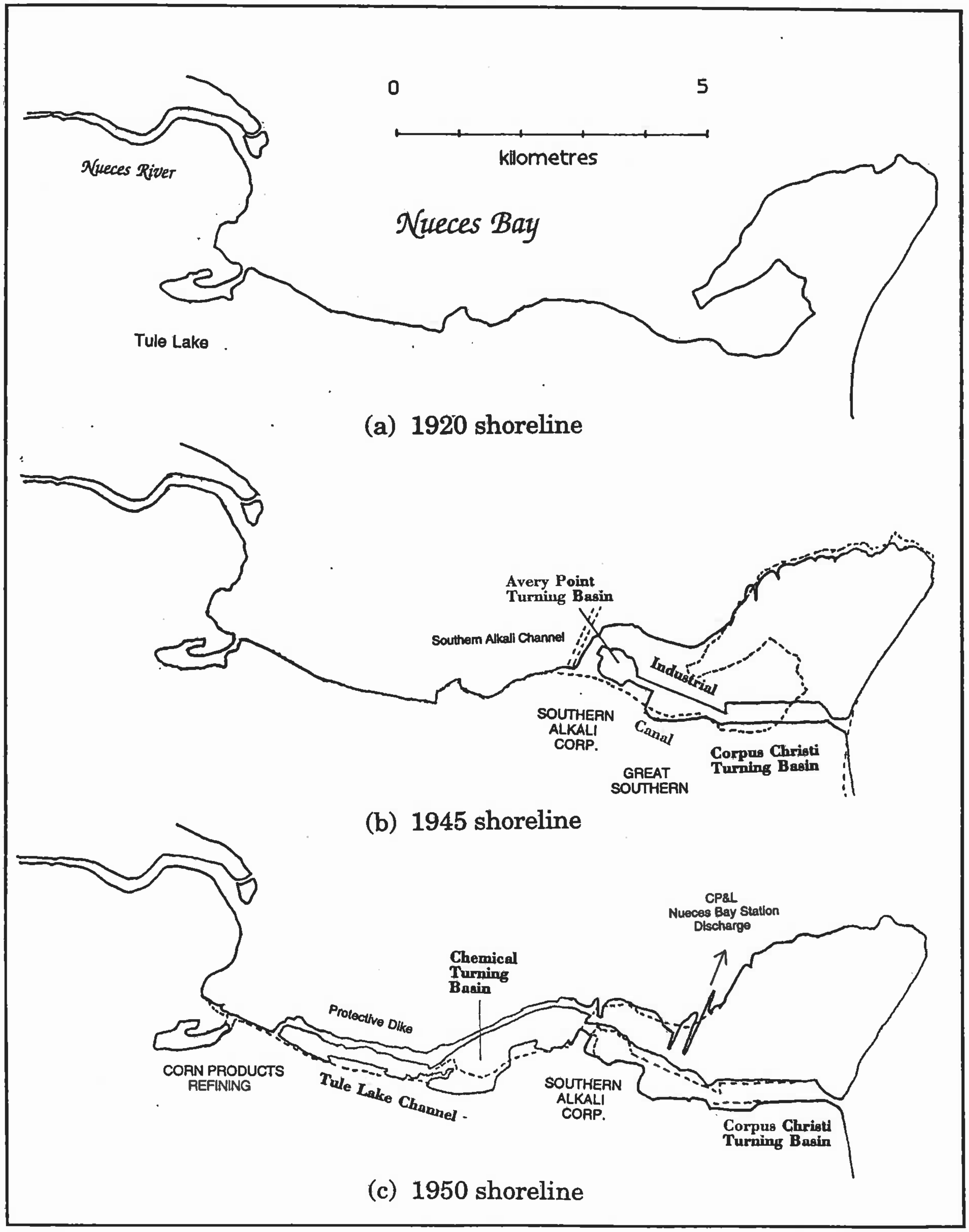


Figure 3-9. Evolution of the south shoreline of Nueces Bay since 1920.

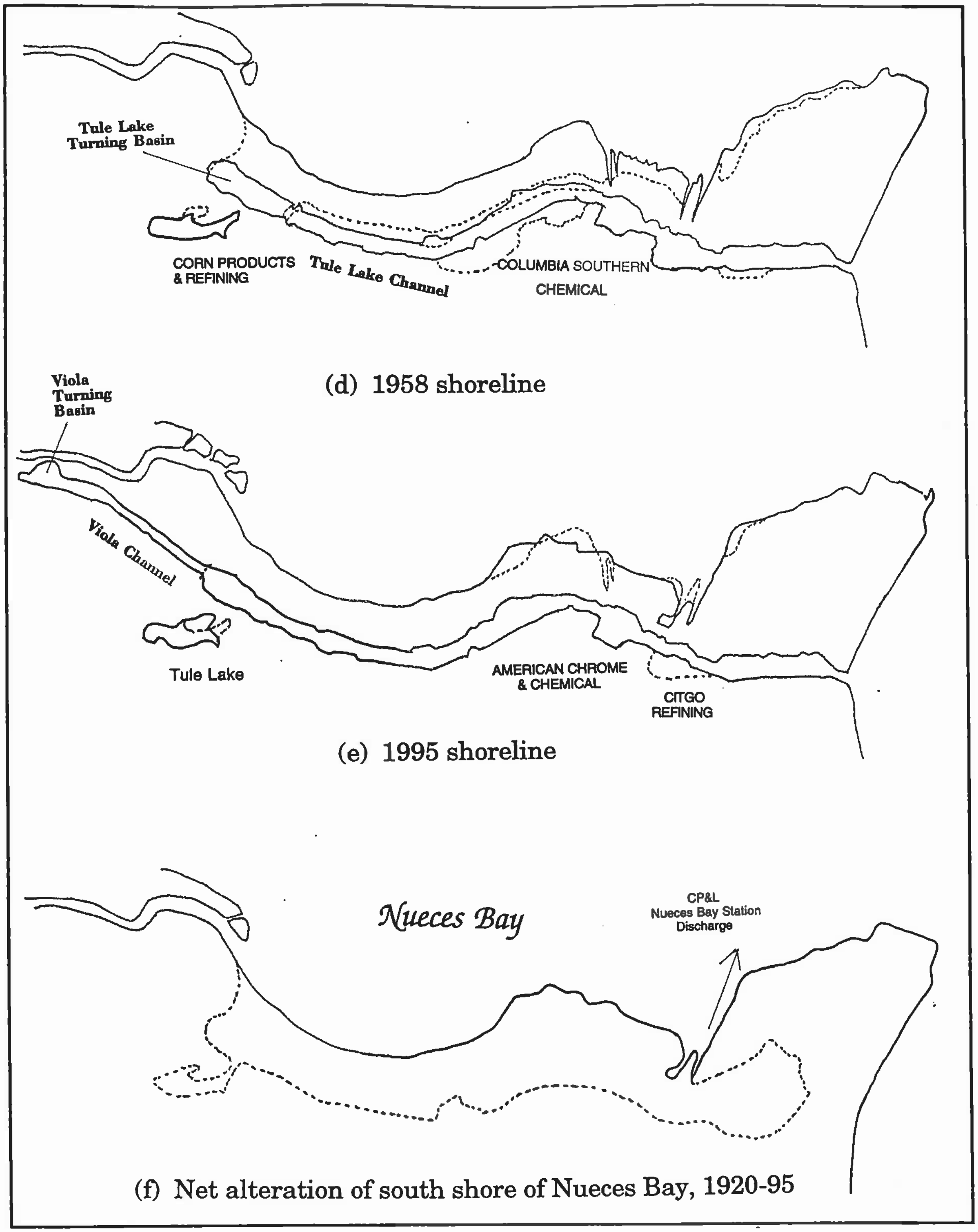


Figure 3-9. (continued)

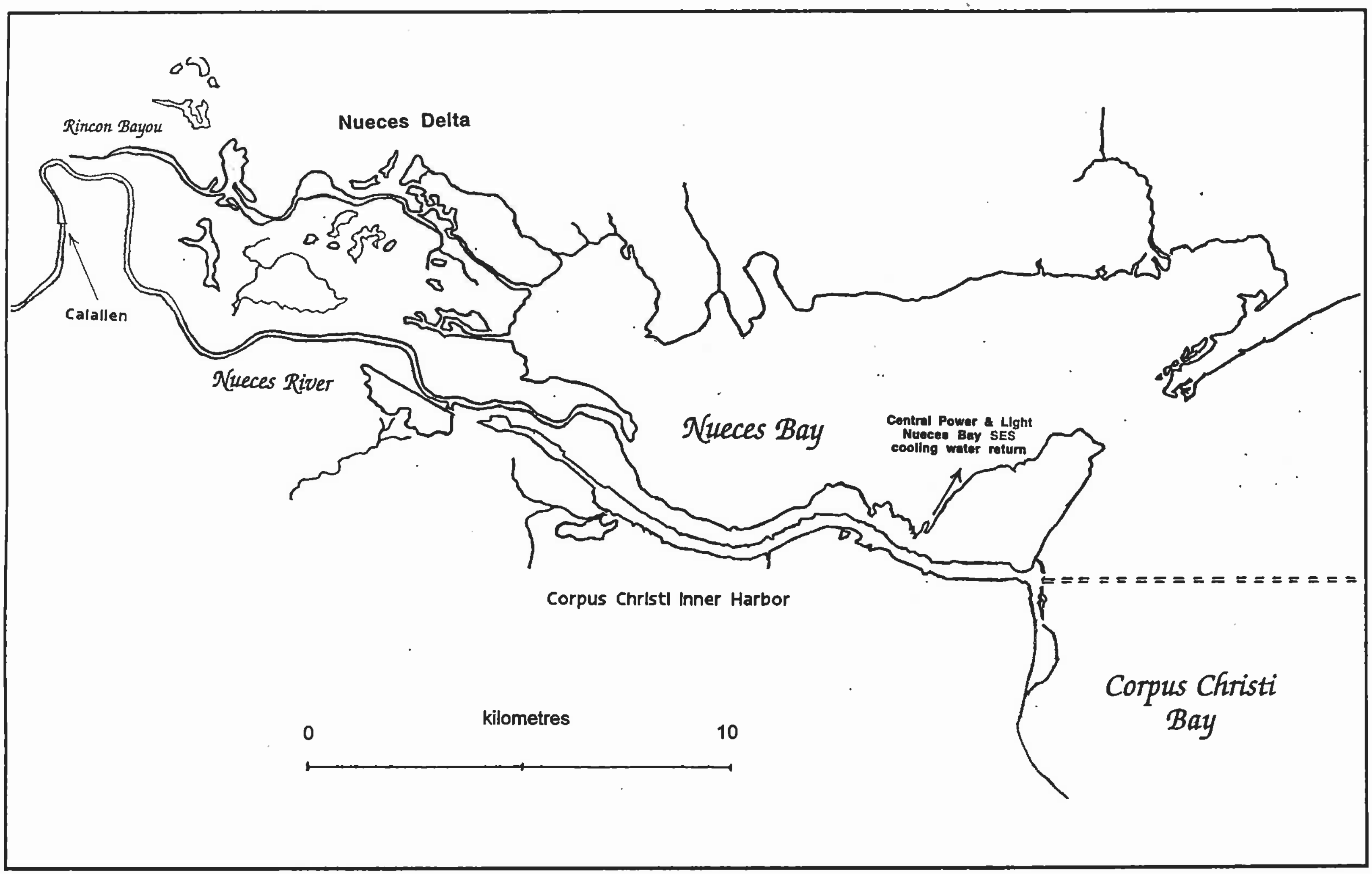


Figure 3-10. Location map of modern Nueces Bay and deltaic marsh of river

3.2.3 Dredged volumes, disposal and fill

What emerges from the chronology of channel development in Corpus Christi Bay is an incremental increase in the dimensions of the main ship channel and its connecting channels over a period of about 60 years. In terms of channel dimensions, each increment represents a quantum increase in channel depth and width. In practice, the actual dredging takes place over a period of months, and the enlargement of the channel ("new work") is performed simultaneously with removal of silted material ("maintenance"). Moreover, a channel is usually overdredged ("advance maintenance") to ensure that the project dimension is achieved for some time after completion of dredging. As a first approximation, new work can be estimated based upon the project dimensions and completion dates (see Appendix H). For the bay reach of the Corpus Christi Ship Channel, i.e. from inside the inlet at Aransas Pass to the entrance to the main turning basin of the Inner Harbor, the cumulative dredged volume computed by this method is plotted in Fig. 3-11(a). For comparison, the contract amounts from USCE files for the portion of each contract attributable to new work was computed and also shown in Fig. 3-11(a). Clearly, the approximate method is sufficiently accurate for present purposes, and was used to estimated dredged volumes for the other channel projects. These are shown in Fig. 3-12. The Inner Harbor is not included in these plots, though the computed volumes are given in Appendix H. The three main reaches of the open bay ship channel are plotted in Fig. 3-11(b). The cumulative volumes dredged from the main channel projects are summarized in Table 3-3. A total of about 200 x 10^6 cu yds have been excavated from the channels of the open bay (i.e., exclusive of the Inner Harbor) since approximately 1910, the vast majority of this being carried out from 1926-1960.

Table 3-3
Summary of dredged volumes from channel projects
in Corpus Christi Bay system (see Appendix H)
Millions of cubic yards

Entrance & Jetty Channel	14.6
Turtle Cove	1.2
Corpus Christi Ship Channel	136.1
Encinal	6.0
La Quinta	24.7
GIWW (Galv to CC)	8.9
GIWW (CC to Brownsville)	11.1
Total (open bay)	202.7
Inner Harbor	54.9

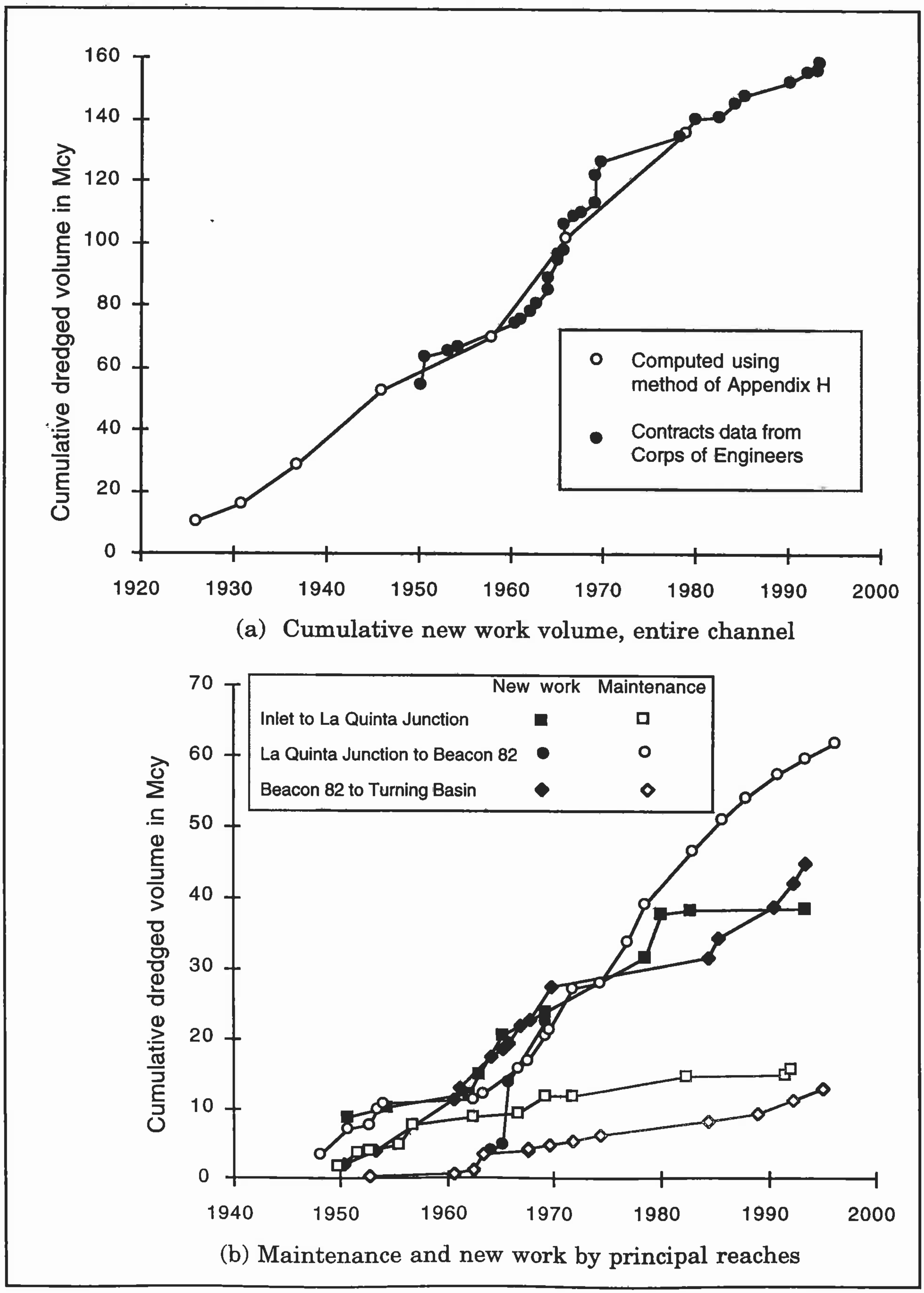


Figure 3-11. Historical dredging volumes in Corpus Christi Ship Channel

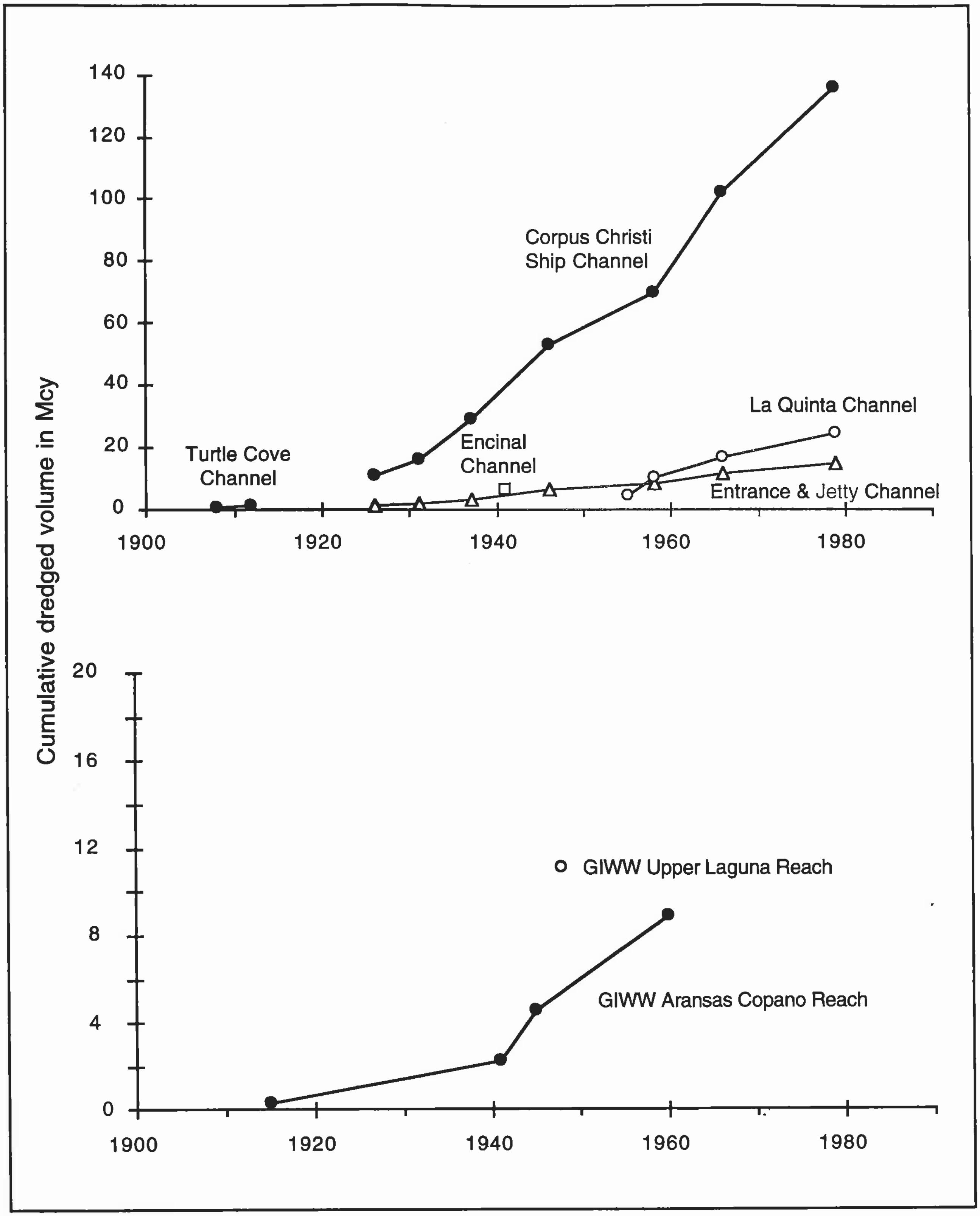


Figure 3-12. New work dredging volumes by project in Corpus Christi system

In addition to inlet modifications and channelization, another important class of physical alterations to the system involves displacing of water by the installation or deposition of sediment. We consider two categories. First is the creation of shoals or emergent land by hydraulic fill, i.e. disposal of dredged material. In Corpus Christi Bay this is primarily associated with dredging of channels, and generally the fill areas are found in proximity to channel projects. The primary impact of hydraulic fill is that water area is replaced by land area. Unless the fill area has a patterned distribution to inhibit or alter current flow (in which it is considered in the second category), the most important measure of impact is the areal extent of the disposal operation. This distinguishes this category from the second, addressed in the next section, the creation of barriers to flow, whose area may be of negligible importance but whose location with respect to principal flow paths entails a disproportionate impact on circulation.

For the Corpus Christi Ship Channel project, the historical spoil disposal practices are summarized in Table 3-4. General locations of the disposal areas in the open bay are shown in Fig. 3-8(b). These disposal areas are unconfined so areas are indefinite; approximately 1500 ha have been used for spoil disposal, about 3% of the surface area of Corpus Christi Bay. Maintenance of the Corpus Christi Ship Channel is comparatively light, especially relative to the channels in the northern bays on the Texas coast, and the slight hummocks created in water depths of 2 - 4 m are considered to have little effect on circulation. The effects on the bottom contours are evident in Fig. 2-2.

Part of the plan for the dredging of the Turtle Cove reach of the Aransas Pass to Corpus Christi ship channel was to use the dredged material to build up the land as a dike or levee to protect the channel. As noted earlier, construction of the channel from Aransas Pass began in January 1925 under federal contract and was essentially completed within the year. The shallow embayment of Turtle Cove has been practically replaced by fast land, and the Harbor Island area to the north of the channel has been built up substantially. It is difficult to determine how much of this represents displacement of water, because of the complex physiography of the Harbor Island and Turtle Cove shoals (see the Frontispiece), but probably on the order of 40 ha on Harbor Island and 80 ha in Turtle Cove have been displaced. From the standpoint of circulation of the system, by far the more important physiographic alteration is replacement of the previous extremely shallow passage through Turtle Cove by a much deeper channel.

With the construction of the La Quinta Channel in 1954-58, the dredged material was used to build up a dike to the west of the channel. To the present, this fill has displaced 420 ha of what was previously bay bottom.

Probably the single most significant filling work was the "reclamation" of Nueces Bay for protection of the ship channel and for industrial facilities. Part of the plan was to use the dredged material to build up the land as a dike or levee to protect the channel. Contracts for bridges and port facilities at CC were let in 1924, including the Nueces Bay "jetty" (Riley, 1951). The main turning basin and associated work were completed in January 1926. Terminal facilities at the port were placed on fill 12-14 ft high to prevent inundation by hurricane surge. In the

Table 3-4
Spoil areas along Corpus Christi Ship Channel
in miles from Entrance at jetties

reach	*water miles*	*disposal practice*
Entrance channel	0 - 3	Gulf of Mexico, in designated areas.
Turtle Cove Channel	3 - 8	on low-lying land 1200 ft from either side of channel (i.e. Harbor Island and East Flats).
Bay crossing to Ingleside	8 - 13	1200 ft S of channel. Navigation passage at Mile 10. Here the natural depths are about 8 ft, but spoil banks now exist.
Bay crossing	13 - 18	1700 ft N of channel. Submerged mounds. Navigation passage at Mile 17. Depth over spoil mounds about 9 ft in natural depths of 11-13 ft.
Bay crossing	18 - 22	1700 ft S of channel. Submerged mounds. Navigation passages at Mile 20 and 21. Depth over spoil mounds about 9 ft in natural depths of 11-13 ft.
Harbor channel	22 - 26	Low-lying land N of channel, on Rincon Point or south shore of Nueces Bay.
Industrial canal	26 - 30	700 ft N of channel on marshy south shore of Nueces Bay.

1929-30 Texas legislature, bills were passed enlarging the boundaries of the navigation district (House Bill No. 90, 41st Legis. 4th Called Sess. Chap 42, 1930) and permitting the use of the salt marshes and flats in Nueces Bay adjacent to the harbor for enlarging the turning basins and extending the ship channel (House Bill No. 58, 41st Legis. Regular Sess. Chap 311, 1929). Fig. 3-9 above shows the modification of Nueces Bay resulting from the Corpus Christi port development. This amounts to a reduction in surface area of Nueces Bay by about 15 per cent.

Other minor filling projects have been carried out around the system over the years, such as construction of the Corpus Christi rock breakwater (12-ft above above mean low tide) completed shortly after the port opened in 1926, grade-raising and construction of the seawall in period 1938-1941 (which included reclaiming 200-400 ft of shoreline land), reclamation of Demit Island by the Naval Air Station in the early 1940's, and restoration of North Beach. While these may have had some local effects on circulation (obviously the case for the breakwater, since this was its purpose), the effects on large-scale circulation processes in the bay are considered negligible.

The scope of the present study precluded detailed determinations of areal impacts of all of the various fill activities underway in the study area. Recently, the National Ocean Service undertook a detailed determination of areal and shoreline features of the nation's estuaries utilizing NOS nautical charts and a scale of resolution on the order of 10 m, to resolve such anthropogenic features as service channels, small boat basins, and modified shorelines (Orlando et al., 1988). All of this work was performed digitally. A summary of the study's findings for the major bays of the study area is given in Table 3-5. In addition to dredge disposal impacts, also shown are the impacts of shoreline modifications, including bulkheading, revetment, dredged material disposal, piers, groins and related structures. While not strictly fill activities, and generally not entailing significant circulation impacts, this class of modification can have some implications for biological utilization of the nearshore environment. The standard of comparison is the shoreline length of the estuary.*

3.2.4 Barriers

Three major barriers have been imposed in the Corpus Christi system, all in the present century. First is the Nueces Bay Causeway. This was constructed in 1914-15 across the reef between Corpus Christi and Nueces Bays in Nueces Entrance, and was 8500 ft long, composed of two sections: the south 2500 ft was comprised of 78 concrete arch bridges, and the north 6000 ft was shell-fill embankment built up to about 5 x 120 ft MSL (Riley, 1951, Stephens, 1964). Thus this causeway reduced the cross section of Nueces Entrance, which was already highly constricted, by approximately 75%. This causeway was damaged by the 1916 storm, which also washed away the old trestle of the SAAP RR, and was destroyed by the 1919 storm, being re-built in 1921 (McCampbell, ca. 1934, 1952) and included a 32 ft drawspan.

The second major barrier is the earthen JFK Causeway (née Padre Island

* The areal determinations are straightforward. Shoreline length, however, is an indeterminate parameter. It is sensitively dependent upon the scale of resolution: as the scale becomes finer, the measured shoreline length increases. The apparent nonconvergence of this length, and the concomitant indeterminacy of shoreline, were remarked by the visionary British scientist L. F. Richardson, and later by B.B. Mandelbrot (1983), for whom the shoreline problem proved pivotal in his study of fractals. Unfortunately, the NOS work presented in its 1988 draft report has been abandoned because the shoreline magnitudes were inconsistent with values determined earlier for the same estuaries as part of the National Estuarine Inventory, according to Paul Orlando (pers. comm., 1992). Since the earlier NEI work involved a much coarser scale of resolution, on the order of 1 km, the inconsistency is to be expected. Neither is incorrect; each reflects the scale of resolution employed.

Table 3-5
Modifications to Corpus Christi Bay system
from Orlando et al. (1988)

bay	surface area (km^2)	dredge fill area (km^2)	percent modified	shoreline length km	shoreline modified km	percent modified
Aransas/ Copano	480	15	4	478	20	4
Corpus Christi*	480	25	6	451	63	14
Laguna Madre†	900	69	9	664	42	6
Baffin	210	0	0	234	6	2

* excluding Nueces, Oso and Redfish
† Upper Laguna, Lower Laguna, and Mudflats

Causeway), connecting the mainland at Flour Bluff with Padre Island. Figure 3-6 depicts this general area of the Upper Laguna Madre in the vicinity of Corpus Christi Pass. This causeway was completed 17 June 1950 (McCampbell, 1952). Two primary passages exist in the causeway affording water exchange between Corpus Christi Bay and the Upper Laguna Madre, namely Humble Channel on the west and the GIWW cut on the east. (There is also a very minor relief channel on the Padre Island side, now associated with a marina, that connects Packery Channel and the GIWW.) Both the Humble Channel and the GIWW have scoured since the JFK Causeway was built, as shown in Fig. 3-13. Bulkhead Flats has always been an extremely shallow area, sometimes with large areas of emergent flats between isolated pools. The JFK Causeway does not, therefore, represent a major reduction in cross section, so much as it may comprise a barrier to the free flow of higher water when the region is inundated. The consequences of this are explored in the following chapters.

The third major barrier is the cordon of spoil islands placed along the longitudinal axis of the Laguna Madre, along the GIWW. Although "circulation passes" are included at intervals along the line of disposal areas, there is little doubt that these islands significantly inhibit lateral circulation in the Laguna.

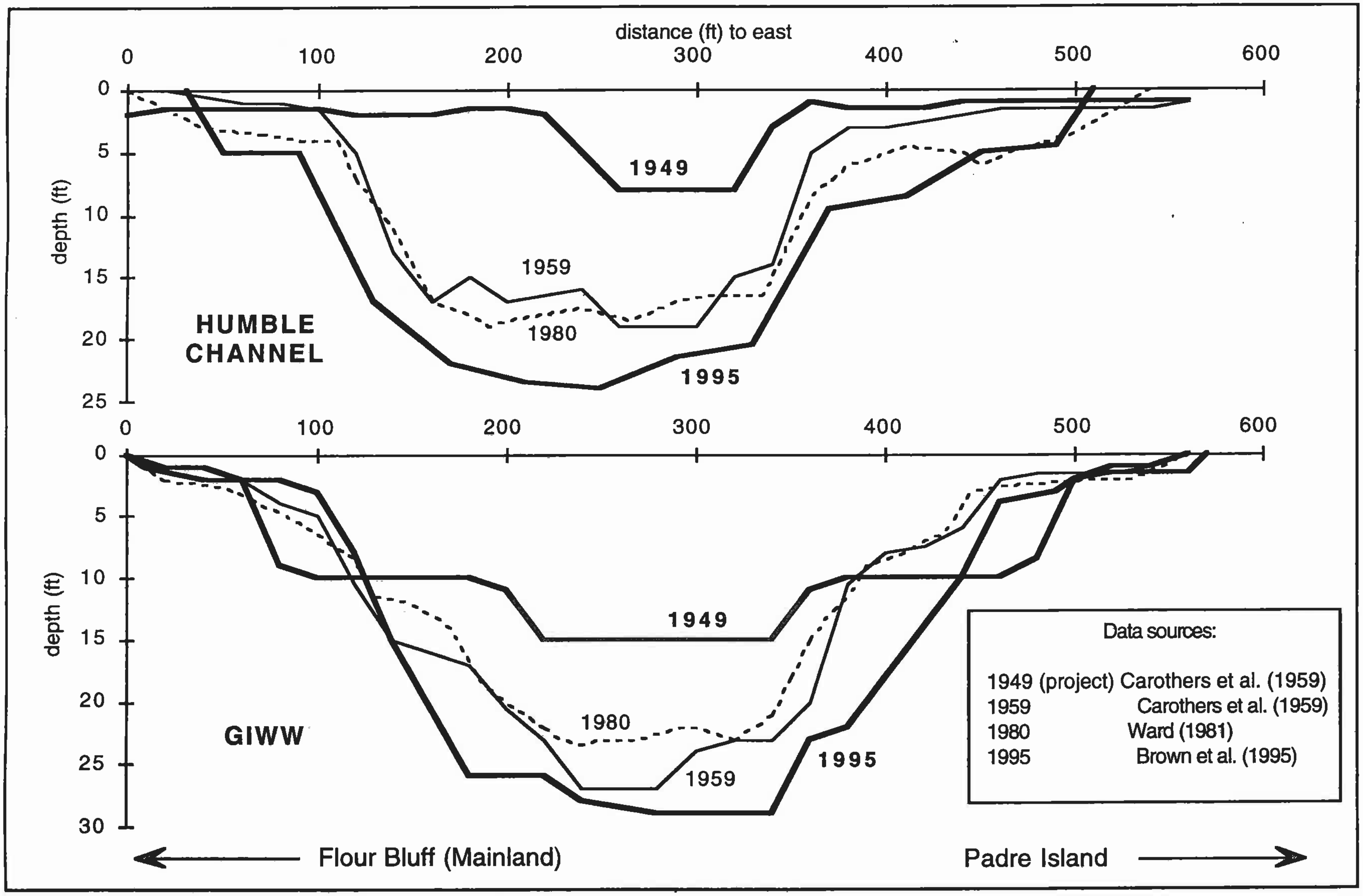


Figure 3-13. Cross sections of inlets in JFK Causeway, looking north, 1949-1995

3.2.5 Shell dredging

Mudshell, the generic and misleading name given to shell dredged from the bottom and periphery of the bay, and comprised primarily of oyster, has been a ubiquitous building material since the beginning of European settlement. The material is readily available, strong, and easily worked. It was an ideal material for roads (Doran, 1965) and could be mixed as "shellcrete" for building construction. The early buildings in Corpus Christi, including Col. Kinney's residence (McCampbell, ca. 1934), were constructed of shellcrete, and many Nineteenth Century shellcrete ruins remain standing from St. Charles Bay to Baffin. Construction shell was easily obtained from the reefs in shallow water, or even more easily from the paleoreefs on land. (Actually, many of these were not reefs, but Indian middens. In the 1920's, arrowheads could frequently be found on the streets of Rockport after being re-paved, according to Martin, ca. 1930. He also reports boys kicking a skull along the Rockport beach that they had found where the city was excavating paving materials.) Shell has continued to be widely used for paving from driveways to highways to the runways at Cliff Maus Field.

It is difficult to determine what volume of shell may have been dredged for these purposes from the Corpus Christi Bay system in the early years, but this volume is negligible in comparison to large-scale commercial dredging which began in the 1930's. The growth of the reef shell industry was stimulated about 1916, when Lonestar Cement (Portland Cement Company) began operations on the Houston Ship Channel, using shell as the raw material for cement. By 1928, there were three cement factories in the world using mudshell, of which two were in Houston (and the third in California, TGFOC, 1928). In the late 1920's, raw shell began to be used as a supplement in poultry feed, especially to facilitate eggshell formation, and two feed factories began operations in Houston (Kerr, ca. 1970). At this time, shell was still a minor industry, however, whose fortunes waxed and waned. The turning point for the industry was in 1929, when a process for manufacturing lime from shell was devised, relying on rotary-kiln technology, thereby opening markets for plaster, mortar, waste treatment, water softening and many other uses. Lime from reef shell began to be used in pulp manufacture, through creation of calcium hypochlorite used in the bleaching process, which, according to Kerr (ca. 1970), revitalized harvesting of cut-over forests in East Texas for paper mills about 1937. In 1941, Dow established its magnesium plants near Freeport, a further market for reef-shell lime.

Most of these markets were located on the upper Texas coast and were supplied by shell dredged from that area, primarily Galveston Bay. The key development for Corpus Christi was the the use of mudshell for production of soda ash. This was the purpose of the Southern Alkali Corporation plant at Avery Point. The Corpus site was ideal: ample supplies of natural gas, access to deep water, and, most importantly, huge resources of mudshell in Nueces Bay. Many of the products of this plant were used locally, such as in drilling muds. Dry ice was an excellent refrigerant. Caustic soda and dry ice were used in refining aluminum from bauxite (Kerr, ca. 1970). In 1934, Southern Alkali Shell leased two million cubic feet of Nueces Bay from TGFOC and began shell dredging operations (Mitchell, 1959). This was the beginning of commercial dredging in the Coastal Bend bays.

With the growing market, commercial mudshell dredgers began to come into operation. Parker Brothers and Company was founded in 1924 and became the dominant producer along the Texas coast (Kerr, ca. 1970). The range of the dredges was extended, and as the reefs in the upper coast began to be depleted, the industry moved down coast for oyster shell. Corpus Christi Bay was the southern limit of shell dredging on a commercial scale. The trends in shell production are shown in Fig. 3-14 for the Texas coast exclusive of Galveston Bay, including data for Nueces Bay. During the early 1940's, production more than doubled its pre-WW II rates, a consequence of the new markets for reef-shell lime, and a harbinger of the boom in shell dredging that was to come. Halliburton Portland Cement plant located on the north shore of the industrial canal in 1950, primarily to utilize oyster shell from Nueces Bay. The plant also used clay from a 180-ac clay deposit on the north shore of Nueces Bay. Both shell and clay were barged to the plant. The Reynolds plants started operations in the mid-1950's. The pads for petroleum wells in Copano, Aransas and Corpus Christi Bay were dredged from the bays themselves.

Major shell producers began dredging in the study area in the 1950's, especially in Nueces Bay. In FY 1958 the total dredged in Nueces Bay was 1,175,000 cu yds by the following producers (Anderson, 1960):

Company	*cu yds*
Corpus Christi Shell Co.	193,273
General Dredging Co.	476,522
Matagorda Shell Co.	180,000
Heldenfels Bros.	324,837

This may be an underestimate, because permits were also held by Bass Brothers Enterprises, Bauer Dredging, and King Fisher Marine (Kerr, ca. 1970). The estimated dredged volumes from Nueces Bay from 1934-66 are shown in the lower panel of Fig. 3-14. Methods by which these estimates were constructed are summarized in Appendix G. A cumulative total of 24.4×10^6 cu yds is estimated to have been dredged from Nueces Bay this century.

But shell was a finite resource. As supplies became depleted, direct dredging of, or indirect danger (due to siltation) to living reefs became an increasing problem (e.g., Benefield, 1976, Hopkins and McKinney, 1976). In 1953, the TGFOC prohibited dredging within 1500 ft of live reefs, and the following year assigned a warden to monitor dredging. In 1963, in response to the dwindling supply of mudshell, the (newly re-named) Texas Parks and Wildlife Department (TPWD) briefly allowed dredging within 300 ft of live reefs, but the next year implemented "controlled dredging," involving the close monitoring by TPWD staff. In 1971, TPWD issued even more stringent rules re-imposing the 300-ft limit, among other provisions (Sidner and Bouma, 1976). The Corps began to require Section 10 permits as well, requiring the lack of an obstruction to navigation posed by the dredger. Even more stringent rules were imposed by TPWD effective 1 October 1974, including more power in the field monitoring staff to move or halt dredging

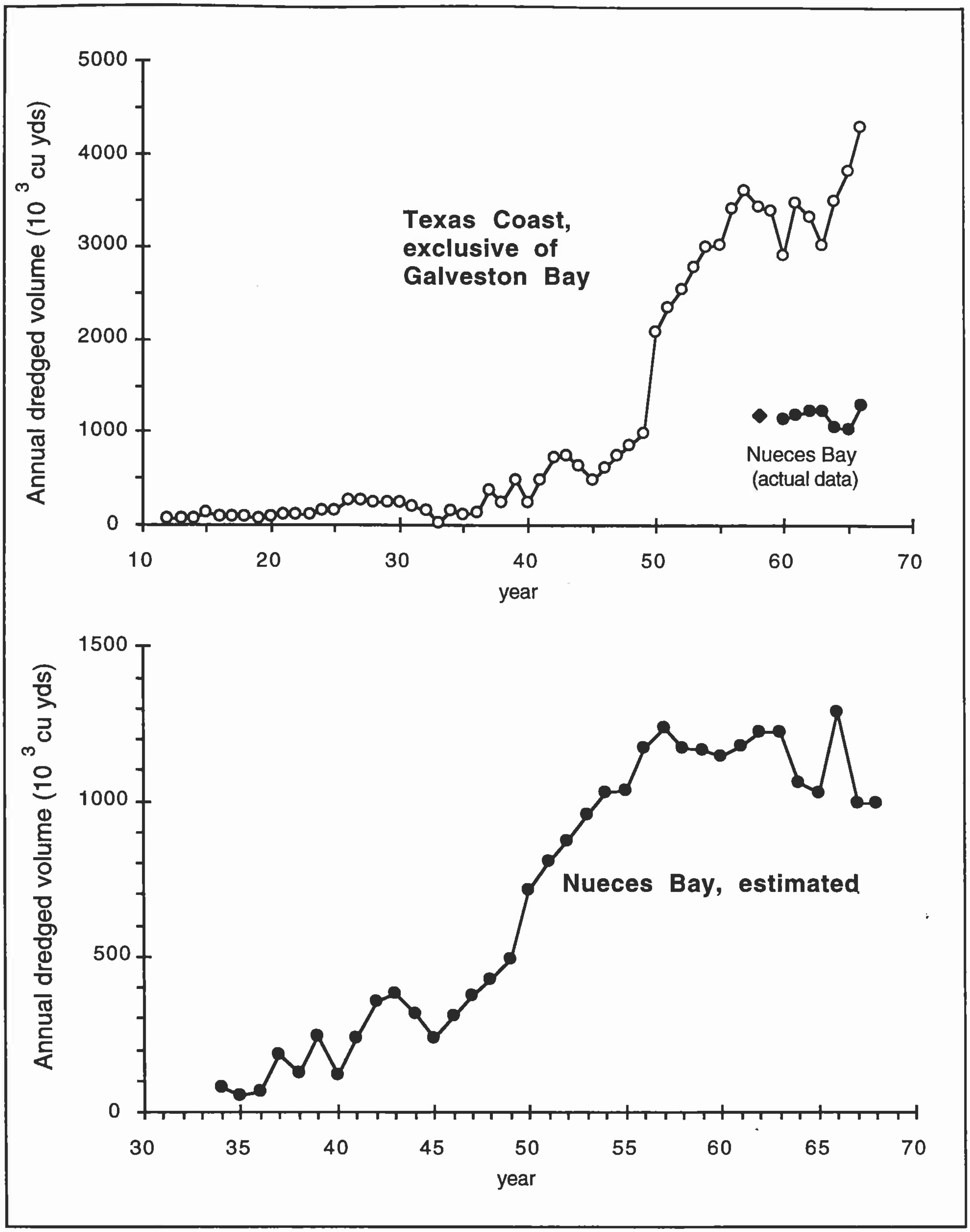


Figure 3-14. Time history of shell dredging in Nueces Bay (see Appendix G)

operations found to be in violation of Department rules. Thus shell removal became constrained on the one side by supply and on the other by regulation. By 1970, shell dredging on the Texas coast had, for all practical purposes, retrenched to San Antonio Bay and Matagorda Bay (see Burg, 1974, Clements, 1975).

As of 1967, Kerr (ca. 1970) reported that Nueces Bay was believed to be nearly fished out for oyster shell. He states that the oyster industry was "...defunct, in fact, before the dredgers moved in." Considering that the period of time in question was dominated by the droughts of the 1950's and 1960's, the dredgers may have taken advantage of high-salinity die-backs. (Anderson, 1960, noted that during high salinity years when oyster populations die back temporarily, oyster-producing reefs were removed from Nueces Bay by shell dredgers.) Substantial paleoreef reserves for mining were thought to remain in Copano Bay, Aransas Bay and Mesquite Bay. The resources in Copano and Aransas were beneath live reefs, though Aransas was being harvested and therefore was off limits to dredgers. Considerable oyster shell was removed from Mesquite Bay and northern Aransas during the 1930's, but no quantitative data are available. It is known that the reefs were originally so dense in this area that Indians could cross the 15 km from Lamar Peninsula to St. Joseph Island on foot by starting at Goose Island and simply following the reefs. Martin (ca. 1930) interviewed a pioneer of the area that personally witnessed the Karankawas crossing here.

3.3 Alterations to inflows

One of the important forcing factors for an estuary is the flows imposed around its periphery (Ward and Montague, 1996), which for Corpus Christi Bay fall into three categories: freshwater inflows, forced circulations, and waste discharges. The last, waste discharges, are of such small flow volumes that their overall effect on bay circulation is considered negligible. The first two are, however, a different matter.

3.3.1 Dams and diversions

The hydroclimatology of the Coastal Bend bays was summarized in Chapter 2 above, and will be addressed again in Chapter 5 below. Significant alterations have been made to only one of the feeding rivers, namely the Nueces, which has been dammed for many years to provide a source of water to Corpus Christi. The first dam, completed in 1929, was called Mathis Dam (Dowell and Breeding, 1967) a.k.a. Corpus Christi Dam, located on mile 47.6 near Mathis, to create Lake Lovenskiold (after the Corpus Christi mayor who was the dam's main proponent). In October 1930 the *Engineering News-Record* (*ENR*, 1930a) carried notice of the dam's completion, and in November it carried notice of the dam's failure (*ENR*, 1930b). The dam failed on 23 November due to undermining of the north abutment wall. (See also *ENR*, 1930c, 1930d, Brown et al., 1948, and Dowell and Breeding, 1967.) The structure was rebuilt in 1934, and renamed La Fruta dam (Dowell and Breeding, 1967, though *ENR*, 1930d, refers to the first dam as La Fruta). Total length was 4080 ft, in two sections, a non-overflow earthfill embankment of 2830 ft and a spillway of 1250 ft. The uncontrolled spillway crest was at 74.2 ft MSL and was equipped with a gated section with five Tainter gates with sill at 54.2 ft MSL. The lake eventually became known as Lake Corpus Christi. Data at USGS on the contents of the lake apparently go back only to 1948.

This was the primary water supply for Corpus Christi, for practical purposes the only water supply. (During the early war years, Corpus Christi became concerned about failure or sabotage of La Fruta, and in 1941 requested an upstream multipurpose project of the Corps.) Then, as now, the Nueces channel was used as the delivery conveyance for the water to Corpus Christi. The low rubble-mound dam at Calallen (mile 12.4) serves as salt barrier and as impoundment to reduce pumping head to the city. Calallen was built in 1898 preceded by a barrier of wooden construction (R. Volk, pers. comm., 1997). Prior to 1942, considerable wastage of water occurred by percolation through Calallen, but in 1942 the dam was repaired to eliminate this loss (Brown et al., 1948). The original capacity of La Fruta was about 55,000 ac-ft. As of 1942, the capacity of the lake was 43,400 ac-ft, and was dropping by 1387 ac-ft/yr due to siltation (USCE, 1944). The SCS surveyed the lake in 1948 and found its capacity to have fallen to 39,390 ac-ft (Brown et al., 1948).

USCE (1944) noted that, "the officials of the city of Corpus Christi are apprehensive concerning the future adequacy of this dam and reservoir to form a dependable water supply for the domestic and industrial needs of Corpus Christi." This concern was due not only to the diminishing capacity of the dam, but the drought-prone nature of the area, and the need for reliable water for future growth. (Cummins, 1953, states that the Humble Refinery moved from Ingleside in 1947 because the price of water had become prohibitive.) At that time 22 dam/reservoir projects were under consideration or planning by local interests, of which only La Fruta had been built.

In 1958, Wesley E. Seale Dam was constructed creating the present Lake Corpus Christi, and in the process inundating the old La Fruta dam. The spillway crest of the dam is at 88.0 ft MSL. The nominal capacity of Lake Corpus Christi when constructed was 300,000 ac-ft at the normal lake elevation of 94.0 ft MSL. A 1987 survey showed the capacity at that elevation then to be 241,200 ac-ft, a loss of about 2,000 ac-ft/yr to siltation.

Harland Bartholomew and Associates reviewed the area's water supply needs in the mid-1960's. Firm yield estimates of Lake Corpus Christi at that time ranged 130,000-140,000 ac-ft/yr (Mitchell, 1959, HBA, 1968), the larger of which was projected to have been committed by 1973. Clearly, a greater supply was needed. A strategy of increasing the capacity and yield of Lake Corpus Christi by raising the dam had been part of the original plan for Wesley E. Seale. It was estimated that if dam were raised 10 ft, the capacity would be increased to 600,000 ac-ft and dependable yield would be 190,000 ac-ft/yr (Mitchell, 1959, from interviews with LNRA staff). But HBA (1968) correctly sized up the situation during the 1960's, stating, "It is unfortunate that the long range planning for Lake Corpus Christi did not include reservation of the shoreline areas for its future expansion since additional expense was incurred at the time of construction of [the] dam so that the reservoir might be raised 10 ft to increase its storage capacity. However, since no steps were taken at that time to control shoreline development, the cost to expand the impounded area, as originally intended, is now prohibitive." Instead, planners looked to the Choke Canyon project, which was anticipated to provide an additional 147,000 ac-ft/yr, considered to be adequate to supply the area until about 1990, when the Texas Basins Project would be in place (HBA, 1968).

Choke Canyon reservoir, located on the Frio, a major tributary of the Nueces, was completed in 1982 and intended to be operated in tandem with Lake Corpus Christi. Capacity at the spillway crest of 200 ft MSL was 270,000 ac-ft when constructed. Deliberate impoundment began in October, though in this context "deliberate impoundment" is a theoretical term, as there was little water to impound, the reservoir remaining below conservation capacity for years. The Choke Canyon Reservoir proved to be a difficult and controversial project, whose permitting ultimately led to the Interim Order specifying mandatory releases from storage in the LCC-CC system for the downstream estuary.

3.3.2 Power plants

Forced circulations result from the transport of water from one section of the bay to another. In the Corpus Christi system, there are two such transports of sufficient volume to potentially affect estuary circulation, both of which are the cooling circuits of steam-electric power plants. These are the Nueces Bay Station on the Inner Harbor, and the Barney Davis Station on Oso Bay.

The CP&L Nueces Bay Station has been a fixture of the harbor area since the 1930's. In those years it was small by modern standards, a 15 MW power plant. In 1941 the Nueces plant doubled its capacity to 30 MW with a second 15 MW unit, and plans were announced for a third in 1942 (WPA, 1942). By 1949 the plant was operating five units (Caller-Times, 1952), the 30 MW Unit 5 coming on line in that year, with a total station capacity of 84 MW and circulating flow of 3.4 m^3s^{-1} (120 cfs, 75 MGD), see Anderson (1960) and McGraw-Hill (1960). During the 1960's its capacity was increased severalfold. Unit 6 rated at 160 MW began operation in 1965, and Unit 7 at 325 MW in 1973, while Units 1-4 were phased out (Ray Allen, CP&L, pers. comm., 1997). At present, this SES is rated at 515 MW generating capacity and is permitted for a 21.9 m^3s^{-1} (775 cfs, 500 MGD) circulating flow (Mierschin, 1992). The actual generation and circulating flow are variable, depending upon the number of units in operation, load demand, and efficiency; a typical circulating flow is 18.4 m^3s^{-1} (650 cfs, 420 MGD).

Ward (1982a) compiled data on the heat rejection of this plant and the resulting thermal plume in Nueces Bay from the 1970's, for which the same nominal circulating flow was indicated. The condenser temperature rise ranges nominally 4-10° C, and the resulting plume at 1°C (temperature rise over ambient) is about 200 ha (500 acres), ranging a factor of two about this value depending upon meteorology, especially wind direction.

From the standpoint of circulation, the important feature of the Nueces Bay SES is that it draws its circulating water from the Industrial Canal of the Inner Harbor and discharges to the southeast corner of Nueces Bay, see Figs. 3-9 and 3-10. Thus this plant has created a virtually continuous transfer of water from Corpus Christi Bay near the entrance to the Inner Harbor, into Nueces Bay. For the past 25 years, this flow has been about 650 cfs, over six times the low flow of the Nueces River. According to Anderson (1960), in 1957-58, Columbia-Southern Chemical Co. generated its own power and circulated about 3.4 m^3s^{-1} (130 cfs, 80 MGD) as cooling water also from the Inner Harbor to Nueces Bay. No information could be located as to the age or history of this discharge (the older discharge permit data files having been destroyed by TNRCC), but it apparently was discontinued when the Nueces Bay SES plant expansion occurred in the 1960's.

The other major power plant that operates in the Corpus Christi Bay system is the Barney Davis Generating Station of CP&L. Like the Nueces Bay SES, Barney Davis is a fossil-fired steam-electric station with once-through cooling. The plant is comprised of two 325 MW units, the first of which came on line in 1974 and the second in 1976, with a combined rated circulating flow of 540 MGD (Ray Allen, CP&L, pers. comm., 1997). Cooling water is drawn from the Upper Laguna Madre near Pita Island and discharged into Oso Bay, at a nominal average circulating flow rate of 19 m^3s^{-1} (670 cfs). Unlike the Nueces Bay SES, the Barney Davis discharge is first detained in a shallow cooling pond of area 4.5 x 10^6 m^2 (1.77 sq mi), the net effect of which is to reduce the temperature rise upon discharge into Oso Bay to less than 1°C (referenced to the ambient intake temperature, which may differ from the ambient temperature in the discharge area). However, the plant does effect a continuous transfer of water from the Upper Laguna into Oso Bay, thence into the southeast section of Corpus Christi Bay.

4. INTRATIDAL CIRCULATIONS

> ARANZA INLET.— In going in, bring the south point to bear W. by S. or W. by N. and after crossing the bar, steer direct for the south point, taking care the tide does not affect you, as it is very strong, and you may go within pistol shot of the point, hauling to the north soon as you have passed it...
>
> —Blunt's American Coast Pilot, 1837

As stated in Chapter 1, the organizational approach of this report is through time-space scales. We first address the short-time-response end of the spectrum. This is referred to here as *intratidal*, though strictly we address time scales from a few minutes to several tidal cycles in this category. This is in contradistinction to *intertidal* scales, treated in Chapter 5, referring to time scales of many tidal cycles. This distinction is imprecise. Some hydrographic events, such as freshets, involve responses in circulation spanning both intra- and intertidal scales, so the category in which they are placed is somewhat arbitrary.

In this chapter we focus on two short-term phenomena that together characterize the vast majority of circulation responses on the intratidal scale: the astronomical tide and short-term fluctuations in wind velocity, especially frontal passages. The primary measurable indicator of both of these in Corpus Christi Bay is water level. Water level is an integral of current velocity, therefore information on water level variation allows inference about current velocity in the main conduits of the system through application of continuity principles. This sentence may seem obscure, but it will be clarified—hopefully— in the following discussions.

4.1 Data sources and data processing

Measurement of water level in the system is effected by the operation of tide gauges (though the name is imprecise, because the water level variation that is measured in fact derives from nontidal influences as well). Such gauges have been operated in the system certainly during most of the present century, primarily by the National Ocean Service (née U.S. Coast and Geodetic Survey, née U.S. Coast Survey) and the U.S. Corps of Engineers. The objectives of the two agencies differed, the USC&GS being concerned with development of tide predictions, and the Corps with maintenance of navigation projects and hazards to coastal structures. The Corps employed by far the widest distribution of gauging stations throughout the interior of the bays. At least 20 Corps gauges have been operated in the study area since the 1960's, according to archiving records of the Galveston District USCE. Harris and Lindsay (1957) identified six USCE gauges in the study area with records then on-hand dating back to 1932. Tide gauges were operated by the Corps in conjunction with the Aransas jetty projects at least since the turn of the century. The USC&GS, in contrast, has operated much fewer long-term gauges, and concentrated these along the Gulf coastline or just inside the inlets. In the 1970's, the U.S. Geological Survey, through sponsorship of the Texas Water Development Board, operated several (at least four) gauges in the upper bays of the study area, the records being filed at the

Houston office. These were all long-term gauging projects, with the intention of the agency of maintaining the gauges indefinitely. In addition, several scientists at the University of Texas Marine Science Institute have installed and operated gauges for relatively short time periods for research purposes.

The agency gauges were mainly Leopold-Stevens-type float instruments mounted in a stilling well and connected to a rotating-drum chart recorder. A few of the USC&GS gauges used bubbler-type sensors but still with rotating drum charts. Therefore, the basic data logging format was hard-copy analog. The Corps program sustained two major blows. First, when the Galveston District moved from the Sante Fe Building to the Essayons Building, apparently many of the older tide scrolls did not make the transition. Second, in the late 1970's, responsibility for the gauges was passed from dedicated staff at the District Office to existing staff at the area offices. Many of the gauges were neglected, some were abandoned, and data recovery from the extant gauges suffered.

From the standpoint of the present project, the most formidable obstacle is the fact that the gauge records are in the form of paper scrolls, which would have to be digitized in order to be usable. Seeking out and digitizing the older tidal records greatly exceeded the resources of this project, though this is certainly an undertaking that should be considered by the natural resource agencies of Texas. Instead, this project effort was concentrated on the processing and analysis of the gauge records from the Conrad Blucher Institute for Surveying and Science (CBI) Texas Coastal Ocean Observation Network (TCOON). CBI, a research unit of Texas A&M University—Corpus Christi, has been building the TCOON program since the late 1980's under the sponsorship of the Texas General Land Office and the Texas Water Development Board. TCOON is a project of automatic gauging of water levels and related hydrographic variables in the coastal environments of the state. The motivating objectives of TCOON are to obtain precise water-level data on which tidal datum determinations can be reliably computed for purposes of establishing ownership of nearshore properties, to provide real-time data on coastal hydrography to commercial, industrial, environmental and recreational interests, and to provide a base of accurate hydrographic data to support general research in the Texas coastal zone. Key features of the TCOON program are:

- a network of gauges within the bays and on the coast with records extending back two or more years;
- state-of-the-art electrometric (acoustic or pressure-transducer) water-level sensors;
- associated measurements of wind velocity and direction at many of the CBI gauges;
- satellite-relay data transmission to central base station at CBI;
- digital data acquisition and storage
- data subjected to error screening and objective rejection algorithms;

- data storage in consistent, uniform format, capable of transmittal by Internet file transfer protocols (ftp)*

These data sets provide measurements of water level to state-of-the-art precision. The problem of time drift, the bogey of *in situ* dataloggers, both rotating drum and robot sondes alike, is completely eliminated because the data are not logged at the gauge but rather at the base station by interrogating the gauges, so that the time of observation can be established absolutely. The basic water-level measurements are obtained every 6 minutes, i.e. ten measurements per hour. A 6-minute measurement is in fact a computed average of 180 separate observations of water level (or any other hydrographic variable) made at 1-second intervals, therefore bracketing the 6-minute sample time by a 3-minute sampling window, from 90 seconds before the mark to 90 seconds after. Data are available from CBI in two temporal densities: either the basic 6-minute measurements, or at hourly intervals on the top of the hour. The latter were used in this analysis.

An observation of water level is always made relative to a fixed datum, i.e. some pre-established vertical level. The actual measurement itself will be made with respect to a piece of hardware. If the measurement is based upon the time of travel of an acoustic pulse to the water surface and back, for example, the implicit datum is the position of the transducer above (or below) the water surface. This level may in turn be related to some more-or-less arbitrary level, such as the top of the instrument housing or the base of the platform piling (perhaps chosen to avoid the occurrence of negative values, no matter how low the level might drop). This arbitrary level is called the "gauge datum" and has no intrinsic physical significance whatever. Whether there is a need to relate this gauge datum to an established vertical reference depends upon the purpose of analysis of the data. There are three basic categories of vertical datum establishment for tide gauges:

(1) relative statistics and harmonic analysis - gauge datum

(2) water surface slopes (hydrodynamics) - consistent relative datum

(3) absolute water surface elevations - geodetic datum

These are illustrated in Fig. 4-1. The first type of analysis establishes the levels of tidal statistics such as Mean Higher High Water, Mean Lower High Water, Mean Low Water, etc., relative to each other, or the values of difference statistics such as Mean Tidal Range. Also, the determination of amplitudes of different harmonic constituents, see Section 2.3, can be made using the gauge datum, since all such amplitudes are themselves relative.

The second type of analysis requires the ability to determine the relative elevation of the water surface *between* gauges. To accomplish this, the observed water

* CBI has recently implemented a home page on the World Wide Web, through which data downloads can be performed (http:// dco.cbi.tamucc.edu).

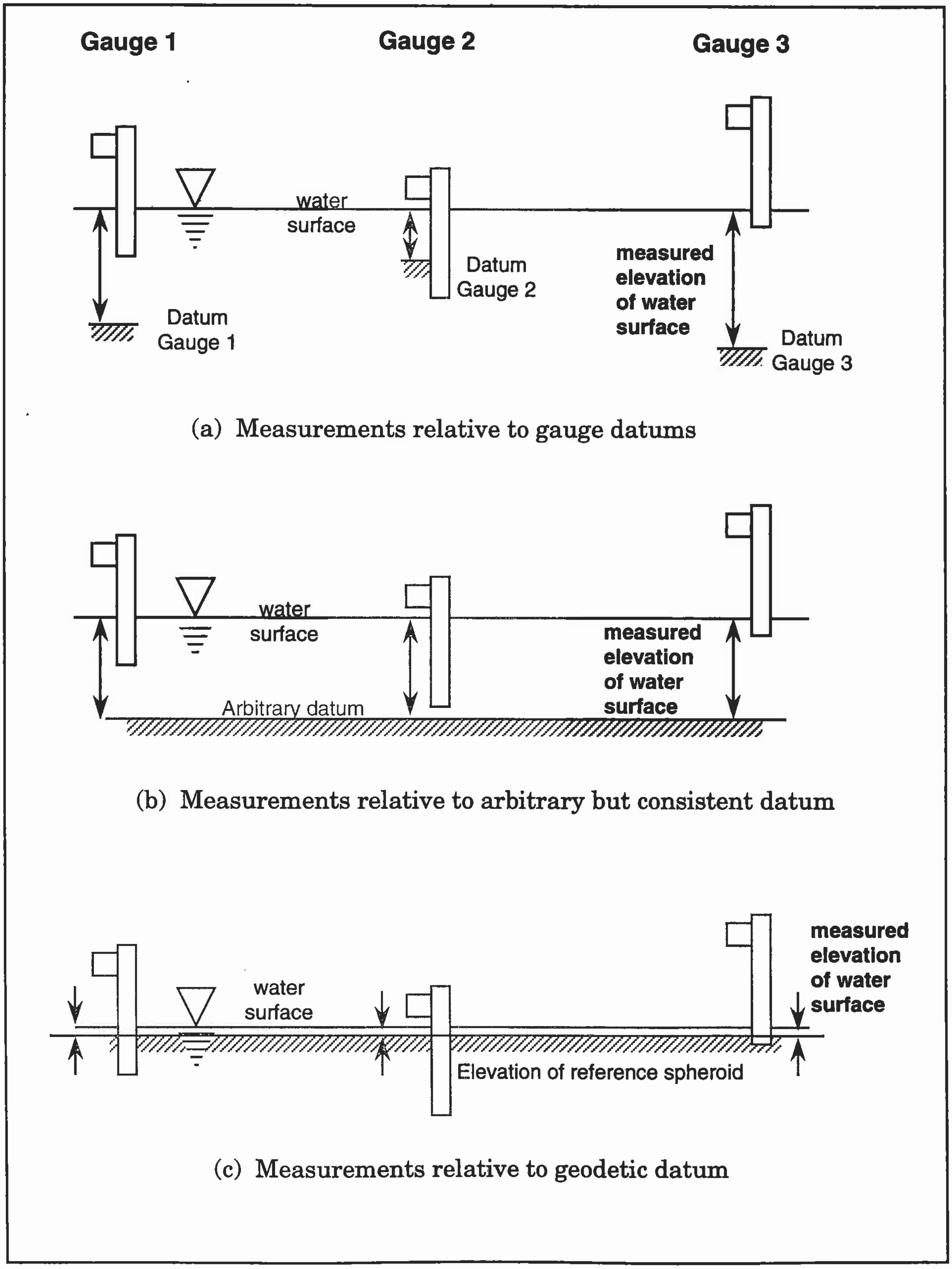


Figure 4-1. Water-level measurement referenced to different types of datums

levels must be related to the same datum level, though this datum can itself be completely arbitrary. This greatly raises the investment of effort, because this necessitates linking each pair of gauges by a vertical survey. This is very difficult in practice, as tide gauges are usually widely separated, and the survey traverses would generally have to be carried overwater. Moreover, because water surface slopes on the order of millimeters per kilometer can be significant hydrodynamically, the necessary vertical survey precision is very exacting.

The third type of analysis is even more demanding, in that the gauge datum must be related to an absolute geodetic reference, e.g. the National Geodetic Vertical Datum (NGVD). This might be involved if the general water level behavior is to be referenced to a standard map datum, for example, or if a mean sea level statistic is desired. Whereas the second category needs accurate surveying between gauges, the third category requires that each gauge datum be surveyed into a specific reference level, generally from a terrestrial network. International conventions for tide datum nomenclature and analysis methods are summarized in Pugh (1987).

As a general rule, each category of levelling subsumes the preceding. That is, if type (3) levelling has been established, this will also provide relative levelling between gauges, and allow water-surface-slope determinations. If relative levelling, type (2), has been carried out, the data can certainly be used for type (1) harmonic analysis and relative statistics. (There is one possible exception, in that the accuracy of the type (3) absolute levelling may not be sufficient to accurately determine water-level slopes, though it may well be sufficient for the reference to a map datum. Thus if one intends to use tide records that have been established relative to a geodetic datum for hydrodynamic analyses, some assurance is needed that the survey accuracy is adequate.)

NOS has established NGVD levels for each of its primary gauges. The NOS gauge at Rockport that is part of the TCOON network has therefore been leveled to an absolute geodetic reference. However, none of the other gauges in the TCOON network have been leveled. This is not surprising, because all of the uses that CBI and others have made of the TCOON data fall into the first category, requiring relative tidal statistics and harmonic analyses of tidal constituents. Some preliminary work on developing a "Blucher Datum" was carried out several years ago (Mike Speed, pers. comm., 1996), but the results proved to be inconsistent and the effort has not been pursued. It should be emphasized that the lack of a consistent datum is not a failing of CBI. Very few coastal tide gauges in the United States, apart from NOS primary gauges—which are too widely spaced to allow hydrodynamic analyses—have been consistently leveled. *None* of the Corps or USGS gauges are relatively leveled. (This lack of relative levelling has been a ubiquitous problem in model validation against tide gauges, as has been remarked repeatedly in the literature.) With the advent of satellite altimetry and Global Positioning System, accurate levelling without the exigency of carrying long overwater traverses may soon be possible, but the vertical dimension is presently problematic for these systems and will require great care and sophistication.

Twelve CBI water level stations were selected for analysis in this project, based upon (1) general location in the Corpus Christi system, and (2) period of record available. These are listed in Table 4-1, along with geographical coordinates, and their locations are shown in Fig. 4-2. The purpose of data analysis in this project is to illuminate the hydrodynamic functioning of the system. Therefore some means of establishing a relative datum for these stations was mandatory. A method was developed referred to as "empirical levelling." This involves defining a combination of hydrographic conditions that would be expected on physical grounds to result in a horizontal water surface, then searching the available data base for the occurrence of this combination of conditions, extracting a subset of the measured water levels at each gauge during these periods and evaluating their behavior and statistics. The hydrographic conditions delineated for empirical levelling are (1) near-zero lunar declination, thereby ensuring a minimal astronomical tidal range, (2) sustained high pressure following a cold-air outbreak (see Section 2.2.3), and (3) sustained near-calm winds, associated with the release of north winds prior to re-establishment of onshore flow. "Sustained" means at least 12 hours. The details and application of empirical levelling to the CBI gauges are summarized in Appendix C. This method proved to be eminently successful, and allowed a degree of analysis heretofore unachievable with Texas coastal tide records.

In the preparation of the CBI data for detailed analysis, this project was the first, apparently, to carefully study the data from some of these gauges. In the course

Table 4-1

TCOON stations used in analysis of water-level response in Corpus Christi Bay system

TCOON Station	*Latitude*		*Longitude*		*UTM-E*	*UTM-N*
	deg	*min*	*deg*	*min*	*km*	*km*
Bob Hall Pier	27	34.9	97	13.0	675.7	3052.0
Port Aransas	27	50.4	97	4.4	689.7	3080.8
Rockport	28	1.5	97	2.9	692.0	3101.5
Copano Bay Causeway	28	6.9	97	1.5	694.0	3111.0
Bayside	28	4.0	97	12.2	676.4	3105.6
Ingleside	27	49.3	97	12.2	676.9	3078.5
State Aquarium	27	48.9	97	23.5	658.5	3077.7
White Point	27	51.6	97	29.0	649.0	3082.5
Naval Air Station	27	42.3	97	16.8	669.5	3065.6
Packery Channel	27	38.0	97	14.2	674.0	3057.3
South Bird Island	27	29.1	97	19.1	666.1	3041.3
Yarborough Pass	27	10.0	97	26.0	655.3	3005.8

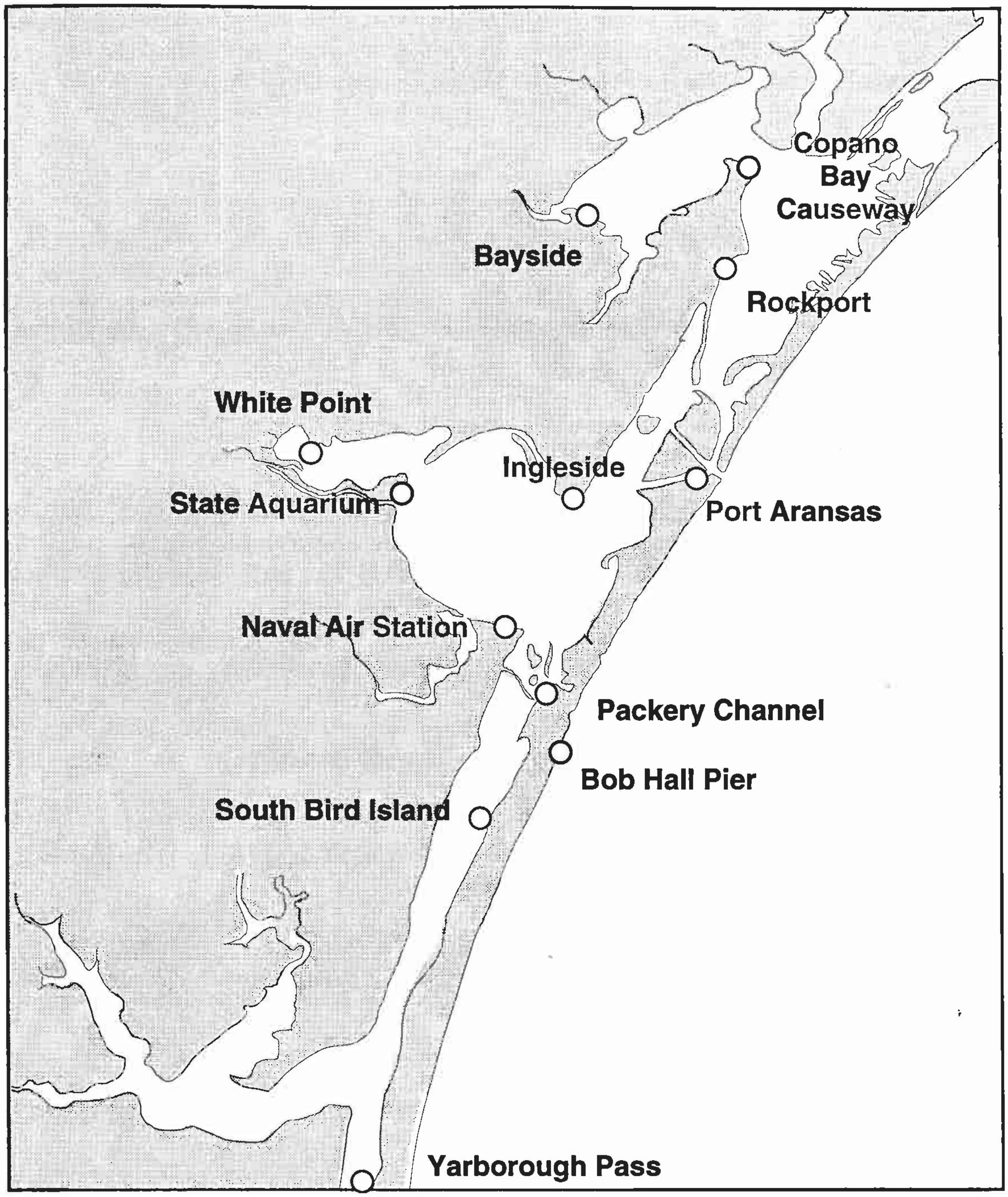


Figure 4-2. TCOON stations used in water-level analyses

of data reduction and re-formatting a number of problems were discovered with the data that had not been detected by the CBI data-screening algorithms. A detailed visual inspection was made of the entire record for each gauge (and anemometer) used in the analysis, noting any odd shifts in values, data gaps, or phasing versus other continuous gauge records. This proved to be a labor-intensive process. Each of the gauge records contains many such events. As many natural events operating in the Corpus Christi Bay system will produce sudden changes in water level or will alter the relative phase of two gauges, most of these manifestations in the gauge data proved to be real. However, there was found a residual of anomalies, evidently arising from gauge malfunctions, settling, or processing errors, that had to be removed manually. All of these data corrections are described in Appendix B. There still remain suspicious elements of some of the data records.

4.2 Hydraulics of basins with constricted connections

At its simplest level, the Corpus Christi Bay system can be considered to be a series of basins interconnected through very constricted inlets, and much of the dynamics of the system can be explicated by this conceptual model. The connecting inlets range from short ajutages such as Copano Pass or Nueces Entrance, to rather long passages choked by shoals and reefs, such as the Bulkhead Flats connection between Corpus Christi Bay and the Upper Laguna Madre. Of course, the major basin is the Gulf of Mexico, connected to Corpus Christi Bay by the inlet of Aransas Pass, which, measured from the ends of the jetties to the end of the passage between Harbor Island and East Flats, is the longest connection in the system.

A diagram of this conceptual model is shown in Fig. 4-3. The time variation of current flow u in the conduit is given by

variation in u	=	head Δh	+	frictional drag	+	entrance/ exit losses
1		**2**		**3**		**4**

The basic driver is the head term Δh, the difference in water level between one end of the conduit and the other. This difference in water level (h_o - h_b in Fig. 4-3) forces a current through the inlet from the higher water level to the lower. Energy imparted to the water by this water-level difference is lost to friction on the bottom and sides of the inlet (Term 3). There is also a loss of energy in forcing the fluid into a curved path, especially as it converges into one end of the inlet and diverges at the other (Term 4). Frictional drag depends upon the length of the inlet and its roughness, as well as the speed of the current. If the inlet is long enough or rough enough, the head may prove too small to drive a current.

There are two basic physical principles to be abstracted from this "equation." The first is that when one basin is much larger than the other, its water level

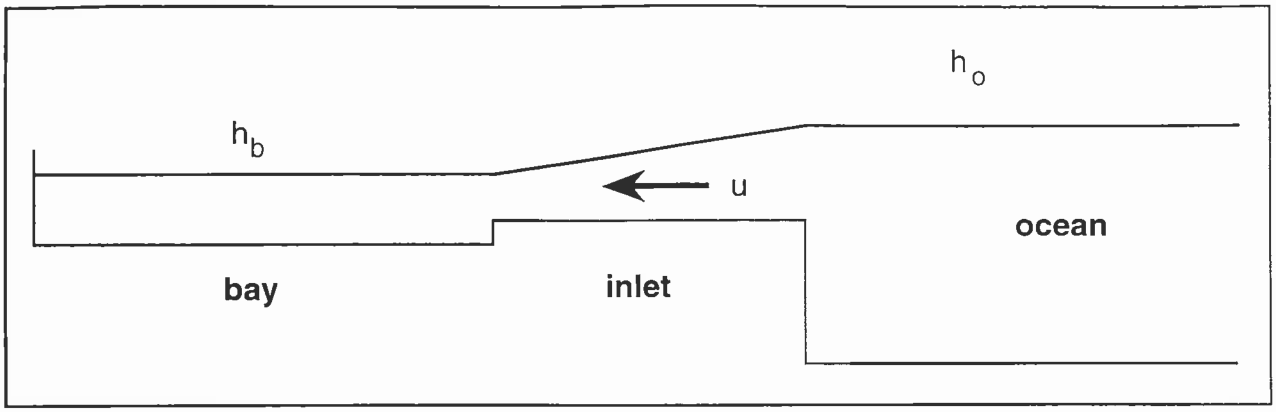


Figure 4-3. Definition sketch for model of inlet hydraulics

variation drives that of the smaller basin, but how quickly the smaller basin can react to the larger is dependent upon the hydraulic capacity of the inlet. This hydraulic capacity depends upon the cross sectional area of the inlet and its resistance to flow. This is precisely how a stilling well works. In application to the Corpus Christi Bay system, one basin is conceived as driving the other. For example, the Gulf of Mexico is so much larger than the bay that the bay has no effect on water levels in the Gulf. The Gulf water level (h_o in Fig. 4-3) is therefore the "driver" and the water level in the bay (h_b in Fig. 4-3) is the "response." Similarly, the water level in Corpus Christi Bay is the driver for water level in Nueces Bay and the Upper Laguna.

To pursue the analogy of a stilling well, assume the driving water level in the larger basin to follow a sinusoidal form with frequency ω, say, and assume a linear form for the frictional drag (so that a closed-form mathematical solution can be extracted). The response of the smaller basin will also be a sinusoid of the same frequency, and the ratio of the amplitude in the basin to that of the driver is given by:

$$\frac{g\,\varepsilon\,/\Delta x}{\sqrt{(\omega^2 - g\varepsilon/\Delta x)^2 + (f\omega)^2}}$$

where Δx is the length of the inlet, f is the friction coefficient, g is the acceleration of gravity and ε is the ratio of cross sectional area of the inlet to the surface area of the smaller basin. This relation states that the higher the frequency of the driving sinusoid, the smaller the amplitude inside the basin. The effect of the constricted inlet is to filter out the higher frequency waves and pass through the lower frequencies. This is precisely the purpose of a stilling well. A corollary to the first physical principle of limiting hydraulic capacity of an inlet is that the inlet acts as a filter for the higher frequency variations of the driving water level.

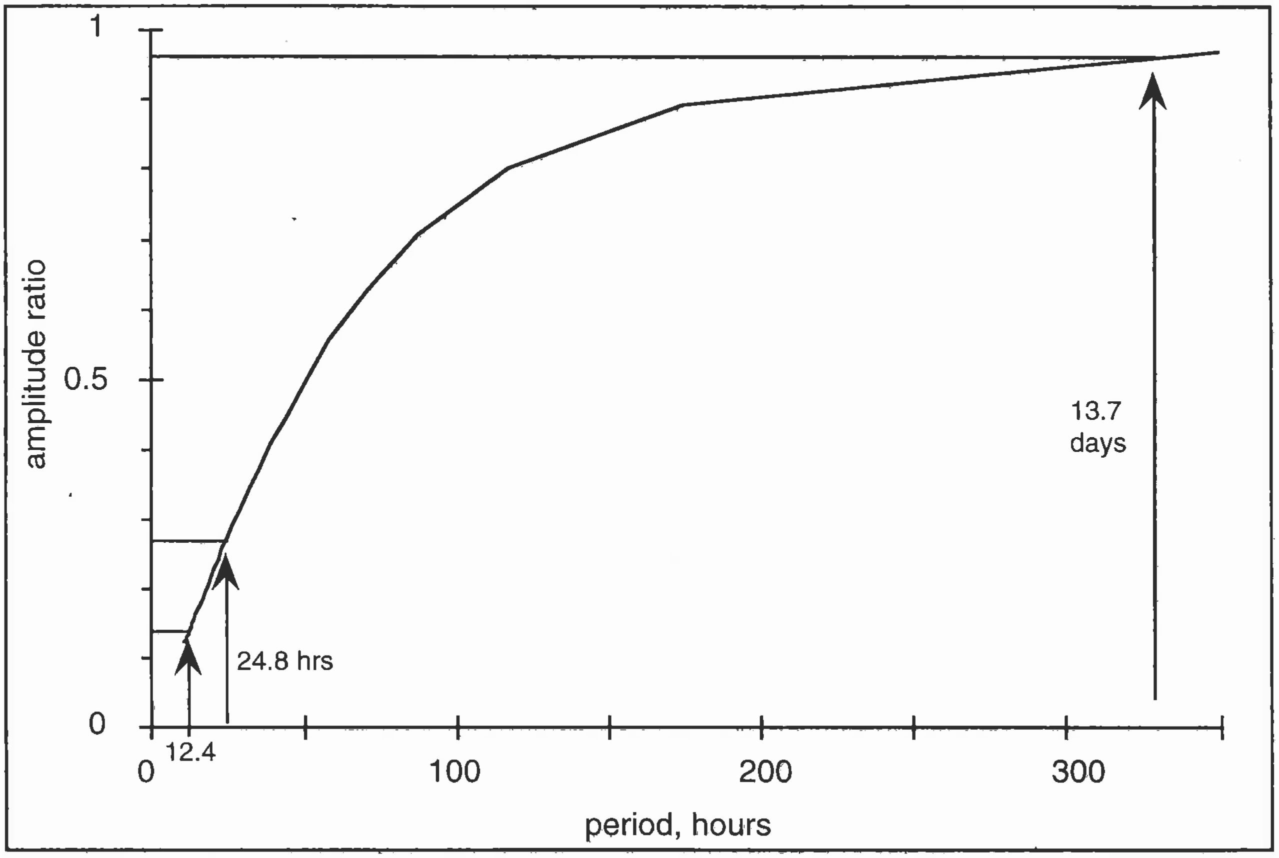


Figure 4-4. Theoretical amplitude response inside a co-oscillating basin for parameters typical of Aransas Pass and Corpus Christi Bay

If we assign values to the above parameters that are approximate for Aransas Pass and plot the amplitude ratio versus period, Fig. 4-4 results. Note the substantial amplitude reduction of the higher frequencies (i.e. smaller periods), notably the semidiurnal and diurnal lunar tide periods, compared to the longer period fortnightly tide. Aransas Pass clearly acts as a stilling well for tidal periodicities, freely passing the longer period components but significantly filtering the shorter period. Also note the steep rolloff with diminishing period. This means that the semidiurnal component is filtered much more (about a factor of 2) than the diurnal.

The second physical principle involves the symmetry of the above "equation" with respect to the direction of current. Both Terms 2 and 3 will yield exactly the same value if the head gradient is reversed, except for a reversal of sign. That is, substituting $-\Delta h$ for Δh simply changes the sign of Term 1. If Term 4 is also symmetrical, so that the entrance/exit loss is the same whether the current is flooding or ebbing, then the symmetry of the equation is preserved. This implies that the long-term average water level inside the basin will equal the long-term average water level outside the basin. (This of course is how a stilling well works.) However, the basin responses of Corpus Christi Bay are not symmetric.

The average water level in Corpus Christi Bay is higher than that in the Gulf. The average water level in Nueces Bay is higher than that in Corpus Christi Bay. The reason for this asymmetry is that the entrance/exit loss is different for the flooding current versus the ebbing, due to the very great difference in inlet configuration presented on the basin side versus the driving side. At Aransas Pass, the ocean tide sees a practically uniform coastline with a smoothly sloping bed and a pair of nearly rectilinear jetties guiding flow into the inlet. From the bay side, the ebbing tide sees a complex of irregular shoals with a narrow channel abruptly curving into the inlet. The net effect is that on the rising tide, the ocean more easily forces an influx through the inlet, but as the ocean tide falls, the bay "drains" more slowly, leading to an asymmetry of response to the tidal head.

There are various solutions for the above "equation" on the market that are derived from different simplifying assumptions. These assumptions include lumping Terms 3 and 4 together as a combined "drag" term, further representing this as a linear friction (as was done to produce Fig. 4-4 above), neglecting Term 1 (the "steady-state hydraulics" model), neglecting Term 3 (the "frictionless" model), dropping Term 4 (the "uniform-channel" model). Solution of the complete unexpurgated equation requires numerical integration. Appendix D provides the mathematical details of this equation and its solution, with the requisite complement of squiggles and del-byes, for the interested reader.

A numerical integration of the equations for inlet hydraulics is provided as EXHIBIT1 on the diskette enclosed with the report. This "model" is based upon the equations given in Appendix D. At this point, the reader is invited to execute this exhibit on the personal computer by simply entering EXHIBIT1 at the DOS prompt. See Appendix A for installation instructions. (If WINDOWS is being used as the operating system, this will require first accessing DOS from WINDOWS, or exiting from WINDOWS altogether.) The execution may be terminated at any point by pressing "Q" or by pressing the CTRL and BREAK keys together.

The user will be presented with a choice of the following inlet configurations:

1. Aransas Pass - Corpus Christi Bay
2. Lydia Ann Channel - Aransas Bay
3. Copano Pass - Copano Bay
4. Nueces Entrance - Nueces Bay
5. JFK Causeway - Upper Laguna Madre
6. Custom parameters

Parameters appropriate to the real inlets for Options 1 - 5 have been pre-loaded in the model. (The "custom parameter" option will prompt the user for values for each parameter in the equation. Some review of Appendix D will be needed to properly implement a custom model.) Upon selection, the assigned physical parameters are summarized for the user, who is then asked whether any of these are to be modified. Later, the reader may wish to experiment with different values, but for now simply reply "N" ("no"). The assumed amplitude and period of the driving sinusoid are next displayed. Default values shown are for the lunar diurnal tide with parameters appropriate to the driving waterbody. The reader is invited to experiment with different periods (following the prompt instructions). The ranges for the graphic display are then shown and the user asked whether these are to be modified. Again, reply "N", but later the reader may wish to modify these.

The model will then execute and display a time graph of driving water level, response water level, and current speed in the inlet (positive for flood, i.e. flow into the basin). The display panel shows 75 hours at a time, at the end of which the model tests for periodic equilibration, i.e. that the model variables start to repeat themselves at intervals of the basic period. When this occurs, the model stops (though the user is offered the choice of continuing the integration). Some basic data on the solution is given at the bottom of the display. Most important is the ratio of response to driver, which indicates the degree of attenuation which that period of oscillation experiences upon passage through the inlet. Time lag of the response behind the driver, and the average water-surface elevation in the bay relative to the driver are also given.

An example output from the model (*sans* garish colors, of course) is shown in Fig. 4-5. The reader is invited to replicate this run using the Custom Parameter option of EXHIBIT1 with the values indicated on the figure. This is an idealized, generic inlet typical in some respects to Aransas Pass, Mansfield Pass or the Matagorda Entrance Channel with a nominal 1-m tide. Several important details of the anatomy of its hydraulics are indicated on Fig. 4-5. The driver is sinusoidal. The bay response appears sinusoidal, but it need not be. The current is clearly nonsinusoidal, being limited at the higher speeds from a true sinusoid variation. The current in the inlet is nearly in phase with the driving tide, the race of the current occurring practically at high water stage. (This is a diagnostic of a progressive wave.) The response of the bay, in contrast, lags behind that of the sea by several hours (in this case 6.5 hours). Also, the amplitude of the bay response is much less than the driving tide, only about 25% of the driver. One of the important controls is the intersection of the driver and bay water-level curves. This is a point of reversal of sign of the head, when the direction of water-level slope along the inlet (see Fig. 4-3) reverses. Note that in Fig. 4-5, there is not an immediate reversal of current, but rather this current reversal lags about an hour after the head reversal. This is primarily a consequence of the long inlet length. If the same case is re-run, but with inlet length re-set to, say, 1 km, the current reversals will be seen to coincide with head reversal. Note, also, that the mean water level in the bay equals that in the sea. This results from the complete symmetry of the inlet hydraulic parameters. The reader should now re-run EXHIBIT1 for this case, but setting Kin = 1, say, and Kout = 10, whereupon the bay response will be displaced upward.

From this example, and similar runs of the inlet model of EXHIBIT1, several features of inlet mechanics applicable to Corpus Christi Bay may be inferred:

- The shorter period constituents, e.g. the diurnal and semidiurnal components, are significantly attenuated upon passage through the inlet;

- In contrast, longer period constituents, notably the fortnightly and semi-annual constituents, are practically unattenuated;

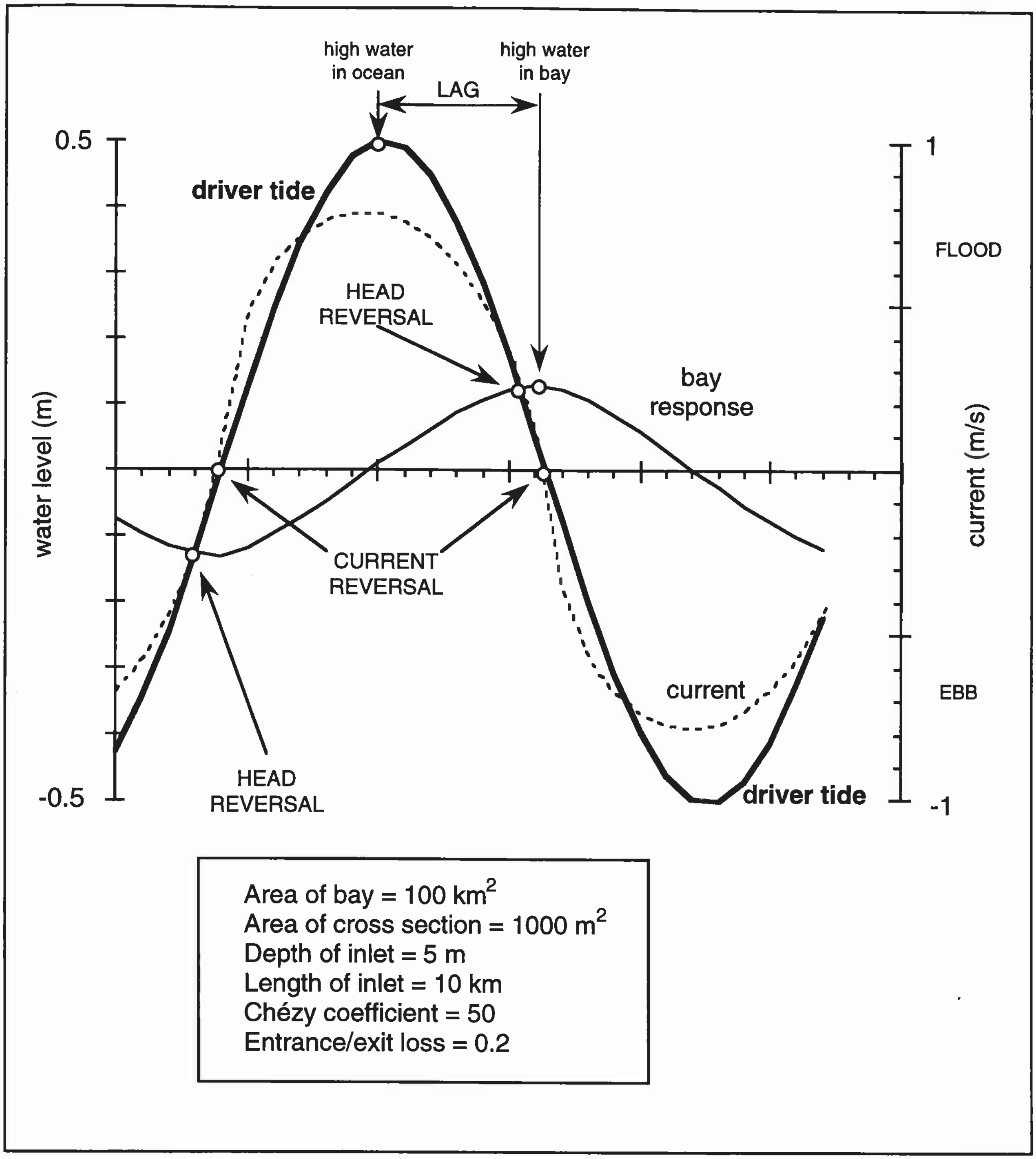


Figure 4-5. Numerical solution from EXHIBIT1 for idealized long inlet configuration (parameters as specified)

- The mean water elevation inside the inlet may be greater or less than that of the driving tide, depending upon the parameters of the inlet;
- There is a phase lag of the response tide behind the driving tide, which varies with period and with properties of the inlet;
- As the inlet becomes increasingly constricted, either through greater friction, increased entrance/exit losses, or diminished depth, the current becomes less sinusoidal, tending toward a more constant value throughout the race of the tide and a sudden reversal at slacks.

4.3 Tidal behavior in the Corpus Christi system

Fortified by the theoretical insight provided by the inlet model of EXHIBIT1, we now examine how the real system behaves. The basis for this is the data files from the CBI TCOON system, discussed in Section 4.1 above. Selected data sets have been re-formatted into a general display-diagram program, EXHIBIT2. The executable code and data files are on the diskette in the endpocket of this report. Installation is described in Appendix A.

4.3.1 Operation of EXHIBIT2

This program is executed by entering EXHIBIT2 at the DOS prompt. (If WINDOWS is being used as the operating system, this will require first accessing DOS from WINDOWS, or exiting from WINDOWS altogether.) The execution may be terminated at any point by pressing "Q" or by pressing the CTRL and BREAK keys together.

After the starting banner, the user is provided a selection from five regions of the study area: the Aransas Pass inlet area or four component bays. The choice is indicated by typing the number of the desired area followed by ENTER. The user is then offered the option of modifying default settings. For now, enter "N" ("no"). Finally, a starting date option is offered, either the beginning of the available period of record, or a (later) date of the user's choice. (To examine one of the specific examples cited later, it will be most expedient to enter the beginning date of that period.) The convention employed is to specify the date by a 5-digit value, YYDDD, in which YY is the last two digits of the year, and DDD is the day number starting with 1 January (in the informal patois, frequently—but incorrectly—called the Julian day). For example, 13 July 1991 is coded as 91194. (A list of day numbers for the last day of each month is given in Table A-1 in Appendix A.) Several key commands are given that control the display, and can be entered at any point in the execution:

R - resume normal display	S - slow display rate
T - step point-by-point	X - freshen anemometer
Q - quit	

These will be explained later. The display panel is then activated that bears some resemblance to Fig. 4-6, which indicates the main areas of the display. Three pieces of information are displayed simultaneously: the hourly water levels at four different TCOON gauges, the corresponding wind velocity at two different TCOON anemometers, and several parameters characterizing the position of the moon in the sky. In the upper left-hand panel, the tide stations and anemometer stations are listed, along with their color codings. Consult Fig. 4-2 to review the locations of the CBI stations. The water levels themselves are plotted hour by hour in the right-hand panel. Date and time are given at bottom left, and correspond to the rightmost data point on the water-level display. At any point in time, five days (120 hours) of water level data are shown in the display. The panel marches from right to left as each new data point is added on the right, and one is dropped off on the left. Thus one can view the evolution of the water level at each of the four stations over the preceding five days. The 00Z terminators are shown as vertical lines, and march across the screen along with the data points.

Wind velocity is plotted as a vector whose end is marked by the small circle on the wind panel at lower left. The length of the vector is proportional to wind speed, the scale indicated by the circle, whose scale is given on the line just above the display, and the direction of the vector points *with the flow* of the air, i.e., in the direction *to which* the wind blows. For example, in Fig. 4-6, the wind is blowing from the southwest quadrant to the northeast quadrant. This vector convention

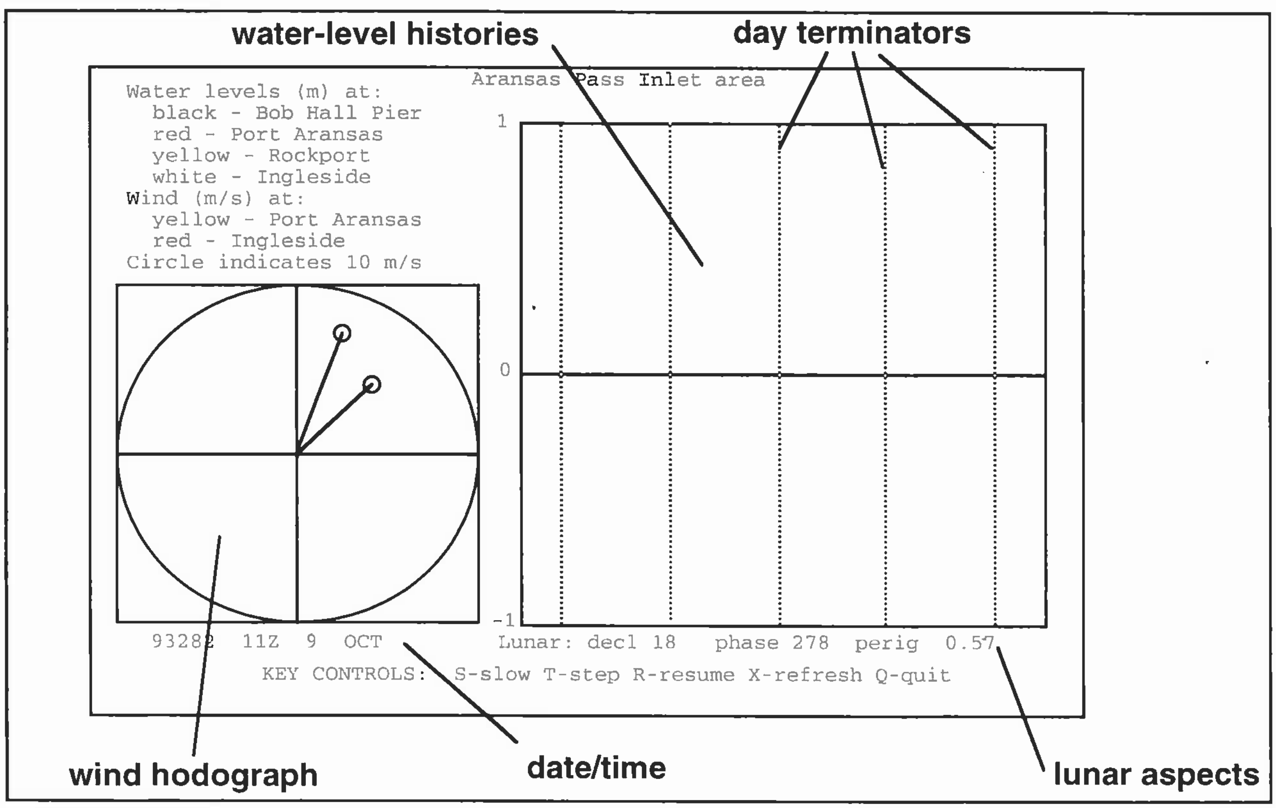


Figure 4-6. EXHIBIT2 display panel indicating main displays (see text)

has greater fidelity to the fluid mechanics of the interaction between wind and bay, but is the opposite of the usual meteorological convention of assigning wind direction to be that *from* which the wind blows. If the user prefers the usual meteorological convention, the vector convention can be overridden as one of the options to modify default settings when the program is started. To remind the user that this is the convention, the radius vector is omitted for this convention, and the wind plotted simply as as a small circle. To assist the eye in following the movement of the wind vector, the previous data point is retained as a fainter circle for one time step. Also, the vector head is marked by a single colored point that is allowed to remain on the display. As these single points accumulate they provide some indication of the general distribution of wind at the two anemometers, a sort of wind rose. Of course, successive wind vectors "paint over" these points. If the wind display becomes too cluttered, the user may simply press "X" to refresh the display.

The lunar aspect values are revised at 00Z every day. The first aspect is the lunar declination measured in degrees north of the equatorial plane (so that a negative value signifies south declination). The second is the phase of the moon, computed as the angle subtended by the moon measured from its new moon position, see Fig. 4-7. A new moon corresponds to 0°, a full moon to 180°, and waxing and waning quarters to 90° and 270° respectively. In the equilibrium tide theory (see Section 2.3.1), spring tides occur at 0° and 180°, and neap tides at 90° and 270°. The last aspect is "*perig*," an index of proximity of the moon to the earth (perigee-apogee), computed as $1/r^2$, where r is the distance between the two, and normalized to range from 0 at apogee to 1 at perigee. (The inverse-square relation is used to mimic the term in Newton's gravitation law.) These lunar aspects are computed from approximate astronomical relations based upon date/time and

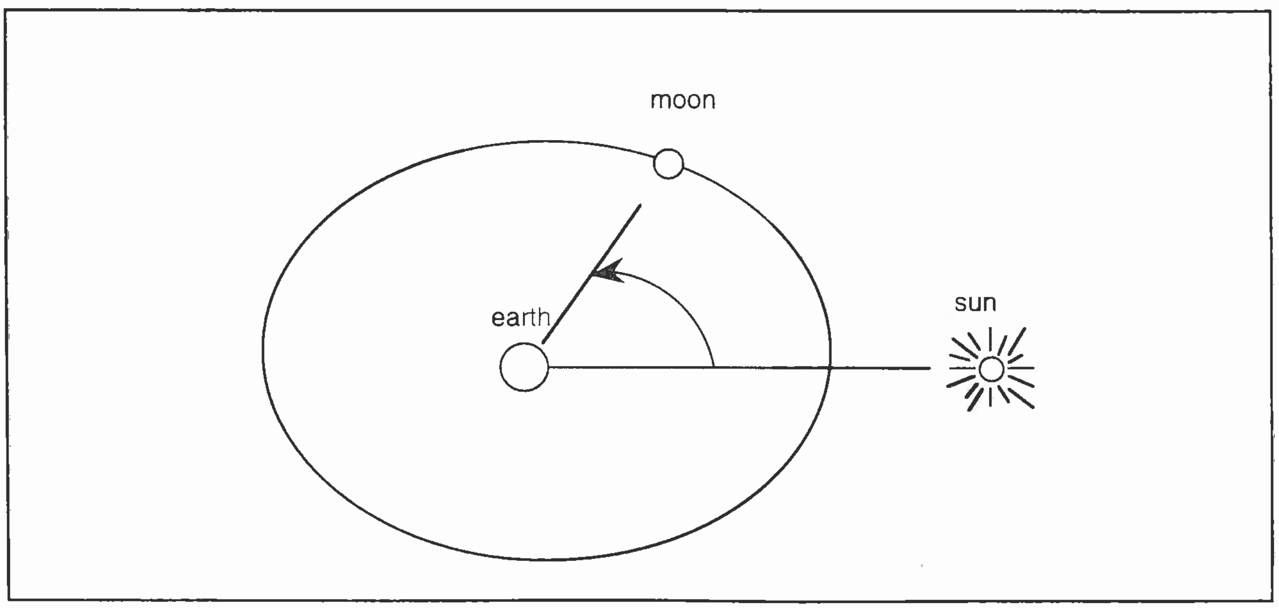


Figure 4-7. Definition sketch for lunar phase

latitude/longitude of Corpus Christi Bay, and were verified against the nautical ephemeris (USNO, 1994). The error in declination is at most a degree, and in the time of great declination at most about 6 hours. Times of phase and perigee are accurate to within 12 hours, usually much better. This is satisfactory for present purposes.

With respect to units, the default system is metric: water levels in metres and wind speed in metres per second. The user has the option of displaying water level in feet, and the options of using knots or miles per hour for wind speed. Time is given in hours Coordinated Universal Time (UTC), née Greenwich Mean Time (GMT), designated by "Z". To convert to Central Standard Time, subtract 6 hours; to convert to Central Daylight Time ("Nixon time") subtract 5 hours. Occasionally a data point is not plotted. This is because the measurement was missing from the CBI data files.

The display may move too quickly to suit the user. Each time "S" ("slow") is pressed, an additional time interval of 0.05 seconds is added to the delay between plotting of data points. Therefore, by pressing "S" several times, the display can be slowed to a desired speed. Or the user may wish to closely inspect a series of data points, in which case pressing "T" ("step") will advance the diagram one point at a time for each time "T" is pressed. This key can also be used to freeze the display. After either "S" or "T" has been activated, the normal data plotting rate is resumed by pressing "R". The "quit" key "Q" may be pressed at any time, whereupon the display is terminated, and the user is given the option of restarting for the same region, selecting an entirely new region, or stopping.

4.3.2 Tidal responses

Begin by starting EXHIBIT2 and choosing Aransas Pass Inlet Area. The pre-loaded data record begins in June 1994 (94160), the start of summer, when the effects of changing meteorology are generally minimal. Indeed, the winds can be seen to be reasonably steady from the SE quadrant. The hourly points for four different water-level traces are plotted, *viz.* the Gulf tide as measured at Bob Hall Pier, the tide inside the inlet at Port Aransas, and two records from the interior bay, Ingleside and Rockport. It is suggested that the reader follow these traces for a few minutes to cultivate the ability to track them by eye. Remember to use the "Slow" key command if necessary.

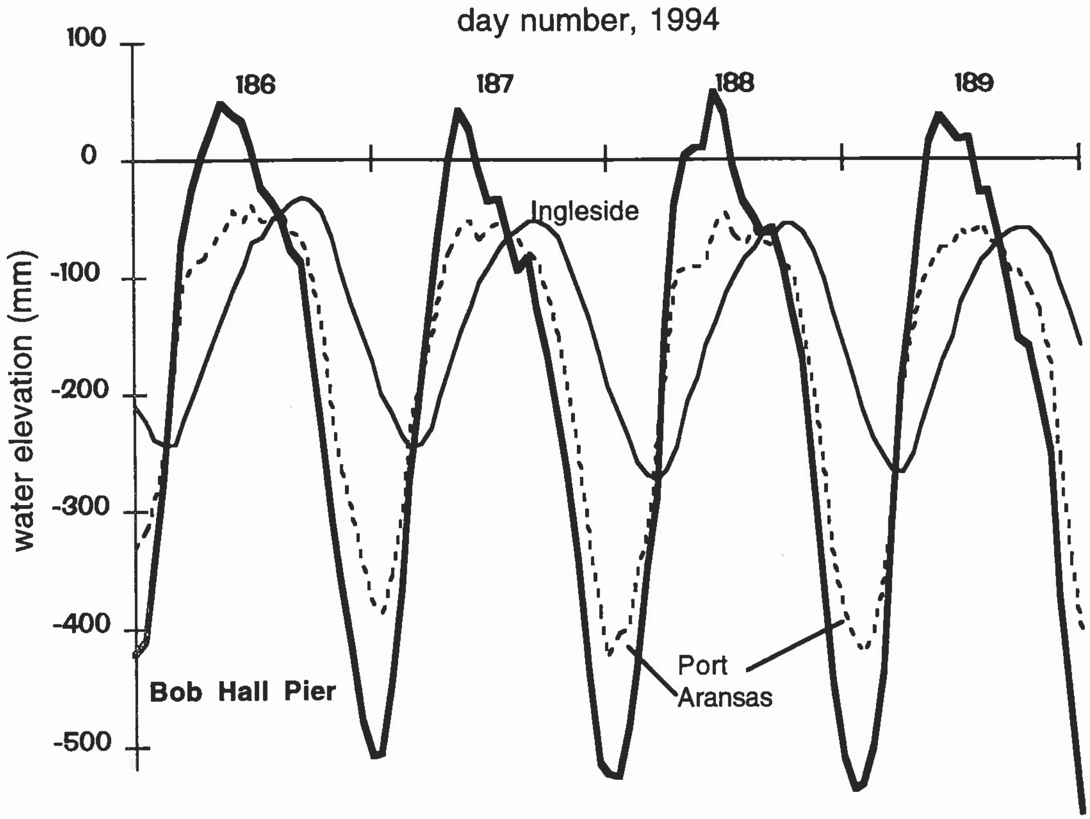
As the record begins at Day 94160, lunar declination is diminishing so the amplitude of the Gulf tide is likewise diminishing. The predominantly diurnal character of the interior tides is well-illustrated by this period. Though there is a semidiurnal component in the Gulf tide that becomes better evidenced by Day 94168, its presence in the Ingleside and Rockport records is barely perceptible. This is a direct result of the filtering action of the inlet, cf. Fig. 4-4. The diurnal component is filtered also, as Fig. 4-4 indicates it should be, but not as much as the semidiurnal, and, since it is a much more prominent constituent in the Gulf tide (cf. Fig. 2-13), even after being reduced in amplitude by about 60%, it is still the prevalent short-term tidal component inside the inlet. Note how the amplitude of this diurnal tide is diminished as the lunar declination approaches zero then begins to increase with the increasing, but negative, values of declination (e.g., Day 94169). From the standpoint of modulation of the diurnal tide, the absolute value, not the sign, of lunar declination is all that matters. The terms "great declination" and "small declination" therefore refer to absolute values near its extrema, and values around zero, respectively. The tides at Ingleside and Rockport appear nearly synchronous, but Rockport has a higher average and a smaller range. The separation between these traces varies with the changing wind. Effects of wind will be considered in detail in the next section, but for now its everpresent influence should be noted.

For specificity, the tidal response of the Corpus Christi Bay system is quantified by considering the tide during the July 1994 summer secular water-level minimum, particularly the great-declination period of 94186 - 94190. Examine the EXHIBIT2 display during this period. Several tidal cycles have been extracted from EXHIBIT2 as the upper panel of Fig. 4-8. Now, please execute EXHIBIT1 and choose: 1. Aransas Pass - Corpus Christi Bay. Rather approximate values have been used in this theoretical model to represent Aransas Pass dimensions and well as the surface area of the study area (excluding Laguna Madre and Copano Bay). While these parameters could be adjusted to accomplish a closer numerical match—if we cared about accomplishing a closer numerical match—the point of the comparison is that the salient properties of the actual Aransas inlet tidal behavior are exhibited by this simplified model, notably:

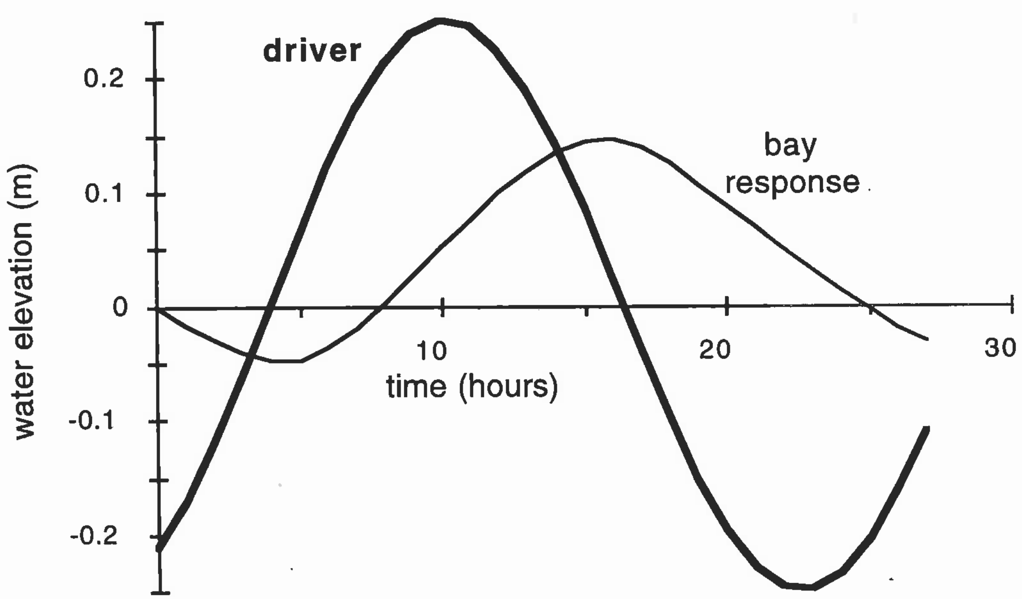
(1) attenuation of the tide to about 40% of the amplitude of the driver,
(2) elevation of the mean water level in the bay about 50 mm above that in the Gulf,
(3) lag of the high water and low water times in the bay about an hour after the crossover of water level gradient,
(4) lag of the time of high water in the bay after the Gulf of 6-8 hours.

These means that the essential physics of the model explicates the behavior of the real system (including the asymmetry of inlet entrance/exit losses for shorter period tides).

The model of EXHIBIT1 also indicates rather high currents in the inlet, approaching 1 m/s or two knots (and the assumed great-declination amplitude is representative, but not nearly maximal). This certainly accords with experience in this inlet. For a time, the dredged section where the Corpus Christi Ship Channel, the Channel to Aransas Pass, Lydia Ann Channel, and Jetty Channel conflow was called the Inner Harbor (e.g., USC&GS, 1949). The currents in this region were reported to be swift, unpredictable and potentially hazardous. Inbound vessels, in particular, often experienced difficulty in maneuvering in this area, and have collided with the Atlantic wharves on Harbor Island. Outbound vessels have a problem with bank suction, especially when it is necessary to stand out from vessels moored at the Humble or Atlantic docks on Harbor Island. USCE (1968) notes "very strong ebb and flood tides" in this area.



(a) Data from TCOON gauges (EXHIBIT2)



(b) Theoretical inlet solution (EXHIBIT1)

Figure 4-8. Aransas Pass inlet area tidal response (see text)

The coastal pilot states that current velocities often exceed 2 knots, and are greatly influenced by wind (USC&GS, 1949). (The wind effect *per se* will be considered in the next section.)

Now, please execute EXHIBIT2 and select Corpus Christi Bay. The four tide traces shown are that in the inlet at Port Aransas and three of the major gauges distributed around the periphery of the main body of Corpus Christi Bay, namely Ingleside, Naval Air Station and the State Aquarium (see Fig. 4-2). The close correspondence of the three bay gauges should be noted. While the traces do spread and cross in response to wind (which will be examined in the next section), their coincidence justifies the conceptual model of the bay as a level basin co-oscillating in communication with the Gulf. Although not included in the pre-loaded data for EXHIBIT2, the record at Shamrock Cove proved to overlay almost exactly the other three records. The same properties of a tide dominated by the 24.8-hr component, with an attenuated amplitude, lagging behind the tide in the inlet apply at all of these gauges. During the small declination period of 94195 - 94196, for example, the tide in Corpus Christi Bay is virtually absent.

Re-start EXHIBIT2, selecting Aransas-Copano Bay, and again starting at 94160. While the mechanics of Aransas Pass inlet are driven by the exchange with the entire interior bay system (or, at least, with most of it), Lydia Ann Channel branches away from the main inlet and connects with the upper bays of Aransas, Copano and the tertiary systems. Approximately, therefore, the tide at Port Aransas, at the seaward end of Lydia Ann Channel, can be considered to be the driver for the upper bays. This is displayed by EXHIBIT2. The tide is diminished in amplitude relative to Port Aransas, and lags several hours. The three gauges in the interior of the bay, while generally synchronous, do not track as closely as those in Corpus Christi Bay. Watch the traces of these gauges in response to the rise and fall of water level at Port Aransas and in response to wind. Copano and Rockport track most closely of the three, while Bayside is lagged more and has generally a somewhat higher range. The July 1994 great declination tides from EXHIBIT2 for Port Aransas at the end of Lydia Ann Channel and Rockport are shown in Fig. 4-9. Quit EXHIBIT2 and activate EXHIBIT1, selecting: 2. Lydia Ann Channel - Aransas Bay. The equilibrated tide levels from this simulation are shown in the lower panel of Fig. 4-9. The striking feature of the Lydia Ann hydraulics is the effect of drag, i.e. the combined effects of frictional stress and highly asymmetric inertial losses. This drag produces a marked attenuation of the diurnal tide: the range at Rockport is only about 10 cm, less than 10% of the range in the Gulf of Mexico. It also entails a much higher average water elevation in Aransas Bay than in the inlet at Port Aransas. The response tide variation is nonsinusoidal, and there is an associated distortion of the tidal current, with high, peaked flood current (nearly 1 m/s at the race) and lower, more steady ebb (less than 0.5 m/s).

Copano Pass behaves very differently. As a relatively short conduit, it functions more as an ajutage. In EXHIBIT1, select: 3. Copano Pass - Copano Bay. Under "Display Parameters," re-set the range on the tidal display to 0.2 m. We note the following properties of this theoretical solution:

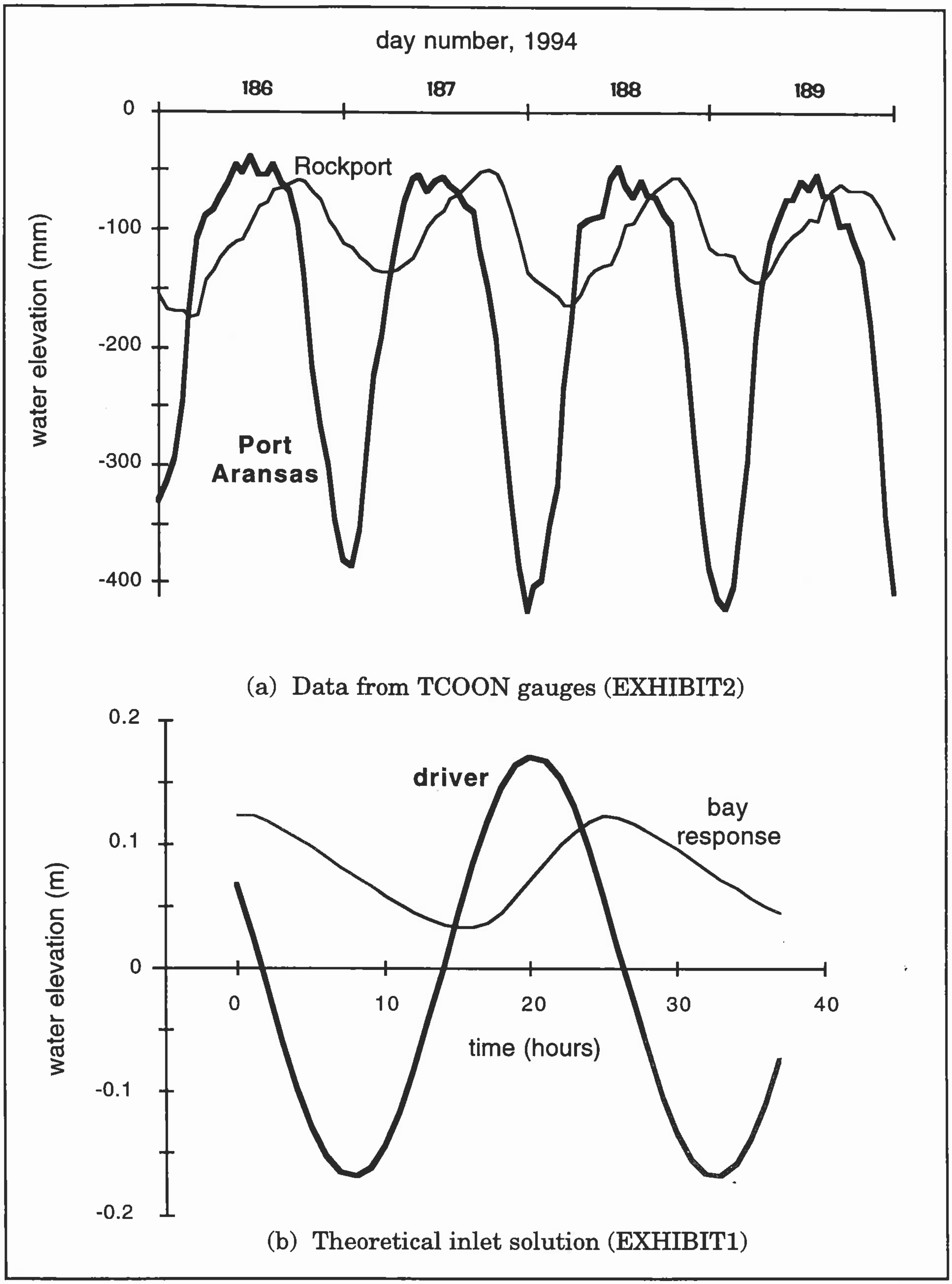


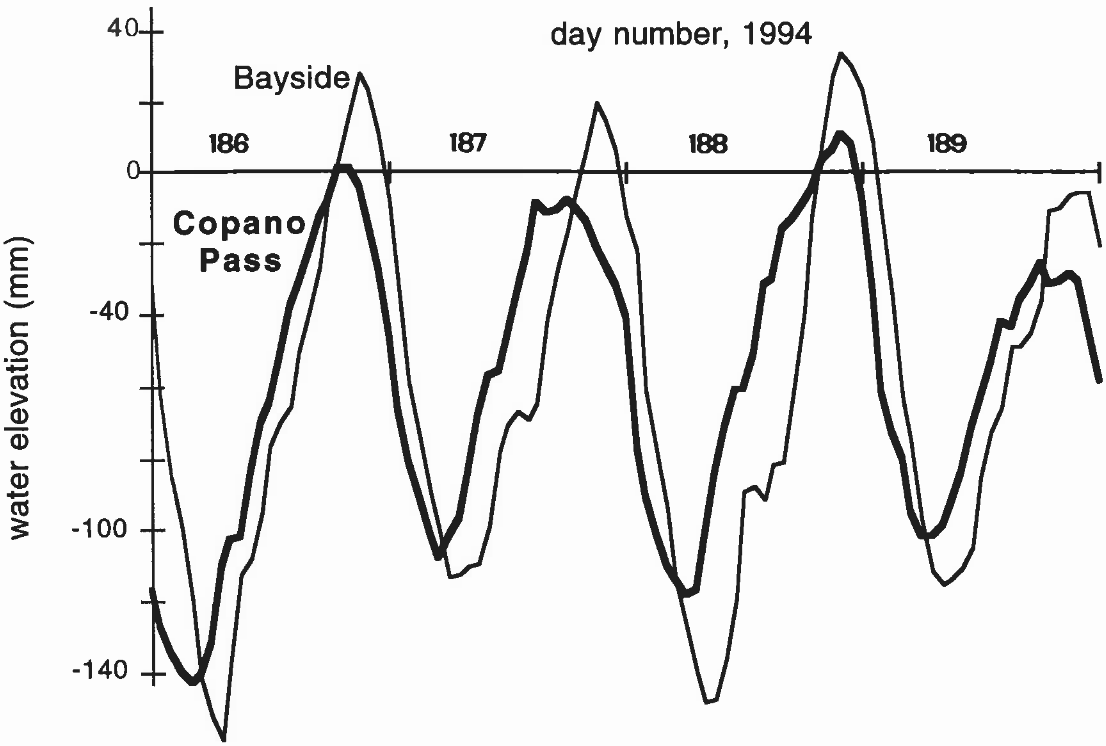
Figure 4-9. Lydia Ann Channel tidal response (see text)

(1) the tide range in the responding bay is amplified slightly, exceeding the driving tide by about 10%, which is why the display range of EXHIBIT1 had to be re-set,
(2) the average water level in the bay is equal to that of the driver,
(3) there is only a slight time lag of the response tide after the driver, about an hour (which is the resolution of the model),
(4) the current is highly nonsinusoidal, with nearly constant race and abrupt reversals between flood and ebb,
(5) the times of slack current now coincide with high or low waters of the bay tide (a diagnostic of a standing wave).

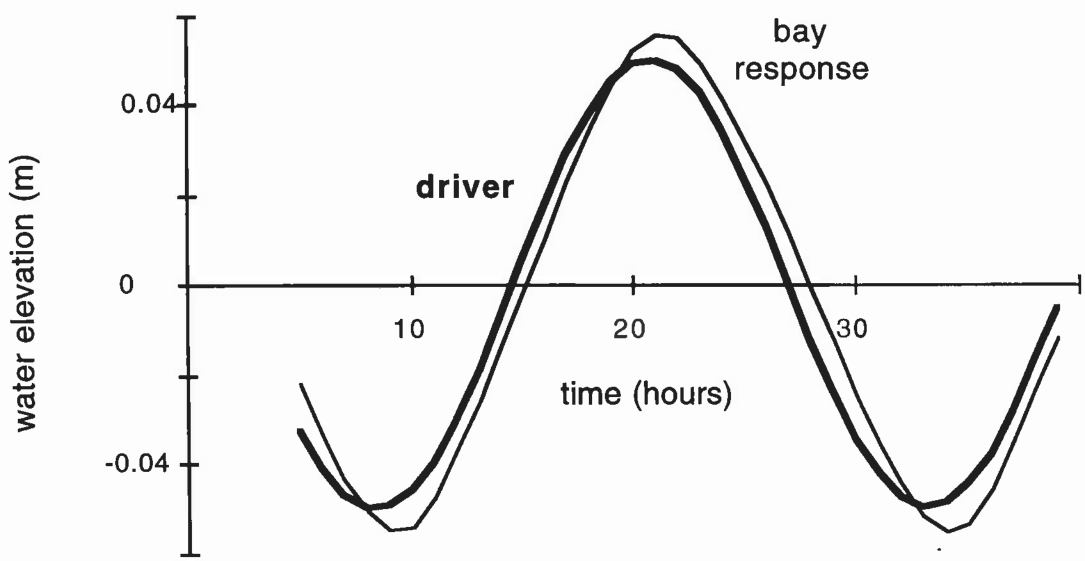
Execute EXHIBIT2 and again select Aransas-Copano Bay. Examine the traces for Copano Bay entrance (i.e., Copano Pass) and Bayside. The two are seen to be nearly in phase, Bayside lagging about an hour behind Copano, with little difference in average elevation, and the Bayside gauge having a slightly greater range. All of these would be properties expected from the character of the inlet and bay hydraulics shown by EXHIBIT1. Figure 4-10 shows the great-declination tide traces from EXHIBIT2 and the equilibrium solution of EXHIBIT1. In fact, the Bayside gauge indicates more amplification, as much as 20-30%. However, location of the gauge does not really reflect the variation of the open Copano Bay. The gauge is actually located at the southern extreme of Copano Bay next to the mouth of the Aransas, see Fig. 4-2, and therefore probably exhibits more amplification than characteristic of the open bay. (It is also more sensitive to wind effects, but that is addressed in the next section.)

The only TCOON gauge in Nueces Bay also suffers from poor placement. This gauge is located off White Point, see Fig. 4-2, in extremely shallow water near the delta. In fact, the gauge pegs when water levels fall below 250 mm (gauge datum), so many of the low-water events are missed. Nueces Entrance, like Copano Pass, is more of an ajutage, and the theoretical response of Nueces Bay has the same properties as enumerated above for Copano. (Activate EXHIBIT1 and select: 4. Nueces Entrance - Nueces Bay.) But the White Point record itself (activate EXHIBIT2 for Nueces Bay region) shows much more amplification. This is most likely a consequence of the extremely shallow water in the western end of Nueces Bay. (There is a net upward displacement as well, but this is related to wind effects, discussed later.)

In many respects, the Bulkhead Flats and Laguna Madre segment is the most complex conduit area in the system. Activate EXHIBIT2 for Upper Laguna Madre region. The Packery Channel gauge is located just north of the JFK Causeway off the GIWW, see Fig. 4-2. The tide here has already undergone significant attenuation in passing over Bulkhead Flats. Very little tidal energy passes through the JFK Causeway, as shown by the South Bird Island record. In Fig. 4-11, the great-declination tide is seen to be barely perceptible at South Bird Island, about 10% of the tide in Corpus Christi Bay, and less than 5% of the tide in the Gulf of Mexico. The simple hydraulic inlet model of EXHIBIT1 (select: 5. JFK Causeway - Upper Laguna Madre) is severely pressed to depict this configuration, since the "co-oscillating basin" of the Laguna is shallow and subject to high

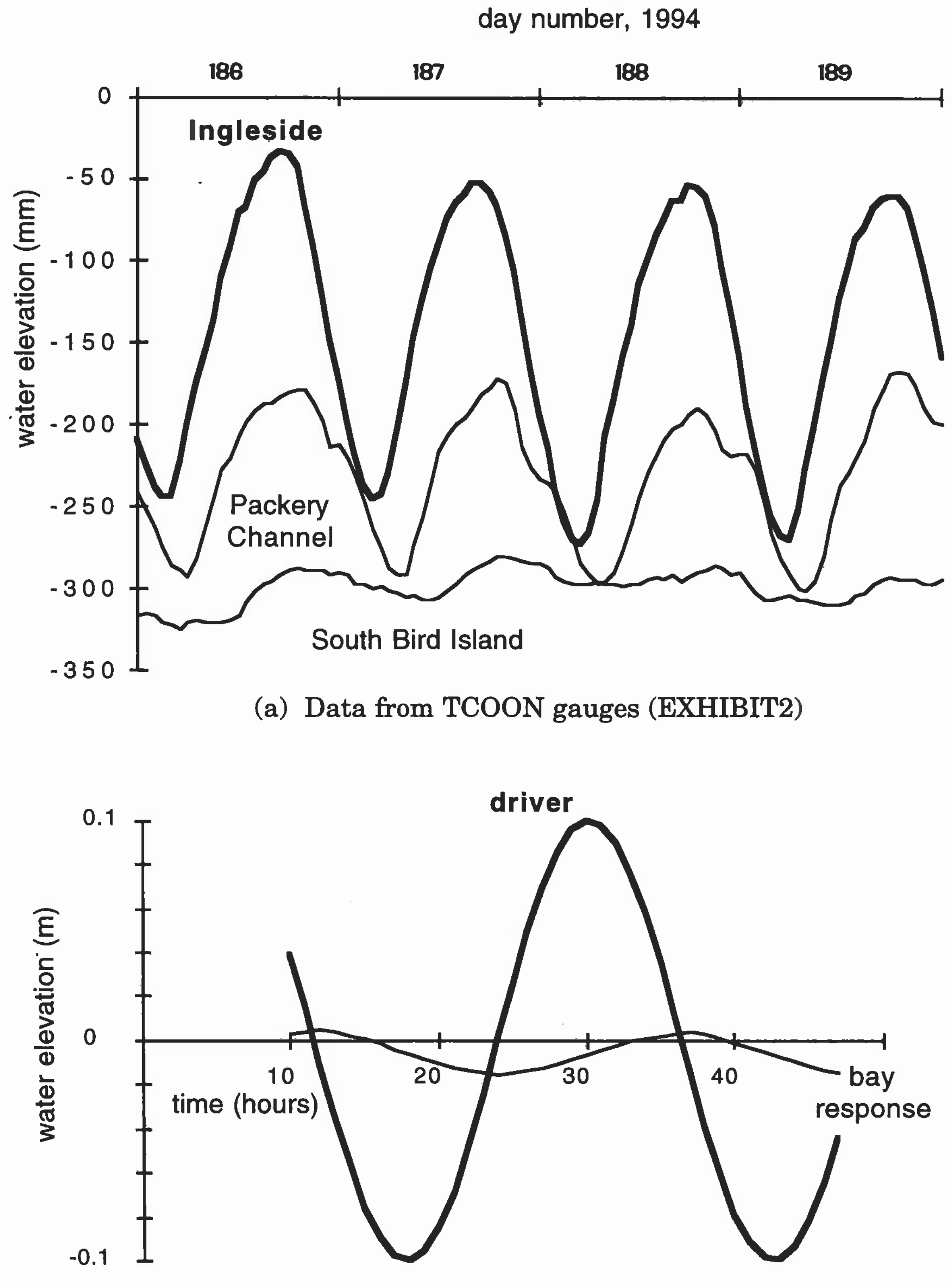


(a) Data from TCOON gauges (EXHIBIT2)



(b) Theoretical inlet solution (EXHIBIT1)

Figure 4-10. Copano Pass and Copano Bay tidal response (see text)



(a) Data from TCOON gauges (EXHIBIT2)

(b) Theoretical inlet solution (EXHIBIT1)

Figure 4-11. Bulkhead Flats and Upper Laguna Madre tidal response (see text) friction—the assumption of a level surface in the basin is clearly inappropriate—and the Bulkhead Flats-JFK Causeway does not even approach a conduit of uniform section. Nonetheless, the parameters of EXHIBIT1 are chosen to approximate the area and depths of the inlets through the Causeway, with a length and Chézy coefficient appropriate for Bulkhead Flats. Unlike the other inlets, the geometry of Bulkhead Flats suggests that the entrance loss for the flood would be greater than the exit loss for the ebb, so the asymmetry is reversed for this system, as indicated by the selection of Kin and Kout in EXHIBIT1. The equilibrium tide is shown in the lower panel of Fig. 4-11, which shows surprising agreement with the actual tidal responses in both amplitude and time lag. Also the average water elevation in the bay is less than that of the driver, as also seen in the real system. What is not replicated is the much larger depression in water surface from north to south across the Causeway area. Note, also, that in the tidal response of the real system, EXHIBIT2, the variation in the southern limit of the Upper Laguna as measured at Yarborough Pass appears to show a much greater tidal response, e.g. the period beginning 94175. This, however, is not a tidal response, but a wind response, discussed in Section 4.4.5.

The above tutorial discussion of EXHIBIT2 is intended to exemplify the mechanics of tide propagation through the system of basins and conduits that comprises the Coastal Bend Bays. EXHIBIT2 is, however, an information-dense display that will reward protracted examination. It is recommended that the display be activated for each region, and the evolving water levels be followed through the seasons, in which the variation of water level with meteorology and lunar position (and other controls) can be observed. After such an extended examination, the following conclusions concerning tidal variation will be drawn:

- Tidal behavior in the system is qualitatively consistent with the conceptual hydraulic model of a bay connected by a narrow conduit to a larger oscillating basin. This includes substantial filtering of the 24.8-hr diurnal tidal component and almost complete elimination of the shorter frequencies, notably the 12.4 lunar semidiurnal.

- The mean water elevation generally becomes higher with progression from the Gulf into the Corpus Christi Bay system, the single exception being the Upper Laguna Madre. There is also an increasing time lag of the tidal oscillation behind that in the Gulf. Both this lag and the relation between water-level head reversal and tidal stage are variable depending on the parameters of the inlet.

- The predominant lunar control on tidal behavior is the declination of the moon. The influence of lunar phase is secondary and mainly affects the semidiurnal component The perigee-apogee variation is at most secondary, and usually obscured by other, non-lunar controls (primarily meteorology).

Consonant with the filtering properties of the system, the longer period fortnightly and semi-annual constituents are practically unattenuated; since these are longer than "intratidal" these are treated in the next chapter.

The last conclusion above may be of some surprise given the frequent appearance of references to spring-neap variation in the popular literature, e.g. Hiller (1974). The error probably arises from two factors: the conceptual simplicity of the lunar-solar alignment (so that it is presented in every introductory oceanography and physical geography textbook), and the fact that lunar phase and lunar declination vary at nearly the same periodicity, 27.6 and 27.2 days, respectively. Their extrema slowly drift in and out of phase. An uncritical examination of the time variation of tidal stage and lunar phase could lead to the conclusion that the two are synchronous, unless a careful inspection is made of their exact relationship. (One example in the period of record provided of the lunar phase and lunar declination being out-of-phase is 94248.) Nearly a century ago, Pitts (1899), who was an experienced worker in the region, stated, "As regards the character of the tidal curve; at the time of neap tides there is a well-marked diurnal rise and fall; but at spring tides there is but one pronounced tide in the 24 hours." Clearly, he should have referred to equatorial and tropical rather than spring and neap tides.

Tidal variation is associated with an influx and an efflux of water from and to the Gulf of Mexico, and there is an associated transport within the system. The former quantifies the exchange between the bay and the Gulf, or between elements of the Corpus Christi Bay system. For most of the system, the relatively steep gradients in depth around the shoreline imply that the surface area does not change substantially from the low to the high tide, and therefore the surface areas of Table 2-1 can be used to estimate the volume of water involved. The parameter employed for this purpose is the tidal prism, defined to be the volume of water transported on the flood part of the tidal cycle (Ward and Montague, 1996). For present purposes, we take this to be the volume of water entering a basin from low stage to high stage. The key points at which tidal prisms must be computed are the conduits of the system, the inlets connecting the major internal basins, from which the prism can be allocated to the individual component bays. Table 4-2 presents the tidal prisms computed from TCOON records for a small- and a great-

Table 4-2
Approximate tidal prism by component bay
(φ denotes lunar declination)

Component bay	*tidal prism (10^6 m^3)* $\varphi = 0°$	$\varphi = 22°$	*m (10^6 m^3 / degree)*
Copano	10	26	0.72
Aransas	12	29	0.79
Corpus Christi	37	84	2.12
Nueces	8.4	21	0.59
Upper Laguna	3.1	6.7	0.16

Table 4-3
Approximate tidal excursion for selected sections
(φ denotes lunar declination)

cross section	*area* (m^2)	*excursion (km)* $\varphi = 0°$	$\varphi = 22°$
Aransas Pass	3000	23.5	55.5
Lydia Ann Channel	2090	10.5	26.4
Mid-Aransas Bay	22000	0.7	1.8
Copano Pass	5900	1.7	4.4
Mid-Copano Bay	14000	0.4	0.9
Mid-Corpus Christi Bay	94000	0.3	0.7
Nueces Entrance	1250	6.7	17.0
Mid-Nueces Bay	2800	1.5	3.8
JFK Causeway	800	3.9	8.4
Mid-Laguna	2500	0.6	1.3

declination period for each of the main component bays (except Baffin whose tidal behavior was not analyzed in this project). To a first approximation, the tidal prism can be considered to be a linear function of declination, given by the small-declination value plus $m\varphi$, φ denoting lunar declination in degrees. Values of m are also tabulated in Table 4-2. In these computations, the surface areas in St. Charles, Mesquite and Carlos bays are ignored to compensate for contribution to the tidal prism from Cedar Bayou and San Antonio Bay. Similarly, Baffin Bay is ignored in the computations for the Upper Laguna.

A measure of the transport effected by tidal variation is the tidal excursion, the total distance traversed by a water parcel carried by the flooding tide (Ward and Montague, 1996). For any cross section everywhere normal to the direction of current, the tidal excursion is approximately the tidal prism divided by the cross sectional area. For each of the major conduit cross sections, tidal excursion has been estimated based upon the tidal prism traversing that section. These estimates for both small and great declination tides are given in Table 4-3. These can be misleading, however, since these narrow conduits are also where the maximum currents occur (and therefore the maximum tidal excursions). In fact, some of these excursions exceed the length of the inlet, such as Aransas Pass, and could not therefore be the actual distance a parcel would be carried. More realistic estimates of excursion are based upon typical sections across the midrange of a component bay. Computations for a few of these are shown in Table 4-3 as well. We would conclude from an examination of this table that a water parcel entering each of the inlets would be carried completely through the inlet but inside the bay the excursion would diminish appreciably, due to the larger cross section. Typical values are on the order of a kilometre, so internal tidal transport in the Coastal Bend bays is quite limited.

One final qualification concerning the tides in the study area is in order with regard to the outer bays. Both Aransas and the Upper Laguna Madre have the possibility of a contribution to their tidal prism from inlets outside the study area. Through Carlos and Ayres bays, Aransas is connected to the San Antonio system, which in turn receives a portion of its tidal prism from Pass Cavallo through the Espiritu Santo connection. The astronomical tide in San Antonio Bay is extremely feeble, see Hall et al. (1976), and the tidal prism received from the Matagorda system is therefore limited. (This is substantiated by the current measurements in the passes into Espiritu Santo made by Kana et al., 1980.) The proportion of the Pass Cavallo prism affecting the study area can reasonably be assumed to be even less important. Whatever contribution it does make is included implicitly in the tidal response at Rockport and the other gauges in the Aransas-Copano segment. The only error entailed is in determining the portion of the observed tidal prism to be allocated to a specific inlet, *viz.* the Lydia Ann Channel.

In the Upper Laguna Madre, the GIWW cut through the Mudflats admits tides from the Lower Laguna Madre, especially Mansfield Pass. The hydraulic capacity of the GIWW cut will be considered in more detail in the next section. In the present context, we note that, while a tidal signal is discernible in the water levels (see Ward, 1981), the associated prism is at least an order of magnitude smaller than that observed in the Upper Laguna at South Bird Island.

4.4 Meteorological responses of the Corpus Christi system

By virtue of the feeble tide and their large surface-area-to-volume ratios, the Texas bays are well-known to be dominated by meteorology, especially frontal passages. The importance of meteorological regimes along the Gulf of Mexico coast was well-summarized 150 years ago in the *Derrotero de las Antillas* (as reported in Blunt, 1837, p. 283):

> From August to April, these coasts are dangerous, on account of the heavy sea upon them, and which makes it impossible for a ship to ride at her anchors; for in that season the E.S.E. wind blows with great violence for 2 or 3 days before it shifts to the north; but in the other months, from April to August, the navigation is very good and secure;... The land breezes are frequent in the summer from midnight until 9 or 10 in the morning, when they yield to the sea breeze;...

In Section 2.3.3, the meteorological sequence associated with a frontal passage was described. As the front approaches the coast, low-level convergence into the frontal zone enhances the normal onshore winds. This is the reason for the "great violence" of the ESE winds noted above. The onshore wind stress builds up water levels along the inshore segments of the bay. Then with the passage of the front, winds freshen and shift abruptly to the north, forcing the waters of the bay from the northern to the southern segments and through the inlets into the Gulf of Mexico. For cold-air outbreaks (see Section 2.3.3), the increasing atmospheric pressure further reinforces the drop in water level, at an approximate rate of 1 cm/mb. The high coherency found by Smith (1979) for 2-6 day periods between Gulf pressure gradients and coastal water levels evidences the contribution of this pressure-driven effect for polar outbreaks, the so-called "inverse-barometer."

The resulting dramatic depressions in water levels, and the associated high currents in the inlets, have been noted since the last century. Pitts (1899), for example, spent several years working on the Reaction Breakwater (i.e., the north jetty) at Aransas Pass during the last decade of the Nineteenth Century, in the course of which he made numerous observations on local currents and hydrography. He described the effect of northers as follows:

> A long-continued southeast wind will raise the water 3 ft. or more above mean high water, and a succession of severe "Northers" will lower it as much below mean low tide. The speaker has seen the tide fall more than 3 ft. in less than six hours during a severe "Norther."

Gillette (1904b) provided a graphic description of the frontal passage response based upon descriptions of experienced field personnel as follows:

> The shallow lagoons inside of the sand cordon, built up by the waves of the Gulf, have habitually only about 1 ft. of tide once a day. At certain seasons, however, it is a frequent occurrence for a southerly wind to blow for a time until the lagoons or bays are raised above their normal level, then the wind changes almost instantly to a strong wind from the north. These are known as "Texas Northers." They start at full speed, and the swollen waters in the lagoons are driven violently to the south, escaping to the ocean with great velocity through any inlets near the southern part of the bay, scouring a deep channel and rapidly eroding the south side of the inlet.

The coastal pilots make frequent mention of the importance of meteorology in affecting the currents in the inlets and the water levels in the bays.

In this section, we examine the response of the Coastal Bend bays to fronts, especially the mechanics of interaction between the bay and the adjacent Gulf of Mexico, and to the seabreeze. The essential process is denivillation, the response of a free surface to an imposed stress, referred to more colloquially as "setdown" or "setup" of water levels. The direct application of wind stress at the surface is the driving physical process, though variations in atmospheric pressure (the inverse-barometer effect) can make a secondary contribution. A fundamental distinction is made between the direct effect of wind stress on the bay, and the indirect response of the bay to the effect of wind stress on the adjacent Gulf of Mexico.

As in the previous section on astronomical tidal responses, this analysis is based upon the data files from the CBI TCOON system, discussed in 4.1 above. A general display-diagram program, EXHIBIT3, has been developed to display selected TCOON records that is similar in some respects to EXHIBIT2, but better depicts the dynamics of various regions of the bay system. The executable code and data files are on the diskette in the endpocket of this report. Installation is described in Appendix A.

4.4.1 Operation of EXHIBIT3

This program is executed by entering EXHIBIT3 at the DOS prompt. (If WINDOWS is being used as the operating system, this will require first accessing DOS from WINDOWS, or exiting from WINDOWS altogether.) The execution may be terminated at any point by pressing "Q" or by pressing the CTRL and BREAK keys together.

In many respects, the operation of EXHIBIT3 is similar to EXHIBIT2, and a review of Section 4.3.1 is suggested. After the starting banner, the user is provided a selection from the same five regions of the study area. As with EXHIBIT2, the choice is indicated by entering the number of the desired area. The user is then offered the option of modifying default settings, followed by the option of entering a starting date. The same convention is observed of representing the date by a 5-digit value, YYDDD, see 4.3.1.

The display panel is then activated, which bears a vague similarity to Fig. 4-12. This is a different format from EXHIBIT2, and better facilitates the hydrodynamic interpretation of the behavior of the selected region of the system. Four pieces of information are displayed simultaneously: the lunar aspects, three traces of hourly water levels, the corresponding wind velocity at two different TCOON anemometers, and in the center panel the slope of the water surface. In the upper left-hand panel, the astronomical parameters of the moon are displayed graphically (in contrast to the numerical display of EXHIBIT2), by means of an icon representing the position of the moon. Phase of the moon is shown by the appearance of the icon, using the usual conventions for new, crescent, quarter, gibbous and full. Proximity is indicated by the right-to-left position of the icon between the vertical lines, in which the value of "perig" is computed the same way as described in Section 4.3.1. Vertical position of the icon shows lunar declination in degrees.

Wind velocity is plotted in the upper right panel in exactly the same format as for EXHIBIT2, as a vector whose end is marked by the small circle. The default convention is that the direction of the vector points *with the flow* of the air, i.e., in the direction *to which* the wind blows. As with EXHIBIT2, the vector head is marked by a single colored point that is allowed to remain on the display, so that as the display evolves, a sort of wind rose is built up. As before, the display can be refreshed by pressing "X".

The most important feature of the EXHIBIT3 display is the center panel. This shows the gradient of the water surface as a vector, using the same convention as the wind vector panel. The stations between which the surface gradient is

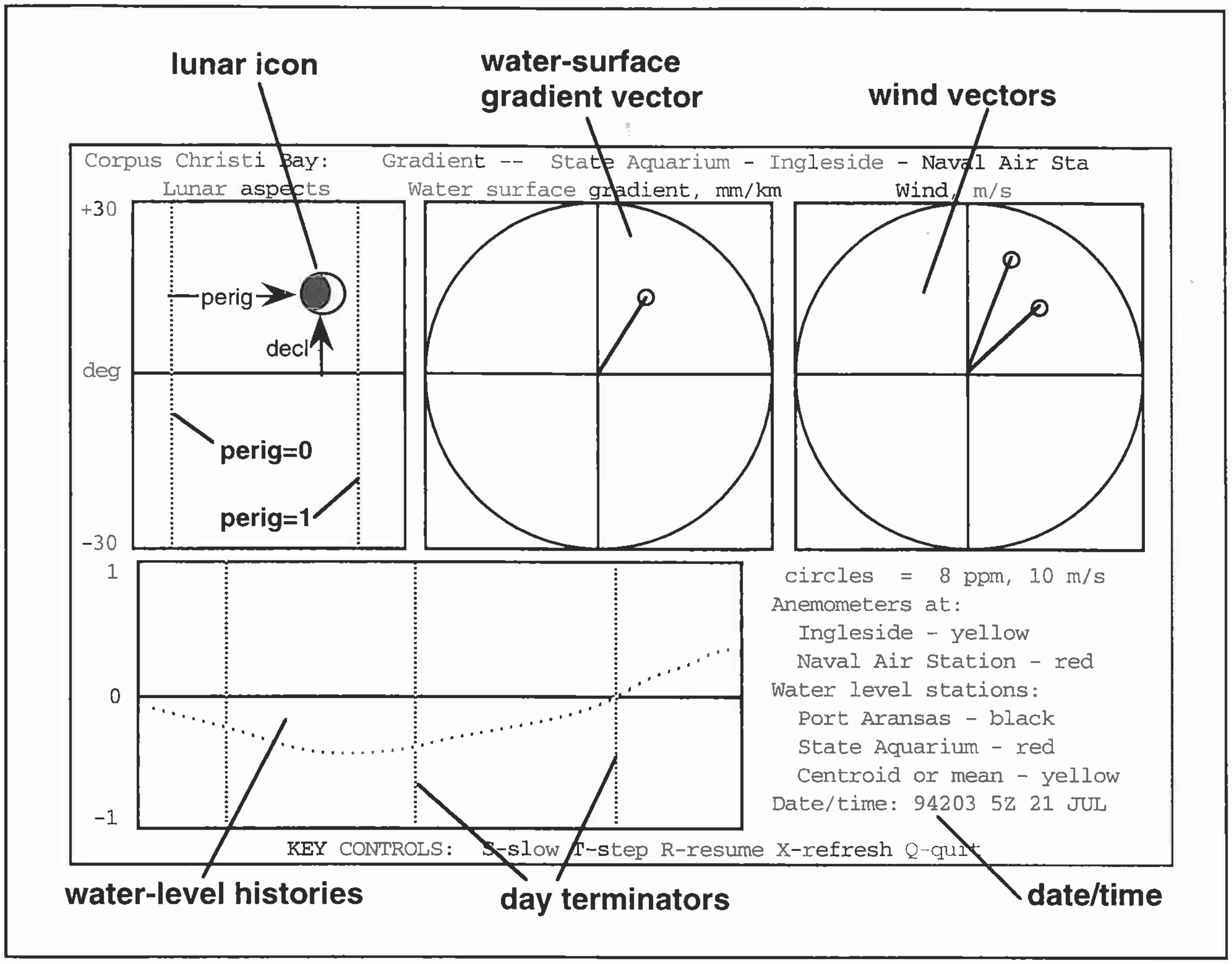


Figure 4-12. EXHIBIT3 display panel indicating main displays (see text)

computed are given on the top line of the display. Slope of the water surface elevation is a dimensionless quantity; units are parts per million (ppm) which can be thought of as mm/km (or half-inches per ten miles, or tenths of a quarterspan per league). As a gradient vector, it is plotted to point *toward higher water*, i.e. up the sloping water surface.

Water levels are plotted hour by hour in the lower-left panel. At any point in time, three days (72 hours) of water level data are shown in the display, compared to the five days shown in EXHIBIT2. The panel marches from right to left as each new data point is added on the right, and one is dropped off on the left. Thus one can view the evolution of the water level over the preceding three days. Three traces are plotted: two CBI station records selected to be indicative of the response of the region of concern, and an *average* of the stations that are used to compute the surface slope. The 00Z terminators are shown as vertical lines on this panel, and march across the screen along with the data points. Date and time are given at bottom right, and correspond to the rightmost data point on the water-level display, and the newest data points on the gradient and wind vector plots. The tide stations and anemometer stations used are listed along with their color codings in the data at lower right. Figure 4-2 should be consulted for the locations of the CBI stations.

Activate EXHIBIT3 and select Aransas Pass Inlet area, starting at the beginning of the data record, Day 94160. The wind vectors in the upper right panel indicate the prevailing SE winds. The lunar icon in the upper left panel shows a new moon at high declination near apogee. The gradient is computed between two stations, the Gulf of Mexico at the end of the jetties and the Port Aransas gauge just inside the inlet (see Fig. 4-2), as indicated on the header line at top. The direction of the gradient is therefore fixed to be along the line between these two points. Accordingly, the vector direction in the center panel does not change, but the magnitude and sign of the gradient vector do change. Slow the display and note the correlation between the vector gradient magnitude and the changing water level in the inlet, shown by the yellow trace in the lower left panel. Remember that the gradient vector points toward higher water, so it points seaward whenever the water level at the jetty exceeds that in the bay at Ingleside. The water level within the inlet tracks the stage at the jetty, cf. Fig. 4-8, so these gradient reversal points coincide closely with the intersections of the Ingleside (black) and inlet (yellow) water level traces.

Now re-start EXHIBIT3 (Option 2), select Aransas-Copano Bay and start at Day 94160. The gradient here is computed between the Rockport and Copano Pass gauges. Again, it is a two-point gradient so the direction is fixed along the line between the two gauges. The tidal variation of the average trace (yellow) is much less than that at Port Aransas, and the gradient does not reverse with changing stage. Instead the gradient is directed northward, so that the water surface slopes upward from Rockport to Copano. The gradient is seen to be coherent with the northward component of the wind. By Day 94169 the wind diminishes, though still from the southeast quadrant, and the gradient magnitude likewise reduces. On 94170 at 13Z wind shifts to north, and the gradient reverses pointing down the bay. With the return of strong southerlies by 94175 18Z the gradient is again systematically directed north. Note the high magnitudes of the surface gradient associated with the strong southerlies of Day 94177-94181. It is recommended that the user spend some time watching the evolving display of EXHIBIT3 to cultivate the ability of tracking the simultaneous movement of the lunar icon, the vectors of surface gradient and wind velocity, and the time traces of water level.

In four of the five regions available for EXHIBIT3, there were only two tide gauges available to define a surface gradient, so its direction was confined to the line connecting the two gauges. The fifth region is the main body of Corpus Christi Bay, which is the single most important display of EXHIBIT3. Here the three gauges at Ingleside, the State Aquarium and the Naval Air Station form a nearly equilateral triangle whose vertices lie on the periphery of the bay, Fig. 4-2. For this region, EXHIBIT3 fits the equation of a plane to the instantaneous values at the three gauges, and computes the surface gradient as the slope of this plane. This is a fully two-dimensional vector whose magnitude and direction are free to vary with the relative changes in water level at the three gauges. Re-start EXHIBIT3, select Corpus Christi Bay, and start at Day 94160. The coherence of the surface gradient and the wind velocity is remarkable and surprising. Corpus Christi Bay exhibits a nearly instantaneous response to the changing wind ("nearly" since the resolution of the data is to one hour). The water level of the yellow trace is at the centroid of the three gauges, for practical purposes the center of Corpus Christi Bay, which is seen to rise and fall with the tide. But the internal slope of the water surface is entirely governed by wind, for these summer conditions. Note how even minor changes in wind direction are immediately tracked by a change in the water surface gradient. Again, it is recommended that the user spend some time watching this evolving display, before proceeding to the topic of frontal passages.

4.4.2 Equinoctial frontal passages

Especially during the spring and fall, the Coastal Bend region falls under the influence of frontal passages which effect a pronounced wind shift, but which do not substantially affect water levels in the adjacent Gulf of Mexico. There are about 20 of these fronts every year, which are referred to here as equinoctial systems, to differentiate from the polar outbreak fronts treated in the next section. Despite the name, nothing is meant to be implied about seasonality, as these can occur in winter, and even—rarely—in summer. Several examples of these types of systems are identified and discussed below. For each, select the bay region and the starting date for EXHIBIT3 as indicated. Then re-start and select component bay systems as indicated. It may also be of interest to activate EXHIBIT2 for the same dates to observe the water level response in more detail.

Day 94279

This was the first strong front of the 1994 fall season. Although there was some, rather minimal response in the Gulf, this event is regarded as an equinoctial-type system. The sequence begins on Day 94279. The winds turn from easterlies to SSE on this day and freshen until 11Z 94281 (06 CDT 7 October) when they shift abruptly to the northeast. Under the influence of the southeasterly winds, there is a rise of about 0.07 m in Corpus Christi Bay and Aransas Bay. At the frontal passage, the surface gradient in Corpus Christi Bay immediately turns to the SW in response to the winds. Under the influence of the prolonged N winds, water level drops about 0.1 m in excess of the falling lunar tide in Corpus Christi Bay by the next day (94282). In Aransas-Copano, there is a much more pronounced response to the front, with a depression in water elevation in excess of the tide of some 0.27 m by Day 94283. In the Upper Laguna, prior to the frontal passage, the water surface evidences its usual northward gradient. At the time of the front, there is an abrupt rise in water level due to the setdown in Corpus Christi Bay moving water over Bulkhead Flats and through the Causeway. The water level gradient is driven down to zero and held there for the next several days.

Figure 4-13 serves both as a summary graphic of this frontal passage and a demonstration of the superiority of EXHIBIT3 for displaying the dynamic

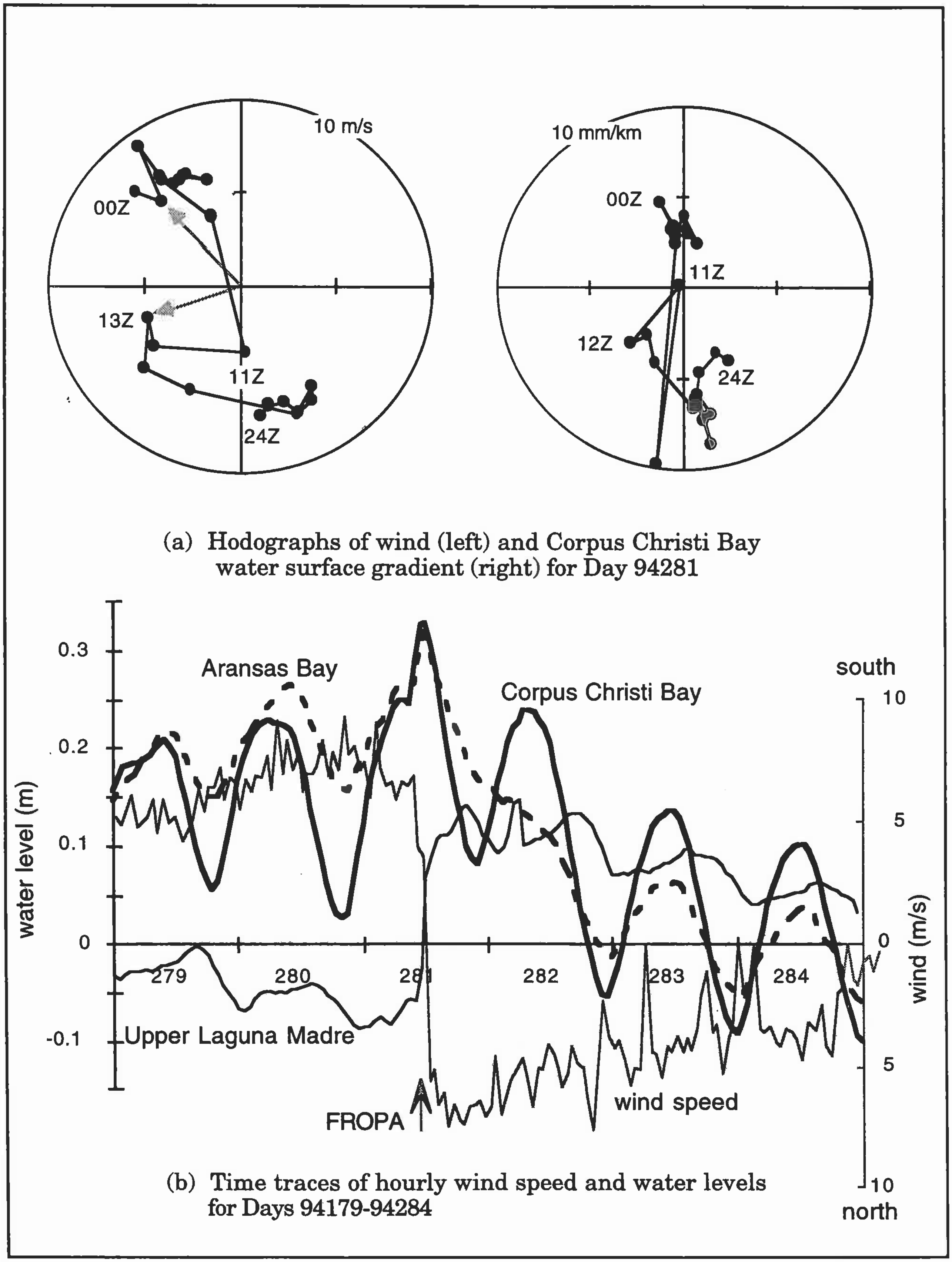


Figure 4-13. Hydrographic response to frontal passage of Day 94281

response of the system to such events. In Fig. 4-13(a) are shown hodographs for the wind and surface gradient vectors in the 24-hour period during which the frontal passage occurred. A hodograph depicts the evolution of a two-dimensional vector—in this case as a function of time—by plotting successive points of the *head* of the vector which are connected by a continuous line to indicate their order. Imagine an arrow from the origin to the data points in the order shown by the connecting line. Examples of two such arrows are shown in the wind hodograph. The dwell of the wind from the southeast prior to the front is indicated by the cluster of points in the northwest quadrant, then the vector shifts rather abruptly around 03Z to dwell in the southeast quadrant, indicative of northwest winds. The surface gradient is initially aligned with the winds, as shown by the dwell of points on the hodograph, then shifts with the wind to the south. Note the high magnitude of the surface gradient and the inertial overshoot associated with the initial transport of water to the south.

In Fig. 4-13(b) are shown the time histories of average water levels in Corpus Christi Bay, Aransas Bay and the Upper Laguna Madre during six days of the frontal passage episode. The wind speed is shown as the screened trace, positive or negative depending upon the sign of the north-south component, so that the occurrence of the frontal passage is very clearly delineated. There is an initial surge in water levels just prior to the frontal passage in both Corpus Christi and Aransas, followed by the frontal depression over the next 24 hours. Separation of tide and frontal response can be estimated by noting the tidal pattern throughout this period, and the total frontal reduction in water level is about 0.20 m in Corpus Christi and 0.27 m in Aransas. In the Upper Laguna, waters are driven southward creating a rise in water level of about 0.2 m with the frontal passage, that slowly diminishes over the next several days.

Day 94306

This date begins a series of several equinoctial frontal passages. At the outset, there are re-establishing southerly winds after a weak norther that are sustained until the frontal passage of 12Z 94309 (06 CST 4 November). The frontal passage occurs coincident with a falling tide so is somewhat difficult to pick out of the water-level traces, but is evident at once in the surface gradients. Water is immediately transported from north to south across Corpus Christi Bay, as evidenced by the reversal in direction of the surface gradient vector. In Aransas Bay, water levels increase slightly in advance of the front, then decline through 94310, in response to a slight setdown in the Gulf. The water level gradient in the Laguna drops to zero, and water levels being to fall in Packery Channel, but this effect is shortlived, and the normal northward surface gradient quickly re-establishes itself. Mean water level in the Laguna throughout this period is practically stationary. By 94311, the north winds have begun to release, and the surface gradient drops to nearly zero.

By 94312, the winds have shifted back to the southerly quadrant, and the surface gradient in Corpus Christi Bay with them. The southerly winds freshen in advance of the next system which blows through on 04Z 94314, again reversing the surface gradient on Corpus Christi Bay and in Aransas-Copano. The winds veer to northeast, paralleling the coast, and there is negligible setdown response in the Gulf. In fact, the average water surface in Corpus Christi and Aransas-Copano is practically stationary through 94315 and into 94316, though there is still a southward gradient across both bays. The response of the Laguna is even less, though the surface gradient does reverse to the south for a few hours on 94315. By late on Day 94316, the wind has veered further to east then to southeast, and the water-surface gradients in Corpus Christi Bay and the Upper Laguna are directed back to the north. Aransas-Copano is slower to respond, and the internal surface gradient remains directed to the south. The small declination and minimal lunar tide throughout this period makes it evident that setup-setdown response in the adjacent Gulf of Mexico is absent. There is yet another frontal passage on Day 94320.

Day 95125

This is practically a type specimen for the equinoctial frontal passage. The synoptic disturbance moved quickly from west to east across the state, and the sequence of events was accordingly compressed in time. The normal southerly flow is established as the period begins. With the approach of the front, winds freshen from the southeast, veering to south just before the frontal passage, which occurs at 13Z 95128 (08 CST 5 May). Under the freshening southeasterly winds, the surface gradient in the Upper Laguna increases. The average water level begins to drop, however, apparently due to water being transported through the Causeway into Corpus Christi Bay. After the frontal passage, the water surface gradients in Corpus Christi Bay and Aransas Bay immediately reverse, tracking the changing wind. As with the event of Day 94279 above, surface waters actually rise in the Laguna after the frontal passage, due to transport from north to south into Bulkhead Flats and through the Causeway. The wind almost immediately veers to the northeast, and continues to veer around to the east, until southeasterlies are re-established by 95129. The entire disturbance moves so quickly that there is no time for the Gulf to respond, even had the wind field extended sufficiently far out.

4.4.3 Polar outbreak fronts

When the Coastal Bend area is under maximal influence of midlatitude westerlies, the disturbances entail major incursions of polar area across the coastal plain and over the Gulf of Mexico, see Section 2.2.3. These "polar outbreak fronts" are primarily, but not exclusively, a phenomenon of winter, and differ from the equinoctial fronts in accomplishing a much more dramatic impact on the coastal waters. It is well-known that these major events cause large-scale modifications to the near-surface salinity-temperature structure in the Gulf of Mexico (e.g., Parker, 1968), partly due to thermodynamics, but mainly due to water-mass transport. These are the events that produce the major set-up and set-down responses characteristic of intense "northers." During the "Big Freeze" (see Section 2.2.3), Dr. Cline (1946) actually waded across Galveston Bay from

Galveston Island to the mainland, the water being so low that he could even ford the channel below the drawbridge.

In the Corpus Christi area, the number of such events in a year is highly variable, but is usually on the order of five. While there are several polar outbreak episodes in the data files loaded with EXHIBIT3, a good, but rather modest example begins on Day 96063. Figure 4-14 presents hodographs and water-level traces for this event, using the same format as Fig. 4-13, but EXHIBIT3 is the principal display device. Winds are from the prevailing southeasterly quadrant at Day 96063, and continue to freshen for the next several days as the front approaches. Lunar declination is nearing zero, one of the reasons for selecting this example. The surface gradient in Corpus Christi Bay is directed to the northwest under the prevailing wind direction. The frontal passage occurs 05Z 96067 (00 CDT 7 March), and the surface slope in the bay changes immediately to the south. The response of surface slope is even more drastic in Aransas Bay. In the Upper Laguna, the response to the frontal passage is an immediate rise in water level, as was the case with the equinoctial front, due to the transport of water from Corpus Christi Bay into Bulkhead Flats and the Causeway area. The surface slope in the Laguna reverses, becoming directed to the south.

For the next 24 hours, north winds are in excess of 10 m/s. Note that the wind speed is higher at the Naval Air Station, with its long overwater fetch, compared to Ingleside, which has terrain lying upwind. (The hodograph and wind speeds of Figs. 4-13 and 4-14 are the average of the two anemometers.) Because lunar declination is small, the north-wind effect is easy to separate from tidal variation, which is minimal. The water levels in Corpus Christi Bay follow the lowering of water levels in the Gulf. In Aransas Bay, under the influence of both north wind stress and falling waters in the Gulf, the water level between Rockport and Copano drops below that of the gauge at Port Aransas, but continues to drop as the Gulf water levels fall. As water levels are depressed in the Gulf, the lag of the Laguna after Corpus Christi Bay results in higher water below the Causeway.

By midday 96069 winds are beginning to veer to the northeast, and the falling water elevations in Corpus and Aransas begin to level off. In the Laguna, the elevations north and south of the Causeway are equal, and the surface gradient between Bird Island and Yarborough in the Laguna is zero. Winds have returned to the southeast by late 96071, but the water level gradient in Aransas continues to be directed to the south. The water level in the Laguna is also slow to re-establish its normally northward gradient, and levels continue to be equal on both sides of the Causeway.

Two other good examples of polar-outbreak fronts, which occur in the data record of EXHIBIT3, are the sequences beginning Day 94340 and Day 95345. For the former, the frontal passage occurs on 18Z 94343, strong northerlies are sustained for the next 48 hours, and 96 hours pass before the Gulf onshore flow is re-established. For the latter, the frontal passage occurs 12Z 95352 and strong winds from the north are sustained for the next nine days. Water levels remain setup to

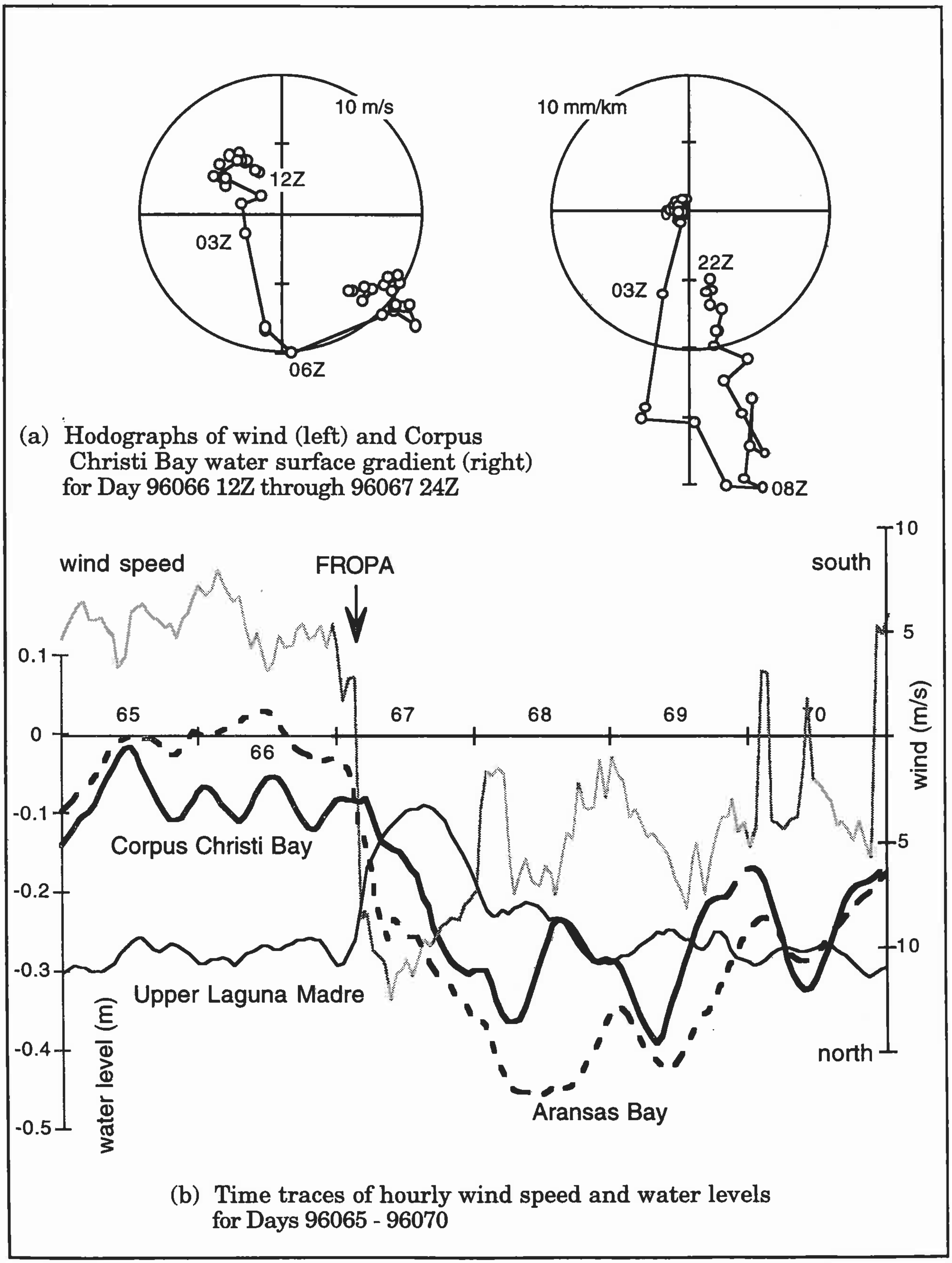


Figure 4-14. Hydrographic response to frontal passage of Day 96067

the south across Corpus Christi Bay, there is a plunge in Gulf water level throughout 95353-95354, and a resurgence (still under the north winds) on 95355 - 95356.

4.4.4 Summary of frontal responses

The morphology of a frontal passage and the associated response of the Corpus Christi Bay system are highly variable, dependent upon factors such as pre-existing atmospheric conditions, atmospheric steering currents, temperature/ humidity structure of the air mass, strength of the southeasterly winds, intensity and translation of the synoptic disturbance, precipitation associated with the event, pre-existing hydrographic state of the bay, energy and southward incursion of airmass replacement over the Gulf, maintenance of post-frontal winds, etc. The classification into equinoctial and polar-outbreak fronts is therefore a gross simplification of a much more complex range of variation. It does serve to emphasize the separate rôles of direct wind-stress setup/setdown on the bay and the indirect response of the bay to setup/setdown of the Gulf of Mexico. The former is measured by the cross-bay variation in surface gradient, and the latter is measured by the time variation in mean water level of the bay.

Table 4-4 summarizes the volume transports of both types associated with the example frontal passages reviewed above, to quantify the magnitudes of transport of each type accomplished by the two types of fronts. The surface gradient is measured along the principal or longitudinal axis of the component bay (or, in the case of Corpus Christi Bay, along the NW-SE axis), positive toward the NW quadrant. Multiplied times the overwater length of the bay, this gradient gives the net difference across the bay. The water-level increment is the net increase (i.e., positive upwards) in average water level in the component bay associated with the frontal passage. The average is computed for a pair of gauges or, in the case of Corpus Christi Bay, from the three gauges distributed on its periphery. These elevation changes are used to compute an equivalent volume transport based upon surface areas of the component bays. The cross-bay transport is the volume transported across the medial axis of the bay due to the change (usually a reversal) in surface gradient. The influx is the volume imported to the component bay. For most of the component bays, a front results in a net efflux of water, so this number is negative. The geometry of the cross-bay and influx responses is sketched in Fig. 4-15. (No cross-bay transport for Copano is computed, because the gradient, computed between Bayside and Copano Pass is too unreliable. However, an examination of the response of Copano Bay using EXHIBIT2 makes it clear that there is a frontal setup-setdown response across the bay. The volume of water transported is probably similar to that in Nueces Bay.) For the three polar outbreak fronts of Table 4-4, the Nueces Bay response could not be computed because the gauge bottoms out at low water elevations. These are indicated in the table by "<" signs. Because these are negative values, however, the actual transport will be greater in absolute magnitude than the entries of Table 4-4; i.e., the values given are lower bounds on the magnitude of the transport effected.

Table 4-4
Frontal passage volume transports by component bays

bay	*surface gradient Δh / Δx* *pre-front* *(mm / km)*	*post-front*	*increment* *(m)*	*transport* *cross-bay* *(Mm³)*	*bay influx*
DATE	94281.0		(equinoctial)		
Corpus Christi	4.8	-8.7	-0.08	-16	-35
Aransas	4.0	-4.0	-0.17	-5	-37
Copano	-	-	-0.20	-	-39
Nueces	9.0	-3.6	-0.07	-1	-5
Upper Laguna	4.9	0.6	0.19	-6	47
DATE	94309.0		(equinoctial)		
Corpus Christi	7.5	-6.6	-0.03	-17	-15
Aransas	5.6	-2.0	-0.11	-4	-24
Copano	-	-	-0.13	-	-25
Nueces	10.8	3.6	-0.17	-1	-12
Upper Laguna	5.4	0.8	0.14	-7	36
DATE	95128.0		(equinoctial)		
Corpus Christi	7.0	-8.1	0.00	-18	0
Aransas	5.7	-13.7	0.00	-11	0
Copano	-	-	-0.14	-	-28
Nueces	16.8	0.4	-0.19	-2	-13
Upper Laguna	6.9	0.0	0.15	-10	39
DATE	94340.0		(polar outbreak)		
Corpus Christi	1.0	-7.8	-0.11	-10	-47
Aransas	-2.4	-10.9	-0.26	-5	-57
Copano	-	-	-0.26	-	-51
Nueces*	5.4	-6.3	<-0.09	-1	<-6
Upper Laguna	1.8	-1.8	0.10	-5	27
DATE	95345.0		(polar outbreak)		
Corpus Christi	1.4	-5.4	-0.37	-8	-159
Aransas	-3.3	-14.8	-0.44	-7	-97
Copano†	-	-	-	-	-
Nueces*	5.9	-15.4	<-0.21	-2	<-15
Upper Laguna	4.6	0.1	0.16	-7	41
DATE	96067.0		(polar outbreak)		
Corpus Christi	1.1	-20.9	-0.23	-26	-98
Aransas	-2.9	-30.3	-0.42	-16	-93
Copano†	-	-	-	-	-
Nueces*	6.5	<1.6	<-0.18	<-1	<-12
Upper Laguna	5.0	4.1	0.20	-1	52

* Gauge pegged
† Bayside record terminates 95329

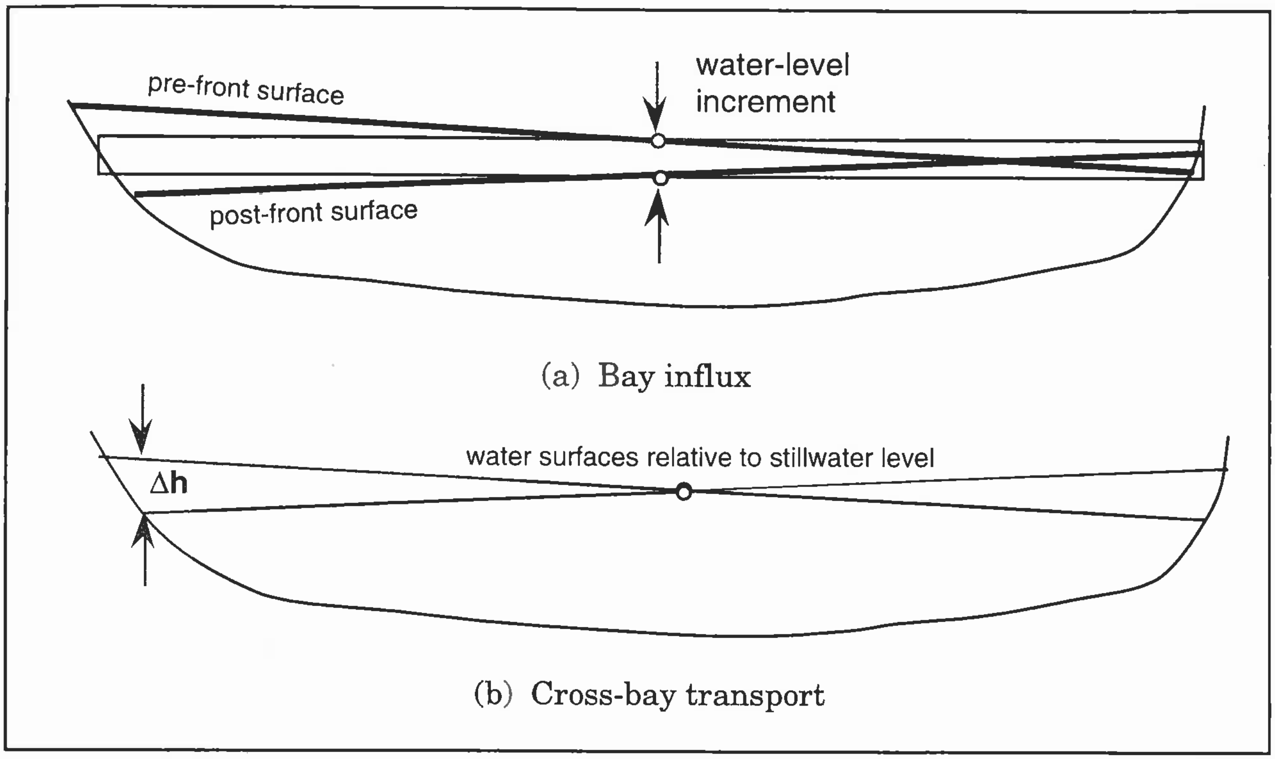


Figure 4-15. Definition sketch of frontal passage transports

Also, the reader is reminded that because the long-term mean water volume does not change, the efflux associated with a frontal passage is compensated by an influx of water, either before or after the frontal event, or both.

Clearly, there are many more such events in the records of EXHIBIT2 and EXHIBIT3 than appear in Table 4-4. While compilation and analysis of the complete population of frontal passages exceeded the scope of this study, it is strongly recommended that both exhibits be displayed for study of the responses typical of the major geographical regions of the study area. Several conclusions can be drawn from the data of Table 4-4 and displays of EXHIBIT2 and EXHIBIT3:

- For a given front, the magnitude of water volume exchanged between a component bay and the adjacent system (ultimately the Gulf of Mexico) is generally greater than the internal cross-bay transport of water;

- The cross-bay transports are about the same magnitude for both equinoctial and polar-outbreak fronts; however, the influx volume is much greater for the polar-outbreak fronts;

- The frontal response of the Gulf of Mexico is the single most important factor determining the response of the bay;

- The frontal influx is on the same order as the great declination tidal prism, and for the outer bays is generally larger than the great-declination tidal prism;

- The time-scale of response to a frontal windshift for the influx is on the order of a day: the larger responses—to polar-outbreak fronts—take place over a longer time frame, perhaps 2-4 days.

In a study treating the upper bays of Texas, Sabine Lake, Galveston, Matagorda and San Antonio, Ward (1980b) concluded that the primary response of the estuary was due to indirect forcing by water-level variations in the Gulf of Mexico, with secondary contributions by the direct windstress on the bay and the inverse-barometer response. The same qualitative conclusion applies to the study area. The Corpus Christi Bay system is generally less responsive to fronts than the bays on the upper coast, in terms of volume exchanged with the Gulf (cf. Ward, 1980b): the largest proportion of volume influx given in Table 4-4 is about 10% of the bay volume, whereas the more energetic fronts evacuate 3-5 times this relative volume from the bays on the upper Texas coast. This is considered to be mainly a consequence of the more constricted inlets of the study area, and their reduced hydraulic capacities. It may also be due somewhat to reduction of energy of the frontal system in penetrating to the more southerly latitudes of the study area, but this would seem to be unimportant except for the marginal frontal systems. Also, the response of the frontal exchange of Corpus Christi Bay with the Gulf of Mexico is more sluggish than the bays on the upper coast, which is also consistent with the constricted inlets.

The response of the Upper Laguna Madre should be especially noted. The frontal setdown effects a cross-bay transport (from north to south) on the order of 7 Mm^3, Table 4-4, but this is a greater relative proportion of the volume of this shallow system than is the case for the other component bays. Unlike the other systems from which there is a net efflux (negative influx) created by the front, the Laguna receives a net influx. As noted earlier, this is a consequence of direct windstress on the Corpus Christi Bay component transporting water into the Bulkhead Flats area, thence through the JFK Causeway. The cross-bay transports of Table 4-4 were inferred from the estimated water-level differences (Fig. 4-14), but any transport into the Laguna would not be included in this transport term (since the water-level head would be reduced). Therefore, the total cross-bay transport for Corpus Christi should be the sum of that given in Table 4-4 for Corpus Christi Bay and the Upper Laguna.

There is practically no tide in the Upper Laguna, so these frontal responses are the primary short-term exchange mechanism for the system. The existence of the GIWW cut through the Mudflats raises the question of whether frontal influx waters would be carried on into the Lower Laguna Madre, perhaps assisted by the direct windstress to the south. Clearly, all of the waters entering the Laguna through the Causeway are not being transported out via the GIWW, or there would not be an increase in average water elevation, as given in Table 4-4. But it is reasonable to inquire whether an appreciable proportion of the frontal influx waters could be removed by this mechanism. The companion question also applies, of whether appreciable water could be imported into the Upper Laguna from the Lower Laguna by the enhanced southerly winds before the front.

To address these questions, the coupled response of the Upper and Lower Laguna basins and the rôle of the Mudflats in this exchange must be considered. The Lower Laguna is a much larger basin with a greater exchange with the Gulf of Mexico. A general location map of the entire Laguna Madre system is shown in Fig. 4-16. Figures 4-17 and 4-18 depict the *natural* topography in two different ways. The former shows cross-sectional area below various elevations relative to the 1927 North American Datum (that used for USGS 7.5-min quadrangles), determined from USGS topography, bathymetry from Carothers et al. (1959), NOS navigation charts and the detailed topographic surveys of Fisk (1949). The much greater cross section of the Lower Laguna is immediately apparent. The three somewhat deeper "basins" of the Upper Laguna are also evident as convexities in these contours, from north to south, the Laureles Basin, Murdock Basin and the Hole (a.k.a. Fish Graveyard). In Fig. 4-18 the elevation relative to the 0-ft datum is plotted, both its average and minimum values across the section. In most bays, this "elevation" would be referred to simply as "depth" but in the Laguna, water depth is a highly variable parameter.

In both of these figures, the potential is clear for the Mudflats to act as a physiographic barrier to exchange between the Upper and Lower basins. In fact, relative to this datum, the water surface has to exceed an elevation over the Flats of 3 ft to establish hydraulic continuity between the two. (Note that this is the elevation of the water, not its depth. In fact, the water depth may be quite shallow since the highest elevations of the surface of the Mudflats bed are about 3 ft.) Creation of a 12 x 125 ft channel through the Mudflats establishes a hydraulic continuity between the Upper and Lower basins that was absent at least part of the time prior to the GIWW. In order to evaluate the flow through the GIWW for frontal events, records from tide gauges at both ends of the GIWW landcut are needed; moreover, these records must be related to a common arbitrary datum. The CBI TCOON program includes gauges in the Laguna, but these gauges are not referenced to a common datum. The resources available to the present project did not allow the empirical leveling of these gauges, as was done for key gauges in the study area (Section 4.1 above). However, during the Humble Oil & Refining studies of the late 1940's several tide gauges were installed and operated along the Laguna Madre. HOR invested the considerable surveying effort necessary to reference these gauges to a common datum. The gauge locations are shown on Figs. 4-16 through 4-18.

Unfortunately, the periods of record of operation of these gauges is spotty, and did not encompass the winter period, so no polar-outbreak fronts could be investigated. However, two case studies of equinoctial fronts were selected for analysis to determine the magnitude of water transport, namely fronts of 28 August 1948 and 10 May 1948. The latter, 10 May, is very typical of this type of system, and in particular is similar to the Day 95125 Case Study of the previous section (with the corresponding frontal passage on Date 95128 in Table 4-4). The August case is not so typical, the winds being mostly northeasterlies (which

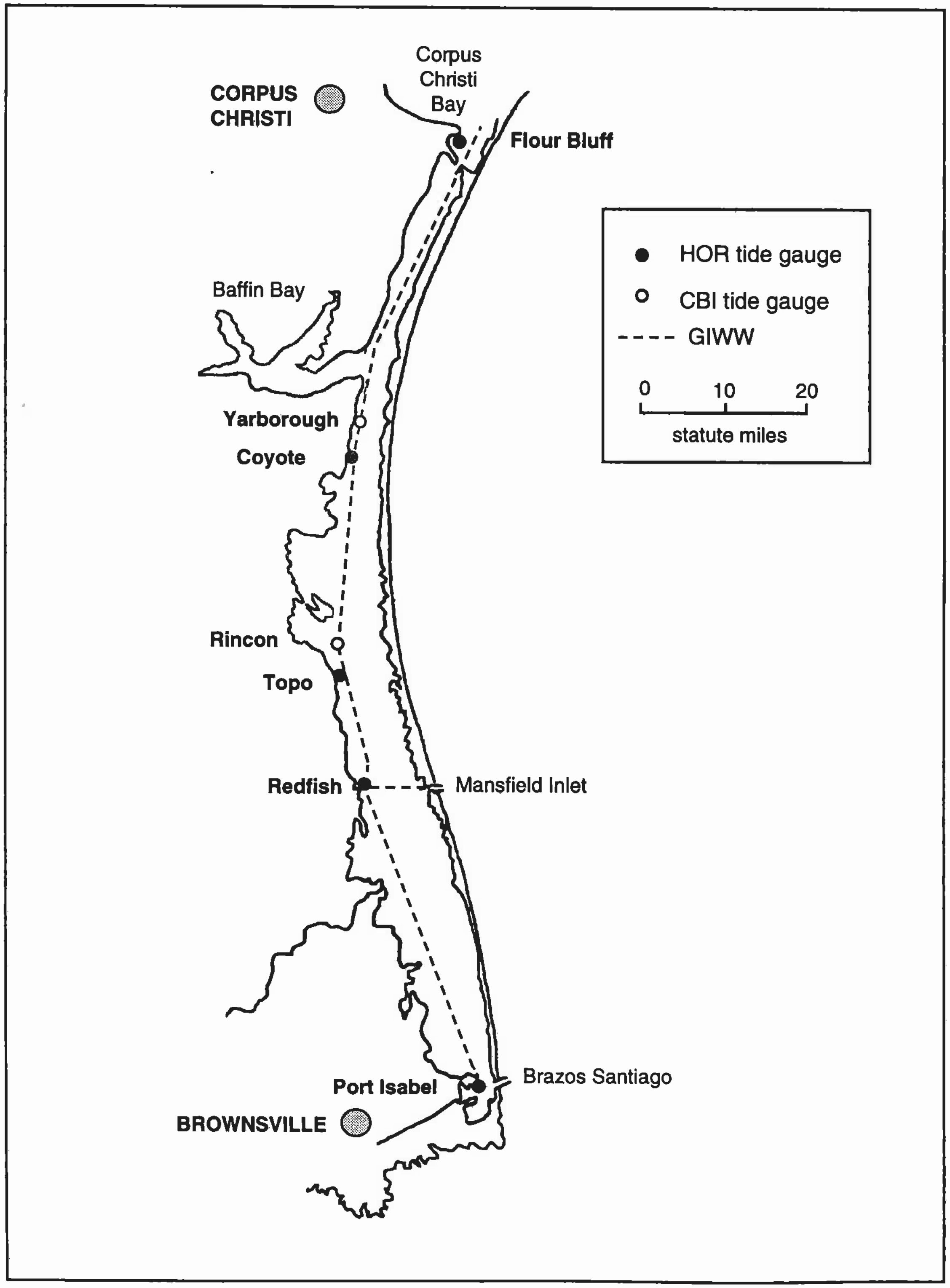


Figure 4-16. Location Map of Laguna Madre

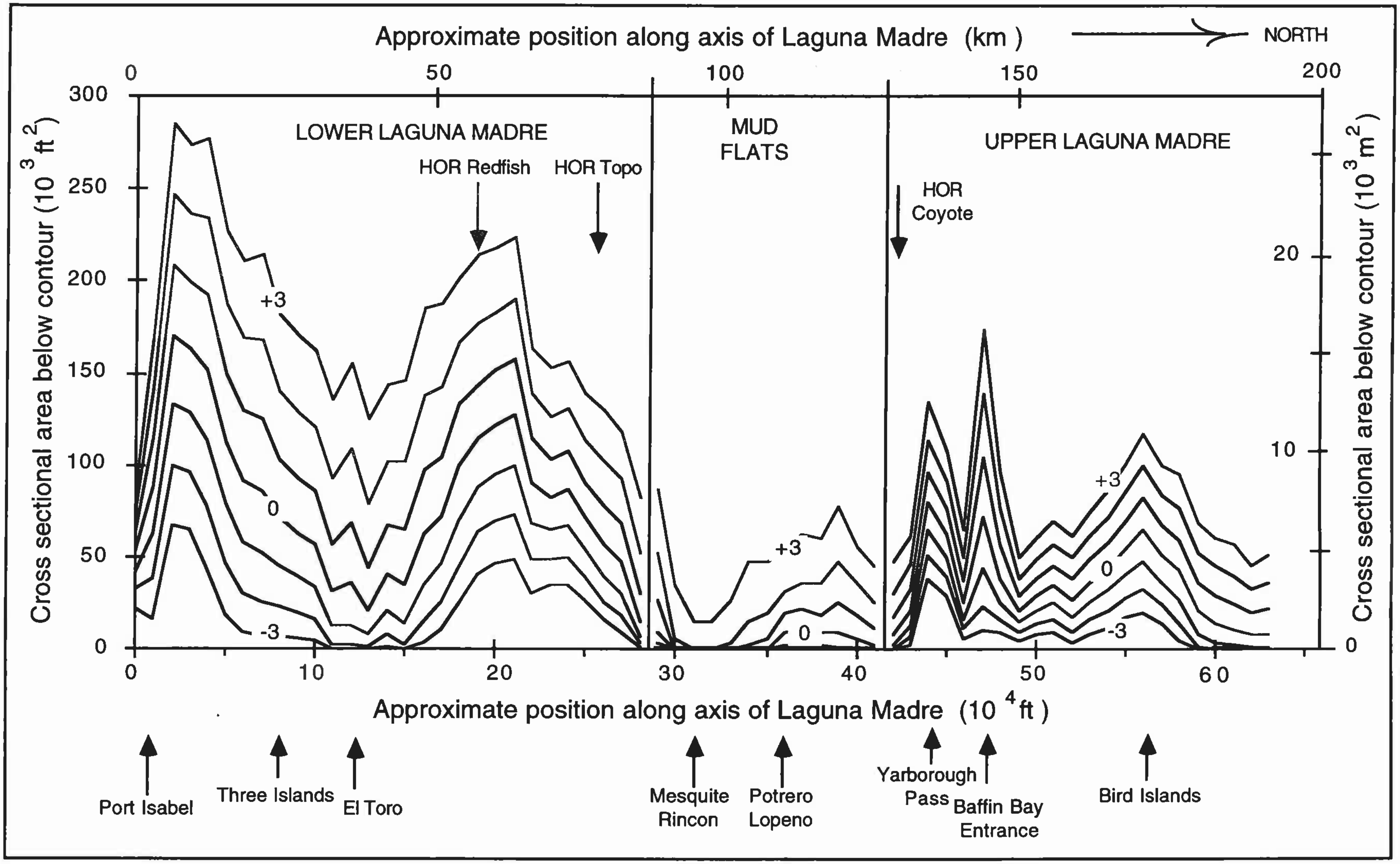


Figure 4-17. Laguna Madre cross-section below fixed level surface

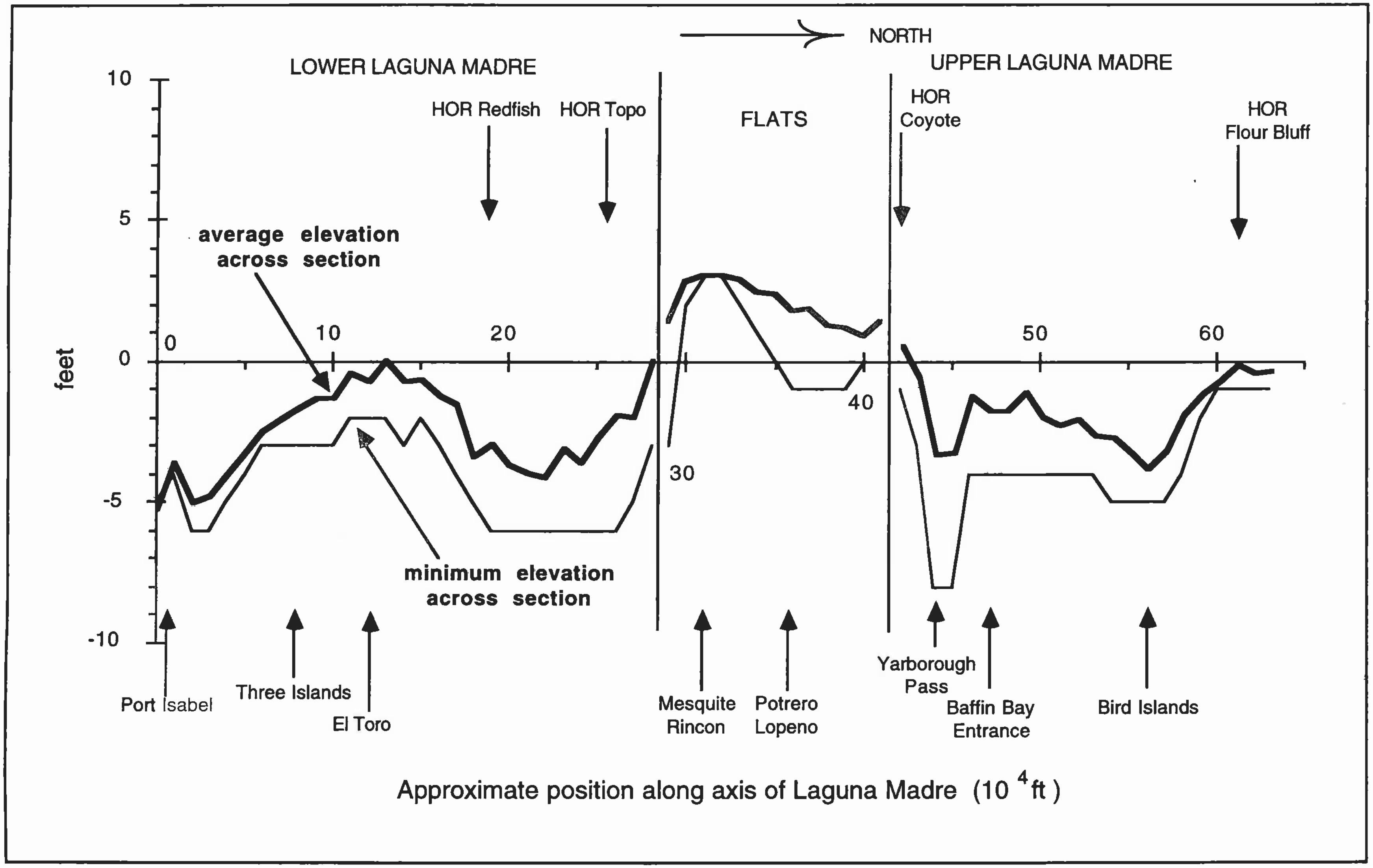


Figure 4-18. Elevations relative to USGS datum

produces the minimal response in the Gulf of Mexico, cf. Table 4-4), but this case does exhibit a strong return of southerly flow after the front, with associated water level change. The variation in daily-average water level at the Topo Gauge at the south end of the Mudflats, and the Coyote Gauge at the north end are shown for these two frontal passage scenarios in Fig. 4-19 and 4-20. The substantial difference in water level between the two gauges should be noted. The flow that would be driven through the GIWW by the associated water-level difference was computed by the methods of Appendix D, assuming that friction would balance the head gradient, i.e. that entrance losses could be neglected, and using GIWW project dimensions with a Chézy coefficient of 50 $\sqrt{m}/s$. The resulting computed flow is plotted on Figs. 4-19 and 4-20. It bears emphasis that in 1948 the GIWW did not exist; these computed flows are theoretical. The May 1948 case is muddled by the fact that the Lower Laguna was set up about 2 ft higher than the Upper Laguna. The frontal passage reduced this difference by about half, but the Lower Laguna still exhibits a positive head with respect to the Upper, implying that—despite the front—water would be transported northward into the Upper Laguna. If we assume the water levels equal as the southerlies begin to freshen in advance of the front (i.e., imagine translating the Coyote trace upward in Fig. 4-19 until the pre-front value of 7 May intersects the Topo trace), then the head difference during the period of northerlies would drive a flow south in the GIWW of less than 5×10^7 cfd (1.4 Mm^3/d).

The total water transport across the medial point of the Upper Laguna, i.e. from the north half to the south half of the Upper Laguna, was computed by a numerical integration based upon superposing the plane of the water surface on the equivalent of Fig. 4-17. The resulting volumes are as follows:

event	*volume transport (Mm^3)*
May 48	27.7
Sep 48	34.3

No separation was made of the cross-bay and influx components, so these volumes represent what would be obtained by adding the cross-bay transport of Table 4-4 to one-half of the bay influx. These results are seen to be quite comparable to those of Table 4-4. (The set-up under the southerlies following the frontal passage in September 1948 was found to transport 26.8 Mm^3 out of the lower half of the Upper Laguna.)

A comparison of the volume of water transported into the south half of the Lower Laguna by the front to the discharge that would result in the theoretical GIWW due to the imposed water level difference shows that the GIWW would not materially affect the frontal volume transport. For both 1948 events, the GIWW could discharge less than 5% of the frontal transported volume per day. The May frontal setdown takes place over about three days, so the GIWW would reduce this volume a total of perhaps 15%. The September 1948 event is protracted over a longer period of time, about eight days, and the integrated discharge for this

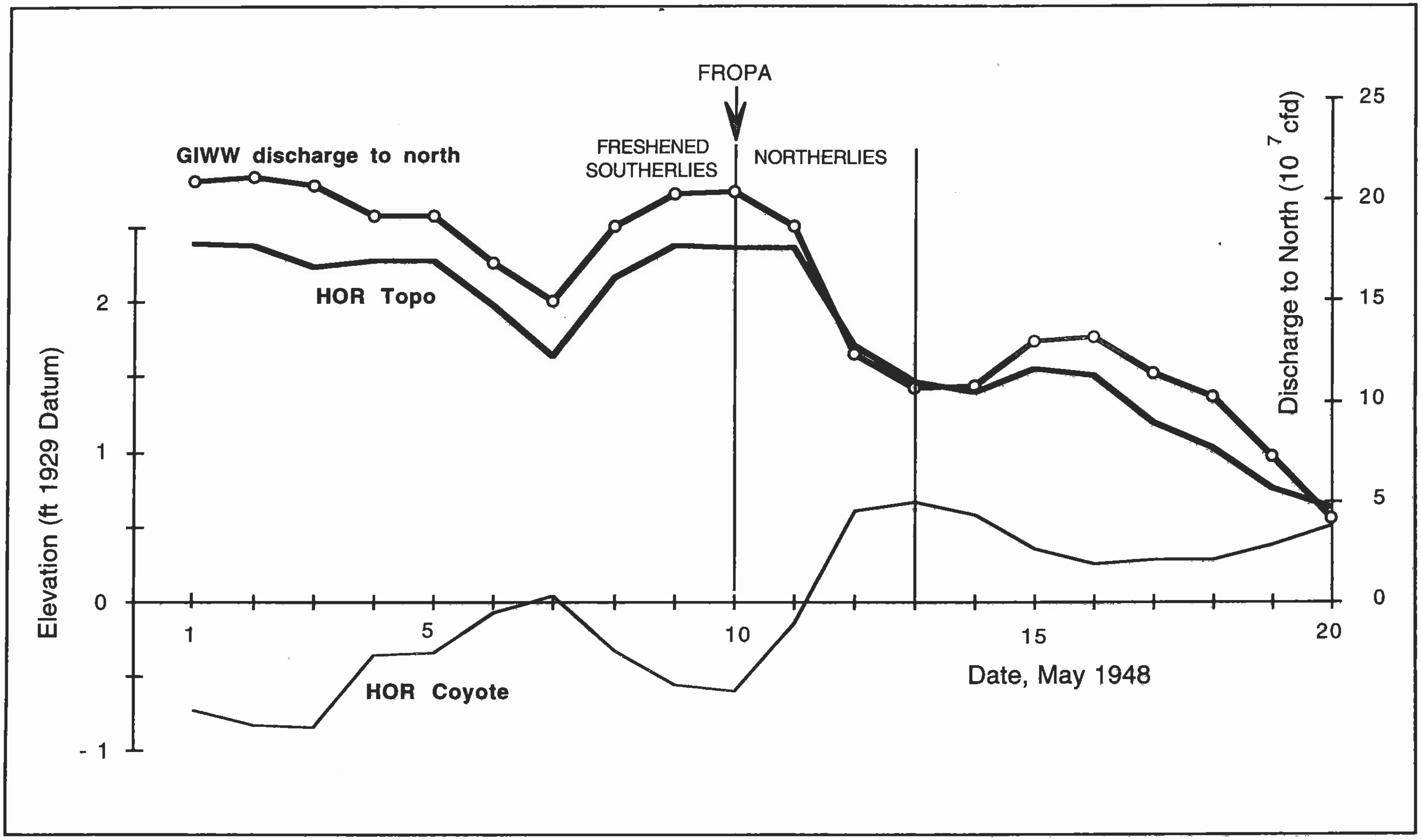


Figure 4-19. Daily-mean water levels across Mud Flats and computed flow in GIWW, May 1948

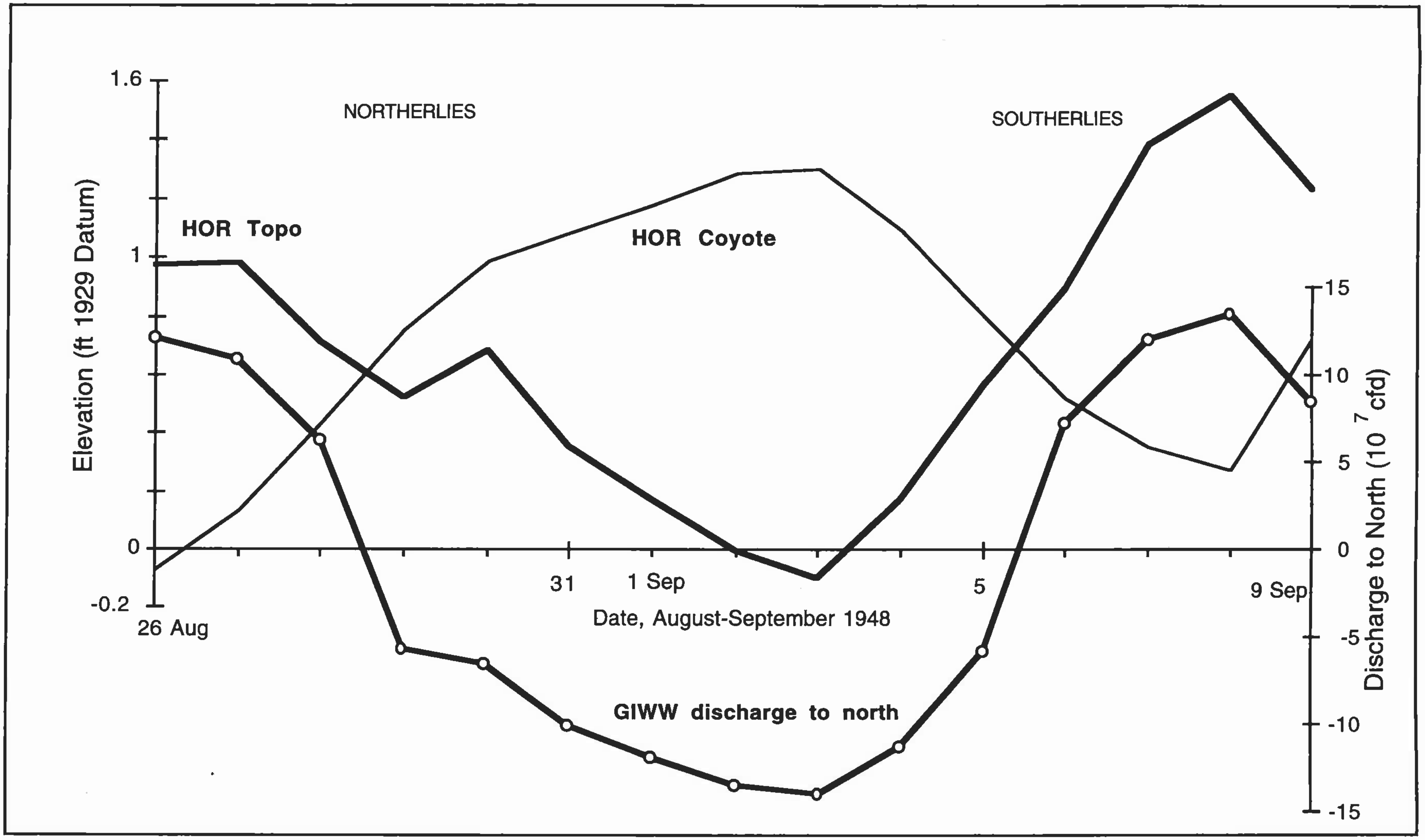


Figure 4-20. Daily-mean water levels across Mud Flats and computed flow in GIWW, September 1948

period from Fig. 4-20 totals about 20% of the frontal volume. We conclude that any effect of the GIWW on the volume transported by fronts, though nonnegligible, is secondary. (It is interesting to note that the same analysis carried out for the Lower Laguna shows that the effect of the GIWW for this much larger system is in fact negligible.) This conclusion is rather intuitive if one considers that the same physical mechanisms that make a long narrow channel unable to pass higher frequency energy, e.g. tides, would also prevent it from reacting to the sudden water level changes of a frontal passage response. (Try operating EXHIBIT1 with parameters appropriate to the dimensions of the GIWW landcut through the Flats.) This conclusion applies *only* to the relatively short timeframe transports of a frontal passage. There are longer-term transports, which will be addressed in the next chapter, in which the effect of the GIWW can be substantial.

4.4.5 Seabreeze response

In addition to the astronomical tide, one other short-period forcing operates in the Coastal Bend area, the seabreeze cycle. This is a solenoidal circulation produced by the diurnal variation in density of the lower atmosphere resulting from the surface temperature differential of the land and sea (Haltiner and Martin, 1957, Dutton, 1986). It is ultimately caused by the difference in thermodynamics of sea water and land surface, and is most pronounced along their boundary, i.e. the coastline. As the seabreeze circulation begins to develop, it imposes an organized circulation in the lower atmosphere that spreads inland and increases the wind speed. This circulation frequently leads to formation of a convergence front, the "seabreeze front," which moves inland from the coast in the afternoons and becomes a locus of convective development that often produces thunderstorms. The reverse circulation develops in the evening as a landbreeze, spreading out to sea from the coastline. In the coastal zone itself, the seabreeze is manifested as a diurnal variation in wind velocity superposed on the normal onshore flow from the Gulf of Mexico. The familiar freshening of winds in the afternoon and the increase of short-crested windwaves (chop) are well-known features of summer hydrography in these bays attending the seabreeze.

The seabreeze is a relatively weak circulation, and its importance depends on other factors affecting wind. The seabreeze is obliterated by more dynamic atmospheric processes, such as airmass replacement or interception of radiation by clouds, and can be masked even by the prevailing onshore flow. A numerical index to the relative importance of the seabreeze is $\Delta T/U^2$, where ΔT is the land-sea temperature difference and U is the (total) wind speed (see Simpson, 1994). Although a seabreeze circulation is capable of being developed at any time in the year when conditions are favorable, the best conditions are under intense insolation in quiescent synoptic conditions when the onshore flow is weak. Thus, the seabreeze is best developed in conditions typical of late summer, when the Bermuda High is beginning to weaken. The strict direct solenoidal forcing would imply a circulation in phase with the sea-land temperature difference, with maximum wind speed in late afternoon and continuing onshore flow for an additional 2-3 hours after sunset (terminated when the land cools down to the temperature of the water). It is, of course, more complex than that. There is an inertial lag, which may vary with distance inland. Moreover, as the solenoidal circulation develops, the rotation of the earth (the Coriolis acceleration) will produce a longshore component that will turn the seabreeze component clockwise (Haurwitz, 1947). The diurnal formation and dissipation of low-level clouds on the marine boundary layer, and the production of turbulence and associated coupling with winds aloft further modify the seabreeze.

For one year, from June 1976 though May 1977, a tall anemometer (elevation 30 m) was operated at the MSI facility in Port Aransas by the UTA Atmospheric Science Group (N.K. Wagner, pers. comm., 1996). Figure 4-21(a) shows the mean hourly wind vector averaged over this one-year period (data keyboarded from graphs of Eigsti, 1978), plotted as a hodograph. The data points of the hodograph are interpreted as indicating the movement of the head of the vector, as indicated by the single vector shown on Fig. 4-21(a), see Section 4.4.2. This total wind vector can be decomposed into a constant average vector and a time varying vector, as shown in Fig. 4-21(b). The former is the prevailing onshore flow from the Gulf; the latter is the seabreeze, and is seen to be substantially smaller in magnitude than the prevailing mean wind, and veers (i.e., turns clockwise) through the course of the day, as expected from the theoretical influence of the earth's rotation.

One year averaged data (specifically for May 1995 through April 1996) for selected TCOON anemometers are shown as hodographs of hourly values in Fig. 4-22. Bob Hall Pier is placed exactly on the Gulf beachfront and displays the cyclical turning of the seabreeze. Apart from the year in which data were taken, the chief difference in this station and the MSI data of Fig. 4-21 is the elevation of the anemometers, Bob Hall Pier being at 13 m, and MSI considerably higher at 30 m. The strength of the seabreeze diminishes with height (Schmidt, 1947), and the southeasterly onshore flow increases with height through the boundary layer, so the higher anemometer will evidence a decreased seabreeze component. The other stations are placed on the periphery of the bay and evidence distortions due to their situation with respect to land and water. Port Aransas in particular is located on the backside of the island at about 5 m elevation. With distance inland, the veering circle is compressed so that the seabreeze becomes more of an alternating onshore/offshore variation that reinforces/opposes the normal onshore wind. The time of maximum onshore wind is about 1800 CST near the Gulf and becomes earlier with distance inland.

Considering that the annual averaged data of Figs. 4-21 and 4-22 reflect frontal passages, winter wind regimes, clouds and thunderstorms, and the annual cycle of airflow about the Bermuda High, all of which are nondiurnal processes that corrupt any diurnal variation, it is remarkable that the seabreeze signal emerges as clearly as it does. This is testimony to its persistence. To display the seabreeze behavior under its most prominent conditions, the same sort of averaged hourly hodographs are shown in Fig. 4-23 for the month of August (1995 except for the MSI 30-m tower data, which are from 1976). The amplitude of the seabreeze is seen to diminish inland, and to diminish with elevation aloft, in accordance with

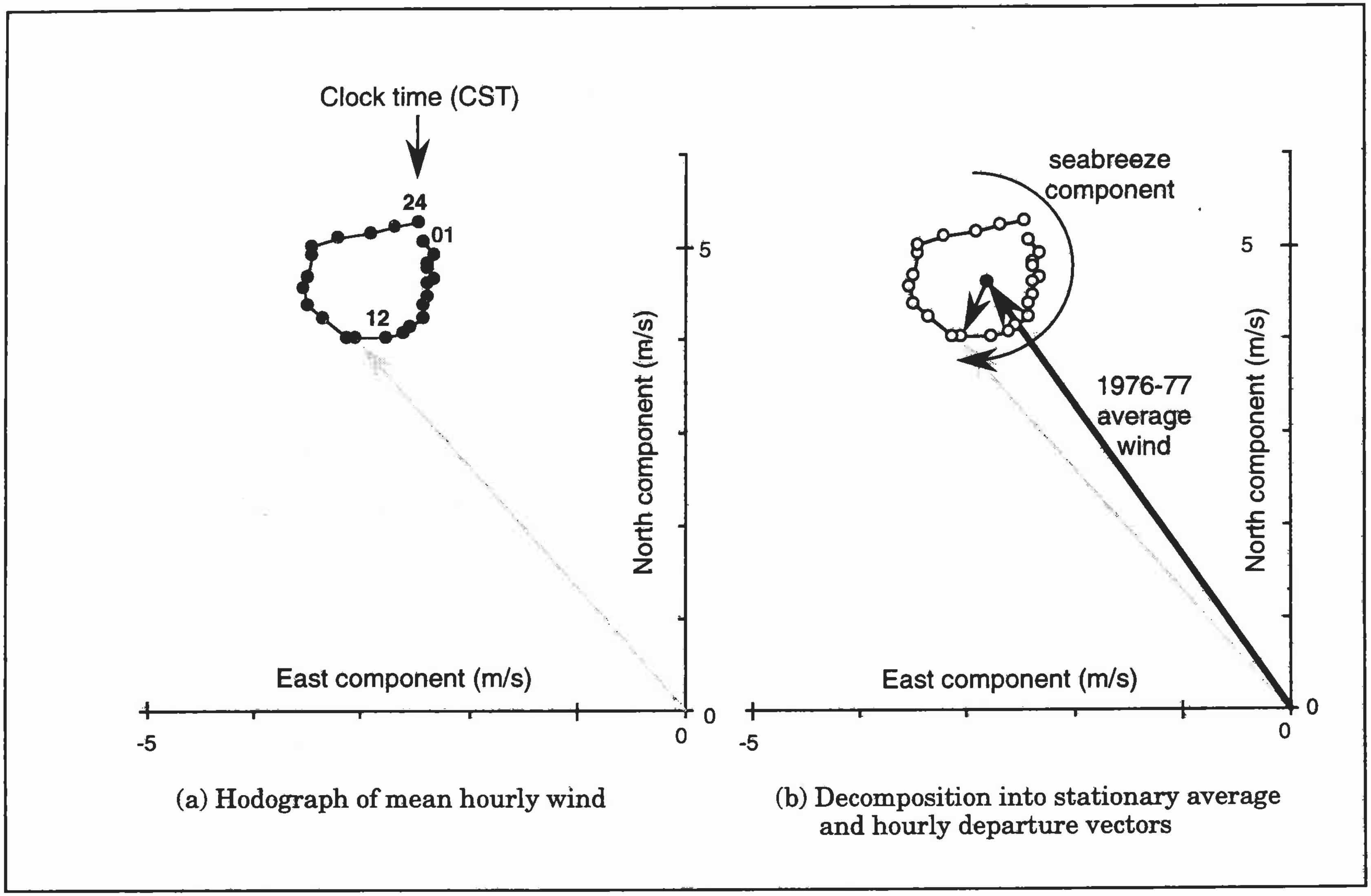


Figure 4-21. Hodograph of 1976-77 annual-mean hourly wind, 30 m at Port Aransas (data from Eigsti, 1978)

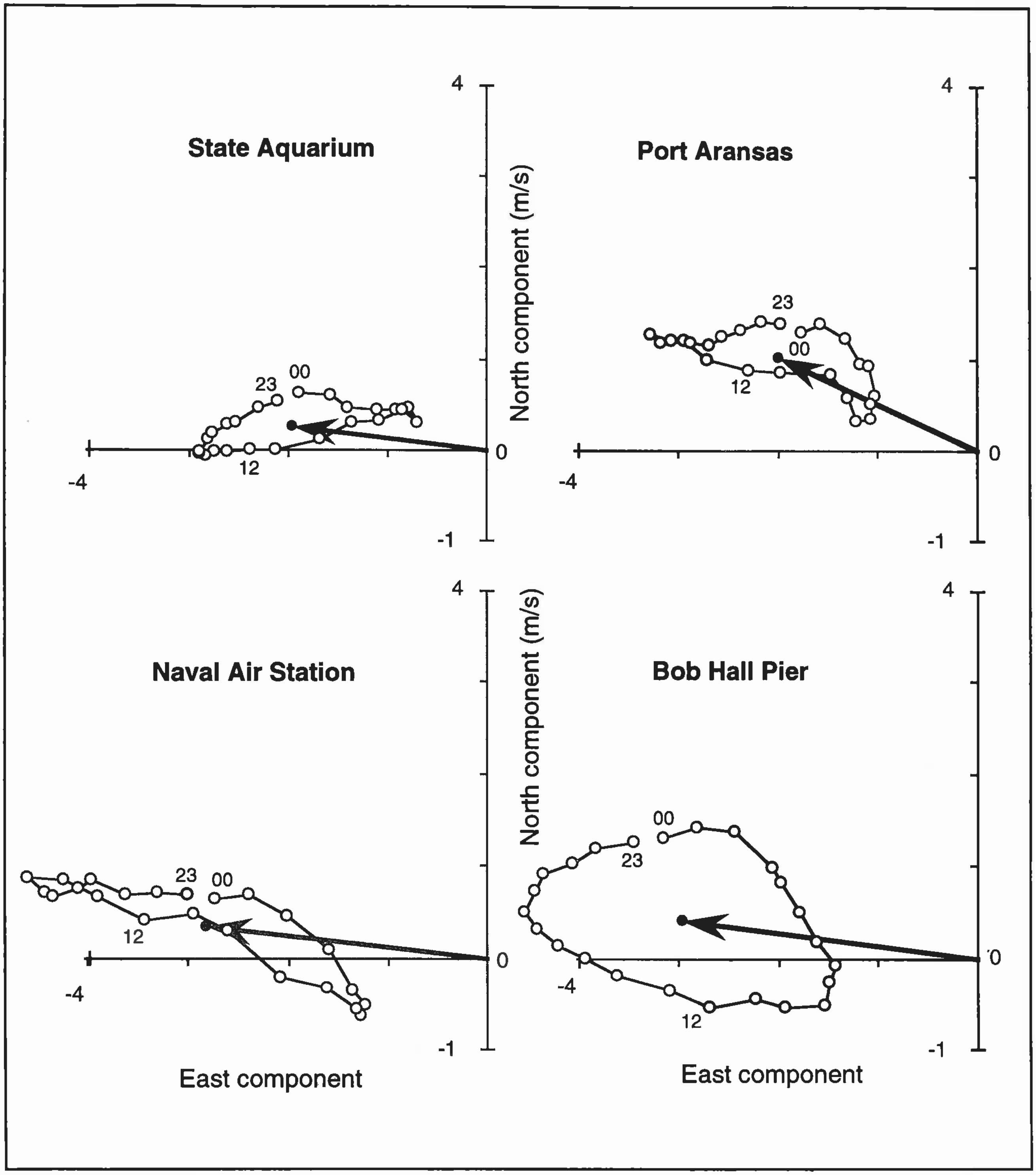


Figure 4-22. Averaged wind by hour May 1995 - April 1996 at CBI anemometer stations. Bold arrow indicates annual-mean wind.

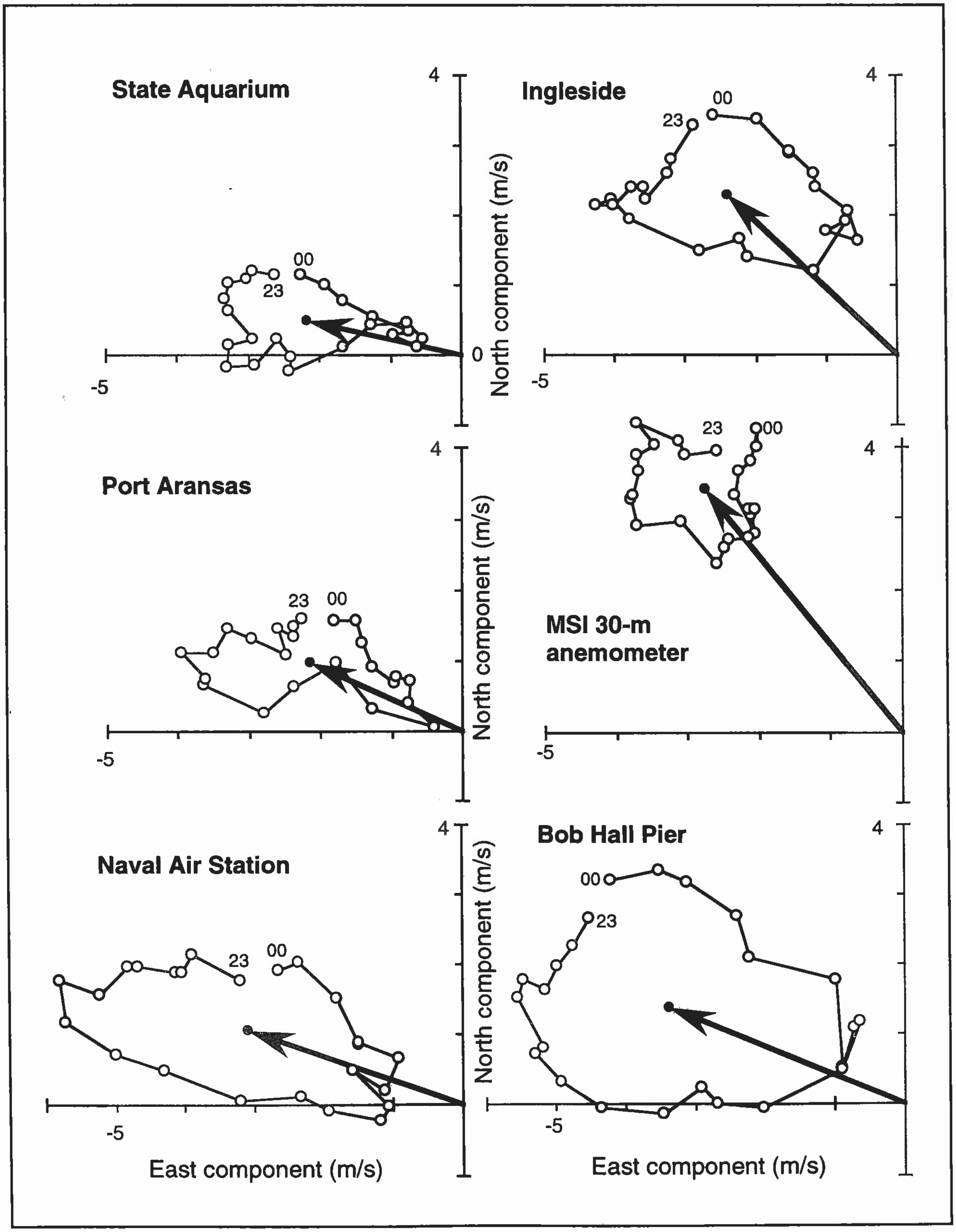


Figure 4-23. Averaged wind by hour August 1995 at CBI anemometer stations. (MSI 30-m data from August 1976.) Bold arrow indicates monthly-mean wind. Times are hours CST.

the underlying physics of the phenomenon. At the beachfront, the averaged amplitude of the seabreeze is great enough that the onshore flow is reduced to a near calm in the early morning hours.

Thus the Coastal Bend bays are subjected to a cyclical wind stress that has the capability for developing a circulation in the bay waters. Such a wind-driven variation would be an additional modulation of the response to the southeasterly wind stress. Judging from the magnitude of water-level responses to the much more dramatic wind variations in association with frontal passages, summarized in Section 4.4.4, we would expect to see any substantive effect only in special situations, e.g. in sections of the study area isolated from the other sources of water-level variability (tides, fronts) but more exposed to seabreeze influences. One such effect is manifested in the southern extreme of the Lower Laguna Madre.

Activate EXHIBIT2 and select Lower Laguna Madre (Option 5), with all default settings. Begin the display on Day 94180 (29 June). This is during the 1994 summer minimum, when water levels were especially low. Note first the more-or-less cyclical variation of the wind with maximum easterly component around 00Z (i.e., 18 CST) and minimum speed and most westerly component around 12Z (i.e., 06 CST). There is considerable irregularity in the hourly values of wind, but a general pattern of diurnal veering will become apparent and more pronounced as the display progresses. Now, examine the water-level variation at Yarborough Pass (the white trace). At the beginning of the display period, it appears tidal (cf. the NAS and Packery Channel traces, which are tidal), and one might note that the amplitude is much greater at Yarborough than at Bird Island farther up the Laguna. This would lead one to surmise (perhaps) that the source of the tide is elsewhere, perhaps propagating up the GIWW from the Lower Laguna. However, as the display evolves, it will be seen that the variations at NAS and Yarborough drift more and more in their time phasing, until by mid-July (94194, say) they are completely out-of-phase. At this point, the daily variation at Yarborough starting at 94180 again should be re-examined. It will be found that the period of this variation is not the 24.8-hr tidal cycle, but a pure 24-hr diurnal, with the daily low water occurring dependably at 00Z (18 CST).

This is clearly a seabreeze effect, but why it should be so dramatically manifest at this station is not altogether clear. It will be noted from EXHIBIT2 that the effect is greatest under low water conditions, especially with a southerly component of the wind (which further depresses the water level in this region). We speculate that this may be a response of Baffin Bay to the seabreeze component of the wind. Since the main axis of Baffin aligns perpendicular to the coast (and parallel to the seabreeze) and there are extensive shallow flats in the Baffin system which would afford additional storage, it may be especially responsive to a seabreeze component. If so, Baffin Bay would draw down the adjacent Laguna Madre during the afternoon onshore flow. Whatever the explanation, the Yarborough gauge offers an excellent example of seabreeze response in the system.

5. INTERTIDAL CIRCULATIONS

> The prevailing summer wind from the south-west [*sic*] is both healthy and agreeable, and tempers the warmth of July and August with its grateful and constant play. ... The strong "northers" set in about the month of November, and in December and January the cold north winds sweep down the plains with nearly as much regularity as the south-west wind in summer. ... The effect of these winds, in changing the depth of the tide-water of the bays, is singular, and applies to the whole line of coast.
>
> — Kennedy, *Texas,* 1841

On a time scale of weeks to months, major volumes of water can enter and exit the Coastal Bend bays. These longer-term exchanges and the associated internal circulations are referred to here as *intertidal*, by which is meant processes operating on a scale of many tidal cycles, in contrast to the *intratidal* scales treated in the preceding chapter. The actual instantaneous current velocities associated with these scales of motion are miniscule in comparison to the intratidal random turbulent currents; what is important is their persistence over time, which effects replacement and modification of water masses within the bays. The indices to this scale of process are the volume fluxes forced around the boundary of the system, and the response of water-mass tracers within the system.

5.1 Gulf of Mexico exchanges

The general tidal behavior of the Gulf of Mexico was summarized in Section 2.3.2 and the specific short-term tidal behavior of the study area bays was examined in detail in Section 4.3.2. In summary, the Gulf of Mexico tide contains several prominent frequencies, including longer term fortnightly and semi-annual periods. (The latter is apparently nonastronomical in origin, but appears in a standard tidal spectrum analysis if, as is usually the case, it includes annual and semi-annual periodicities.) The filtering properties of the inlets and the shallow bays greatly attenuate the shorter period frequencies, but pass the longer periods with virtually no attenuation. In particular, the cyclical variation from small lunar declination to great declination at 13.6 days, and the quasi-semi-annual secular rise and fall of water level in the Gulf represent a long term influx and efflux of water to the Coastal Bend bays. The associated exchanges of water were estimated from the TCOON data (see Section 4.1).

For this purpose, the 25-hour mean of water-level data from selected TCOON gauges was computed, to filter out most of the diurnal and semidiurnal variation. These averaged values were in turn subjected to a sliding 7-day average to better expose the fortnightly and longer-period variation. (Rigorously, a sliding 163-hr average should be applied to the original data. The computational effort is much greater, however, and experiments with the Ingleside record demonstrated that only a minor improvement in accuracy resulted, so this simpler approach was elected.) The sliding 27-day mean was then subtracted to remove longer-period variations. An example is shown in Fig. 5-1 of the 7-day mean water levels for Ingleside for 1994, and the associated water levels with the 27-day mean removed. The semifortnightly prism, i.e. the volume of water brought into the component bay on the semifortnightly rise, analogous to the tidal prism (see Section 4.3.2), was then computed. The statistics of the semifortnightly prism for the principal component bays are summarized in Table 5-1. Activate EXHIBIT2, select Area 1 (Aransas Pass inlet area), and begin the display at day 94160. This period begins with a large lunar declination, which by 94167 has declined to zero. There is not only a diminishment of the range of the tide, but also an increase in average elevation. It is the change in mean elevation that reflects the semifortnightly storage and evacuation of water from the system, shown in the averaged data of Fig. 5-1. Of course, meteorological processes, which have no correlation with astronomical tides, but also have a typical quasi-periodicity of several days, make a random contribution at this time scale. This in large part accounts for the range in semifortnightly prisms given in Table 5-1.

An even more dramatic demonstration of the variation in water level on the semifortnightly period is given by re-starting EXHIBIT2 at 95164. Lunar declination is reducing in absolute value to zero at 95171. Note the diminishment

Table 5-1
Average semifortnightly prism (10^6 m^3) in component bays computed from TCOON data (see text)

bay:	Corpus Christi	Aransas	Copano
gauge:	Ingleside	Rockport	Bayside
period used:	92149-96305	90253-96305	92095-95316
prism (Mm^3)	46.5	21.8	20.3
range: low	1.7	0.9	1.1
high	167.5	75.5	66.5
duration (d)	7.3	6.7	6.7
bay:	Nueces	Upper Laguna	System
gauge:	White Point	Bird Island	(total)
period used:	93083-96305	93112-96353	
prism (Mm^3):	5.7	23.6	117.8
range: low	0.5	0.2	
high	26.2	96.8	
duration (d)	5.8	7.5	

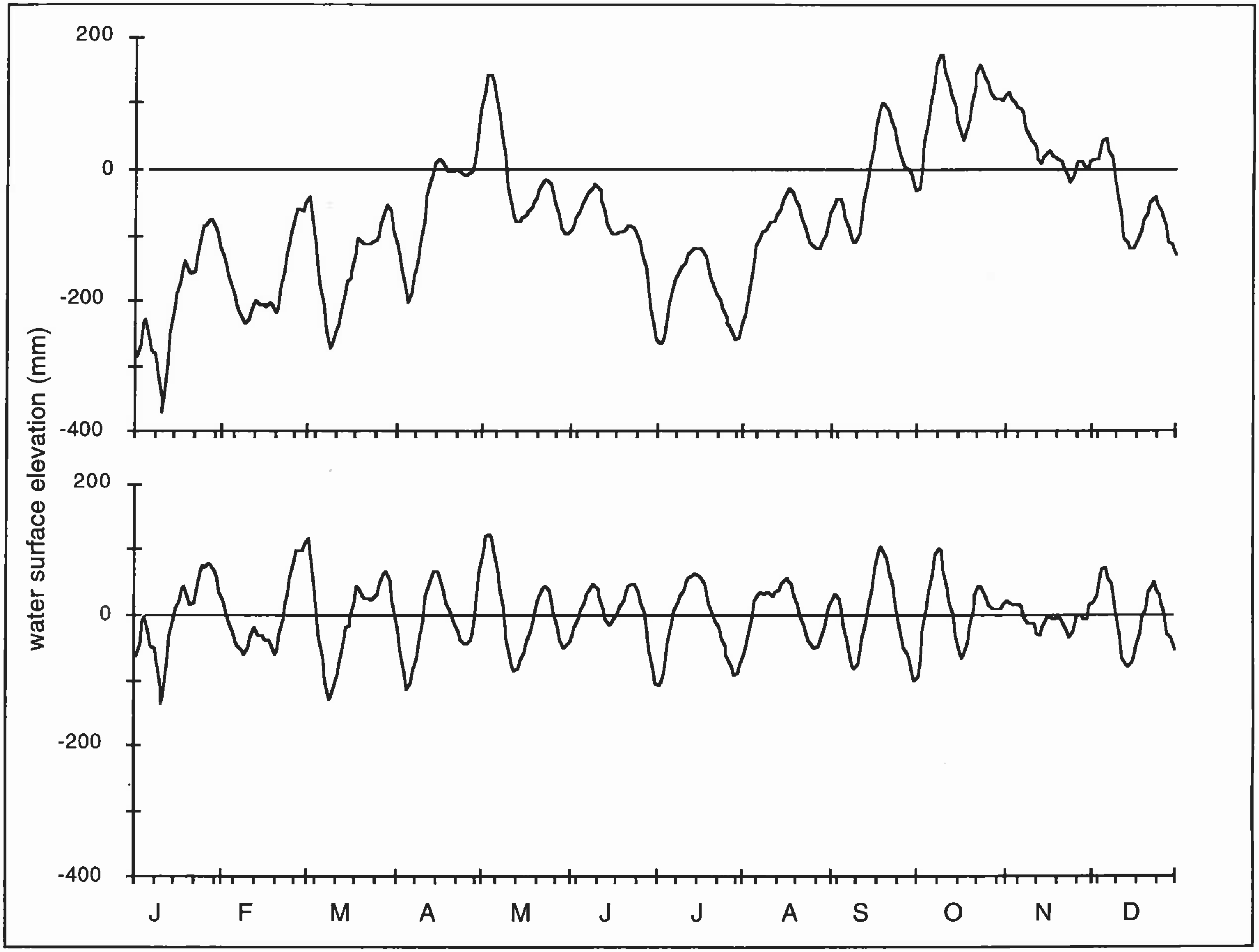


Figure 5-1. Tidal record for 1994 at Ingleside (consistent datum) after 7-day sliding average, above, and with 27-day mean removed, below.

in tidal range as well as the elevation in mean water level, which subsides as declination increases to its maximum positive value over the next seven days. The rise in water level during this cycle is, in fact, too large to be solely attributable to astronomical influences, but it is not apparent what other causative agent is at work.

The secular seasonal variation in the Gulf was addressed in Section 2.3.2 above, see especially Fig. 2-14. The following observations summarize the features of the secular variation, but we note that the period of record (about five years) is short compared to the "period" of the signal and therefore some of these are tentative:

- There are considerable year-to-year differences in the seasonal water-level variation.
- The fall maximum is usually the highest mean water elevation of the year, and the winter minimum is usually the lowest.
- The summer minimum in July and the fall maximum in October are the most consistent in terms of seasonal regularity.
- Both the winter and spring extrema have a considerable seasonal range in which they occur, December to March for the former and April through June for the latter, and can exhibit multiple extrema during these periods.
- Despite reference to its semiannual "period," this is not a harmonic signal. Both the fall maximum and the summer minimum, especially the former, tend to be more sharply focused in time, extending over two-six weeks in duration.

In the second property above, "mean" refers to an averaging period sufficiently long to eliminate the lunar tidal variations, which therefore has to be at least 14 days. The last property above renders many of the usual explanations for the phenomenon suspect, especially those based on meteorology, since these would imply a much longer time period over which the rise and fall of water level would take place.

The 27-day sliding-mean daily values were used as the basic data base for estimating the semiannual prisms: the spring rise from the winter minimum to the spring maximum is the spring prism, and the fall rise from summer minimum to fall maximum is the fall prism. The individual computed values and their averages (treating spring and fall prisms separately) are tabulated in Table 5-2. Both the water level rise (Δh) and the associated volume influx are given in the table, as well as the date of the maximum water level. The date of the fall maximum is evidently much more consistent from year to year than that of the spring maximum. Only a lower bound on the total system influx in 1996 (indicated by "<") can be computed, because there is no record at Bayside. Also, the minimum elevations at White Point are corrupted by the fact that this gauge pegs, so the Nueces prism volumes are also, at best, lower bounds on the actual influx. The 27-day averaged signal for Rockport and Ingleside are plotted in Fig. 5-2, to display the year-to-year variation in high and low water stands. The other gauges track these, so are omitted to simplify the figure. The differences between

Table 5-2
Secular seasonal prisms, computed from rise of seasonal maxima, in 10^6 m^3, for principal component bays, from TCOON data (see text)

year	***season***	***day***	***Δh (mm)***	***vol (Mm³)***	***day***	***Δh (mm)***	***vol (Mm³)***	***day***	***Δh (mm)***	***vol (Mm³)***
bay (gauge):		*Corpus Christi (Ingleside)*			*Aransas (Rockport)*			*Copano (Bayside)*		
91	*spring*				140	398	87.1			
	fall				268	242	53.1			
92	*spring*				151	171	37.5	151	100	19.5
	fall	284	316	137.6	284	284	62.3	284	271	52.9
93	*spring*	168	199	86.5	169	249	54.6	169	282	55.1
	fall	287	243	105.9	287	236	51.7	286	216	42.0
94	*spring*	112	273	118.9	113	303	66.4	112	334	65.1
	fall	288	301	131.1	288	297	65.1	288	263	51.3
95	*spring*	100	386	167.9	101	412	90.2	139	412	80.3
	fall	279	401	174.2	280	377	82.6	280	351	68.4
96	*spring*	143	169	73.4	143	220	48.2			
	fall	290	434	188.7	290	417	91.3			
average:	*spring*	131	257	111.7	136	292	64.0	143	282	55.0
	fall	286	339	147.5	283	309	67.7	285	275	53.6
bay (gauge)		*Nueces (White Point)*			*Upper Laguna (Bird Island)*			*Total system*		
93	*spring*									
	fall	286	182	12.7	291	267	68.7			280.9
94	*spring*	113	258	18.1	116	222	57.0			325.6
	fall	288	216	15.1	291	383	98.5			360.9
95	*spring*	138	323	22.6	102	362	92.9			453.9
	fall	280	331	23.2	280	441	113.3			461.7
96	*spring*	141	189	13.2	101	104	26.8			>161.5
	fall	290	372	26.0	291	461	118.5			>424.4
average:	*spring*	131	257	18.0	106	229	58.9			>313.7
	fall	286	275	19.2	288	388	99.7			>382.0

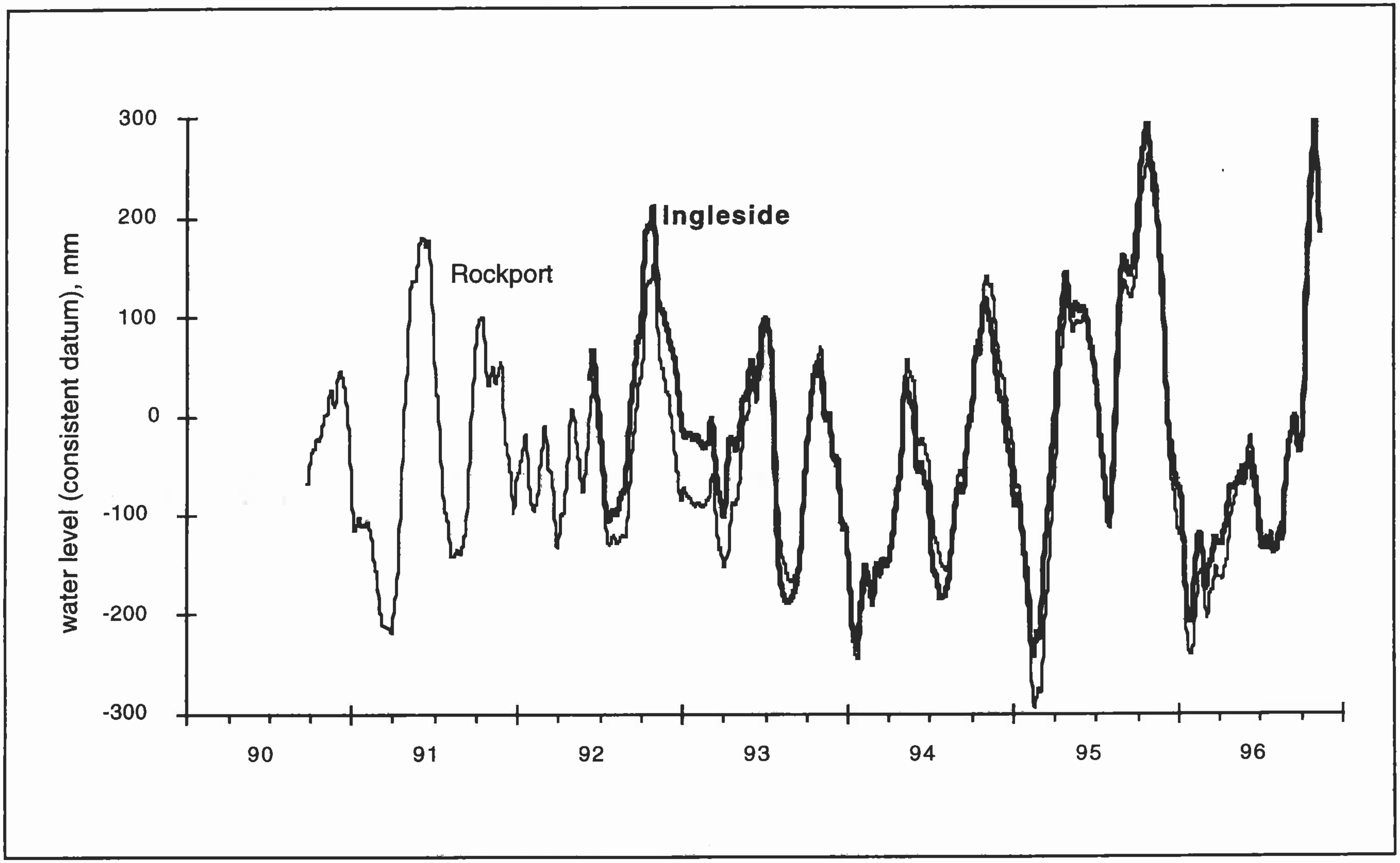


Figure 5-2. Water-level variation, 27-day sliding mean of leveled date, showing secular variation for period 1990-96

this figure and Fig. 2-14 given earlier to introduce the secular seasonal variation are: (1) these data have been reconciled to a common datum, whereas the data of Fig. 2-14 are relative to the individual gauge datums; (2) these data are smoother, having been subjected to a 27-day sliding average, compared to the 14-day means of Fig. 2-14.

From this figure, the highest high-water stands, at least since 1990, have been the fall maxima in the last two years, 1995 and 1996, see Figs. 5-3 and 5-4. One might wonder whether there are any obvious explanations for these unusual events. By activating EXHIBIT2, selecting Area 1 (Aransas Pass inlet area) and starting at 95265, one can watch the 1995 event develop. In examining the hourly water-level behavior, one must be aware of the differences between these data and the long-term average data from which the elevation and dates of seasonal maxima are determined. These are illustrated for the 1995 high water in Fig. 5-3. The seasonal maxima of Table 5-2 are based on the 27-day (nodical) means, which eliminate the shorter period tidal and semifortnightly variations (as well as shorter period meteorological responses). The actual hourly values are the sum of these, so there are instantaneous water elevations that exceed the "seasonal high." In fact, the highest water level attained in this 1995 period was on day 303, three weeks after the exact seasonal maximum, due to the great declination high tide on this date combined with the elevated water levels. Water levels begin to increase on 95267. During this period there are several minor frontal passages, for instance on 24 (95268) and 30 (95274) September, 5 (95279), 11 (95284) and 19 (95293) October, apparent in the wind shifts. Both of the high water events, of 95274-6 and 95302-4, coincide with a large declination and lunar perigee, as well as strong easterly wind components.

The October 1996 high-water event received considerable media attention due to the fact that it was accompanied by high wind and waves, leading to closure of ocean beaches, Bob Hall Pier and other shore facilities. Part of the JFK Causeway was submerged, and at one point traffic was constrained to a single lane. All of this occurred coincident with Tropical Storm Josephine in the Gulf of Mexico, and the tropical storm was widely blamed for the high water (e.g. Donaghue, 1996, Grant, 1996). Josephine began as 1996 Depression Ten, a region of poorly organized convection with multiple centers east of Tampico. The National Hurricane Center advisory of Sunday morning 6 October located it 330 km (180 n.m.) due east from Brownsville (NHC, 1996), and reported maximum winds of 55 km/hr (30 knots). This was the closest it came to the Texas coast. It dissipated, reformed over 150 km to the east that afternoon, then tracked northeastward over the next 24 hours. It was upgraded to a tropical storm that night, and made landfall near Pensacola on Monday afternoon 7 October. If Josephine could render such impacts as a minimal depression 400 km from the Corpus Christi area, one might wonder why even more dramatic high-water and wave damage did not result from Tropical Storms Dean and Gabrielle in August 1995, both being much more intense and closer to the study area (landfalling near Galveston and north of Tampico, respectively). Or, for that matter, Tropical Storm Arlene in June 1993 which made landfall in the Baffin Bay area. Or, for that matter, the

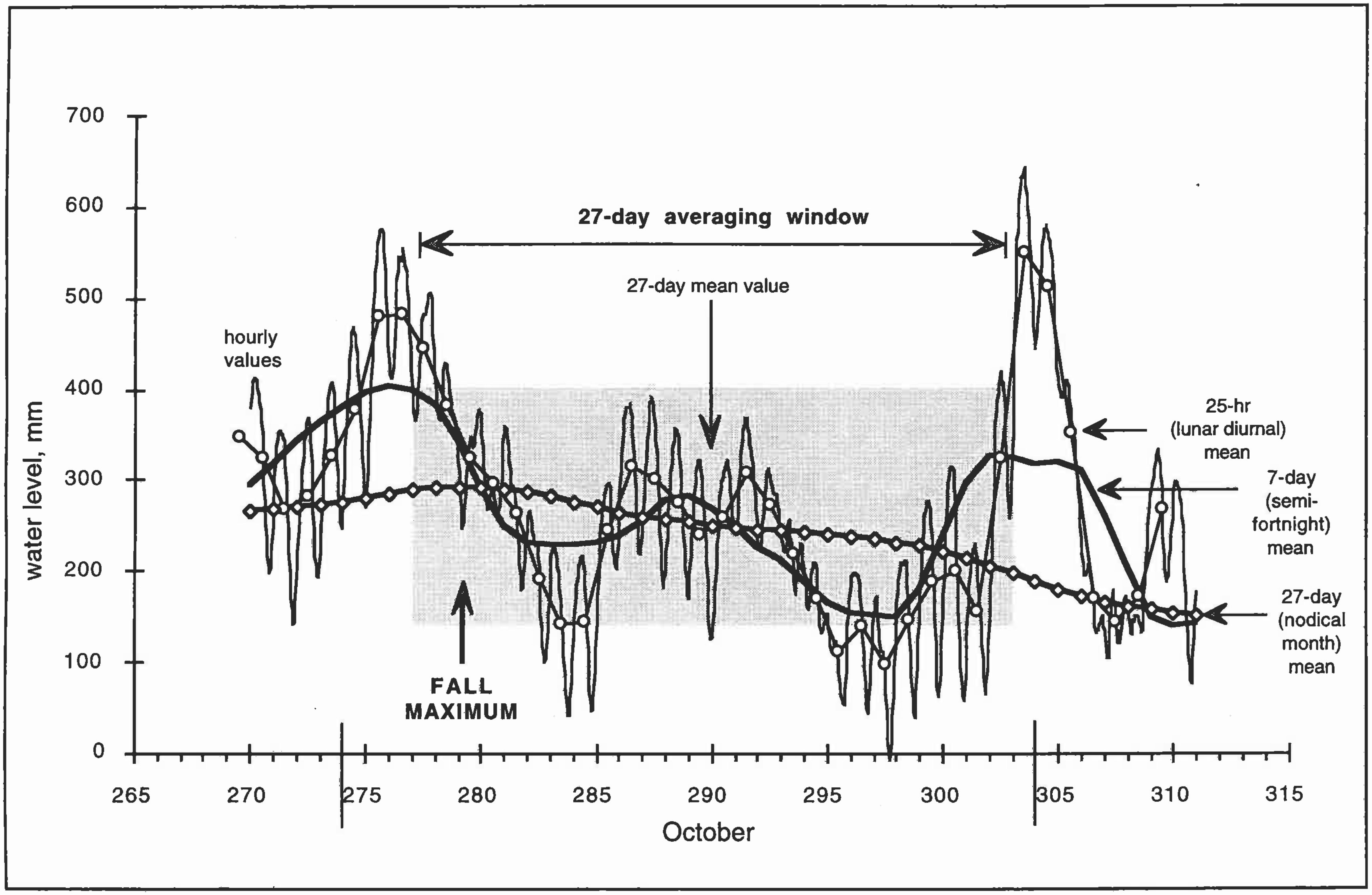


Figure 5-3. Fall 1995 water-level maximum at Ingleside depicted in four different time resolutions

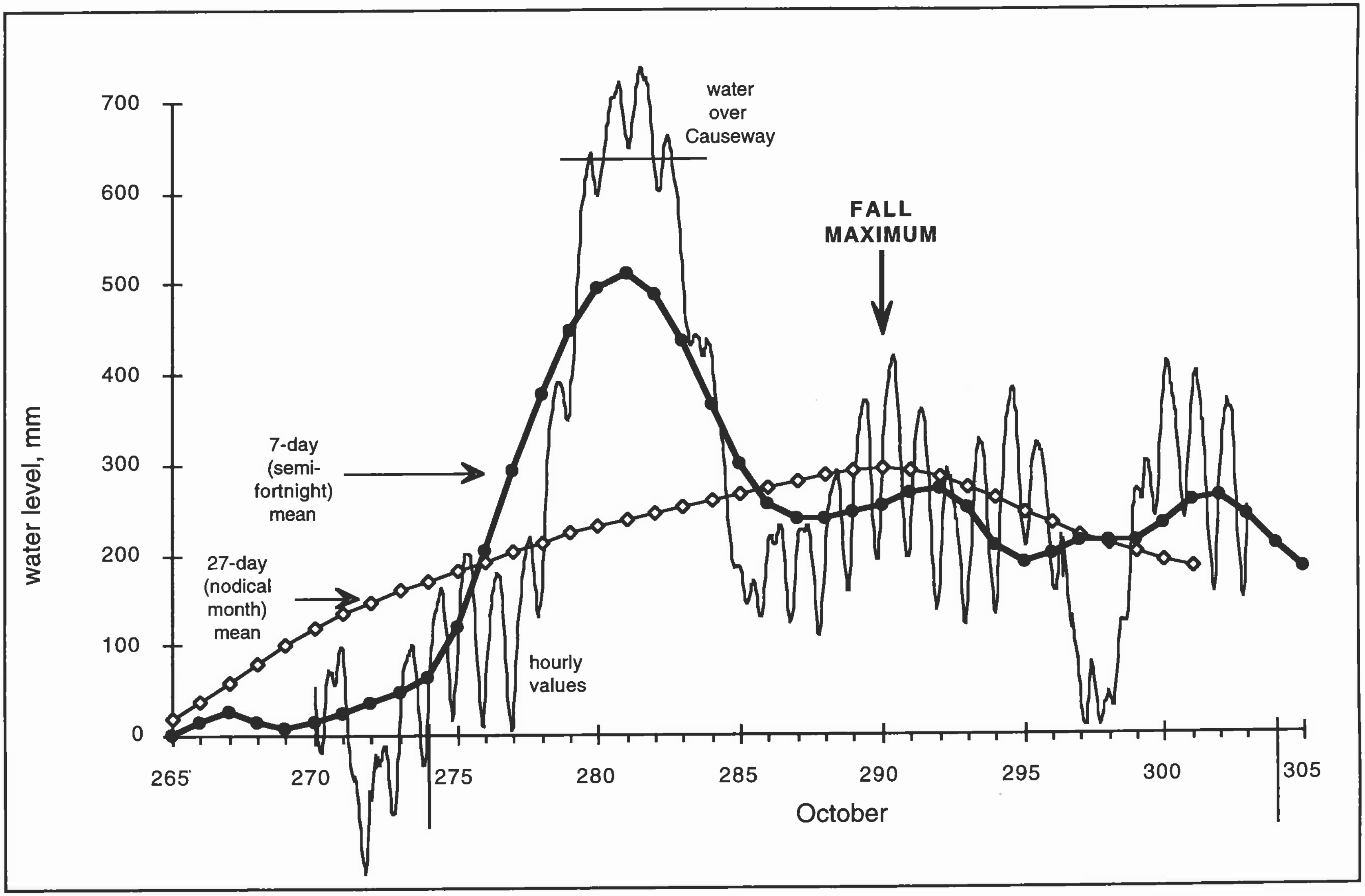


Figure 5-4. Fall 1996 water-level maximum as recorded at TCOON Ingleside gauge

considerably more powerful Tropical Storm/Hurricane Jerry in October 1989 whose formation and movement were similar to Josephine until Jerry turned to the northwest toward Galveston.

It would appear that the 1996 event resulted from a juxtaposition of three factors. First and foremost was the October seasonal water-level maximum. Second was a great-declination tide. Third was an energetic frontal passage on 28 September resulting from an unseasonably strong high-pressure system over the midwest. This front had the features of a polar-outbreak system, despite the earliness of the season. Winds were sustained from the north, veering slowly to the northeast by 3 October, and strengthening even more on 4 October. These northeast winds did not release until 8 October. During this period, the entire northern Gulf of Mexico was dominated by strong winds from the north quadrant due to this particularly strong high-pressure center, by then positioned over the eastern U.S. These winds had nothing to do with the tropical storm. Northeasterly winds usually do not provoke dramatic hydrographic responses (which can be verified by following EXHIBIT3 through the fall-winter season). It is the involvement of the Gulf of Mexico from Texas to Alabama, as well as the time sequence of development, that permitted the extreme hydrographic impacts of this system, in that the northeasterly winds seemed to develop from the northern coast and spread southward into the study area (rather than the reverse). Of course, such systems are more likely to occur in winter when water levels are much lower and coastal structures are not so exposed to the effects of waves and high water.

Activate EXHIBIT2, select Area 1 (Aransas Pass inlet area), and start the display at 96265. For the first several days, winds are light and generally onshore. They begin strengthening on 26 September (96270) in advance of the approaching front. Note that the water levels are stable and predominantly tidal until 27 September (96271) when a marked set-up from Port Aransas to Rockport develops under these freshening southerlies. The frontal passage occurs 00Z 28 September (96272), with strong northerlies and immediate water-level responses in the bay. By 3 October (96277) the winds have veered to the northeast; average water levels have drifted upward during this period, no doubt due to the seasonal increase. Under the continued strong northeasterlies the water level in the Gulf begins to climb on 4 October (96278). This, it should be noted, is before the formation of Depression Ten. We also observe that the high water in the Gulf on 5 October (96279) coincides with large lunar declination, but the sun and moon are in exact quadrature (270°) and the moon is very nearly at apogee. Early on 7 October (96281), the north winds begin to diminish and there is no further increase in elevation. By 8 October (96282) the winds have released, and the superelevated Gulf waters begin to decline.

Now re-activate EXHIBIT2, select Area 5 (Upper Laguna Madre) and the same starting date of 96265. Note the dramatic water-level response in the Upper Laguna to the frontal passage (96272). As the water levels build under the increasing northeasterly winds, the Laguna lags by 1-2 days after the rise in the adjacent Corpus Christi Bay, clearly a result of the limited hydraulic capacity of the inlets in the Causeway. As the water levels subside, the Laguna lags so much that its water levels exceed Corpus Christi Bay for three days (96284-6). The same event should be followed using EXHIBIT3, which better depicts the gradient responses of the water surface, especially Area 3 (Corpus Christi Bay).

Detailed analysis of this event was beyond the scope of the present study, but this superficial treatment would indicate that the strong northeasterlies blowing over the long fetch from Louisiana, and the accompanying response of the Gulf of Mexico, in conjunction with the fall water-level maximum, are the true factors that made the 1996 high-water event memorable.

5.2 Freshwater inflows

One of the principal influxes of water to the study area bays is that carried by the rivers and tributaries. It is this freshwater inflow that is ultimately responsible for the estuarine character of the bays, and is generally considered to be an important control on the productivity of the system. The principal direct riverine inflow to the Coastal Bend bays is the Nueces River. (The key word is "direct" because an important indirect riverine inflow is the combined inflow of the San Antonio and Guadalupe Rivers, which does not enter the study area *per se*, but debouches into the next bay to the north, San Antonio Bay.) The watershed-scale freshwater inflows into the study area and their general hydroclimatology are considered first, then more detailed analysis of the Nueces is provided.

5.2.1 Coastal Bend watersheds

In addition to the Nueces River, there are several smaller rivers such as the Mission and Aransas Rivers, and numerous minor tributaries which drain the watershed of the study area and can be locally important as freshwater sources. These include Copano Creek, Oso Creek, Olmos Creek, San Fernando Creek, and Petronila Creek. There is free communication through Ayres-Carlos-Mesquite Bays between San Antonio Bay, into which flow the Guadalupe and San Antonio Rivers, and the Aransas-Copano system. The salinity analyses of Ward and Armstrong (1997a) indicate that on a long-term basis this inflow has an effect on salinities in the upper part of the study area.

The flow of the Nueces River is important to the hydrography of the main body of Corpus Christi Bay, and the variation of this river is central to the overall effect of inflow on the bay system (see TDWR, 1981). The Nueces is also the only riverine source for which an accurate history of gauge measurements exists. (Some of the other tributaries to the system, such as Oso Creek and the Mission River, are also gauged, but the proportion of their total watershed that is gauged is much lower than that for the Nueces.) Thus one problem in analyzing freshwater inflows to the overall system is the lack of measured streamflow.

The work of a companion CCBNEP project, the Freshwater Inflow Status and Trends Study performed by the U.S. Geological Survey (Mosier et al., 1995), provided the basic data on inflow from the ungauged watersheds. USGS subdivided the watershed of the CCBNEP study area into seventeen distinct subwatersheds. For each of these, the HSPF model (essentially the Stanford Watershed Model, e.g., Singh, 1989) was applied. This is a numerical runoff computation utilizing inputs of soils, land use, precipitation, wind and air temperature to compute a complete surface water budget, from which daily streamflow in the drainage channel is calculated. USGS then combined these subwatersheds into watershed totals for component bays of the study area, as listed in Table 5-3. The simulated ("synthetic") inflow from these six component watersheds together with the gauged flow in the Nueces at Mathis are considered to comprise the total inflow to the CCBNEP Study Area. (No accounting is made for runoff from the barrier islands to the bay, and the watershed draining into the south shoreline of Baffin Bay is not addressed. Neither of these are considered to be of importance to the overall freshwater inflow to the system. Also no explicit consideration is given to the freshwater inflow entering Aransas Bay from the San Antonio system.) USGS provided digital copies of the simulated daily flows for each of these component watersheds to this project. The reader is referred to the USGS report Mosier et al. (1995) for detailed information on application of the watershed model and analysis of the simulated data.

River flow in the Texas climate is governed by surface runoff derived from storm systems, see Section 2.2.1. This means the rivers are "flashy", exhibiting large, sudden excursions in flow. The daily flow of the Nueces, as a case in point, spans four orders of magnitude. One would therefore expect a seasonal variation, correlated with the climatological pattern of precipitation. Flows on the upper

Table 5-3
Watershed drainages and 1968-93 runoff
for freshwater inflow accounting of Corpus Christi Bay study area

watershed	*drainage area*		*runoff*
	10^3 ac	*km^2*	*10^{-3} ft/yr*
St. Charles Bay	131	530	577
Copano Bay	1336	5407	496
Redfish Bay	22	89	521
Corpus Christi Bay*	388	1570	370
Upper Laguna	39	158	110
Baffin Bay	1900	7689	56
Nueces River (gauge at Mathis)	10660	43140	48
Total	14476	58583	105

* including the ungauged Nueces watershed downstream from Mathis

Texas coast, e.g. the Trinity River (see Ward and Armstrong, 1992), have a predominant pattern of an annual "flood" and an annual "drought," the flood being the spring freshet, which typically occurs in April and May, and the drought is the summer low-flow season typically extending from July through October. With distance down the Texas coast, the spring freshet diminishes in importance, due to the increasing rainshadow effect in combination with reduced southward penetration by midlatitude disturbances. But a fall maximum, originating from tropical processes, such as the interplay of Gulf windflow with subtropical disturbances and from landfalling tropical depressions, becomes increasingly important with distance south.

This is illustrated by the patterns of inflow in the Nueces River. Figure 5-5 shows the daily flow of the Nueces at Mathis averaged over the 26-year period 1968-1993. This period was employed because it corresponds to the period used by USGS for generating synthetic inflow hydrographs from the component watersheds; it is also sufficiently long to encompass a range of variation in the controlling parameters. Figure 5-5 shows the degree of smoothing achieved by longer averaging windows. On a daily basis there is little year-to-year consistency, because the occurrence of quickflow spikes within a given season is more-or-less random, and therefore the 26-year means of daily flows are clearly influenced by individual spikes of inflow occurring randomly in the data record. When the daily flow record is further smoothed by a sliding 11-day window centered on a given day, the spikes are diminished, see the broken trace of Fig. 5-5, but the record is still subject to random surges. For most of the analyses of this study, we employed a monthly averaging period. In Fig. 5-5, the basic bimodal character of the seasonal Nueces inflow is apparent in the late spring and early fall maxima. The spring freshet is, on average, more important than the fall freshet, in terms of volume of flow delivered to the system. The precipitation at Uvalde (Fig. 2-5) is consistent with this pattern, this precipitation station being more indicative of the Nueces Basin above Mathis than the stations located nearer the coast.

Additional features of the monthly averaged inflow record of the Nueces are shown in Fig. 5-6. In Fig. 5-6(a), the study analysis period of 1968-1993 is compared to the longer gauge period of record of 1939-93. Despite the fact that the latter includes the 1964 drought of record and the extended drought of the 1950's, the mean annual monthly pattern is quite comparable to the 1968-93 study period. The variability of the Nueces is extreme even at a monthly averaging level, as evidenced by the standard deviation of the monthly means, shown by the vertical bars of Fig. 5-6 (a). Of course, negative values of monthly mean flow do not occur. The fact that the standard deviations extend into negative values indicates the skew in the data record toward more frequent occurrences of low monthly flows. As the monthly flow increases, so does the variance in the data record, as demonstrated by the plot of standard deviation versus monthly mean flow of Fig. 5-6 (b). This means that the coefficient of variation is fairly constant for the Nueces monthly data, and is high, about 175%.

Table 5-4 presents the monthly mean and mean annual inflows for each of the component watersheds for the CCBNEP Study Area, including the gauged

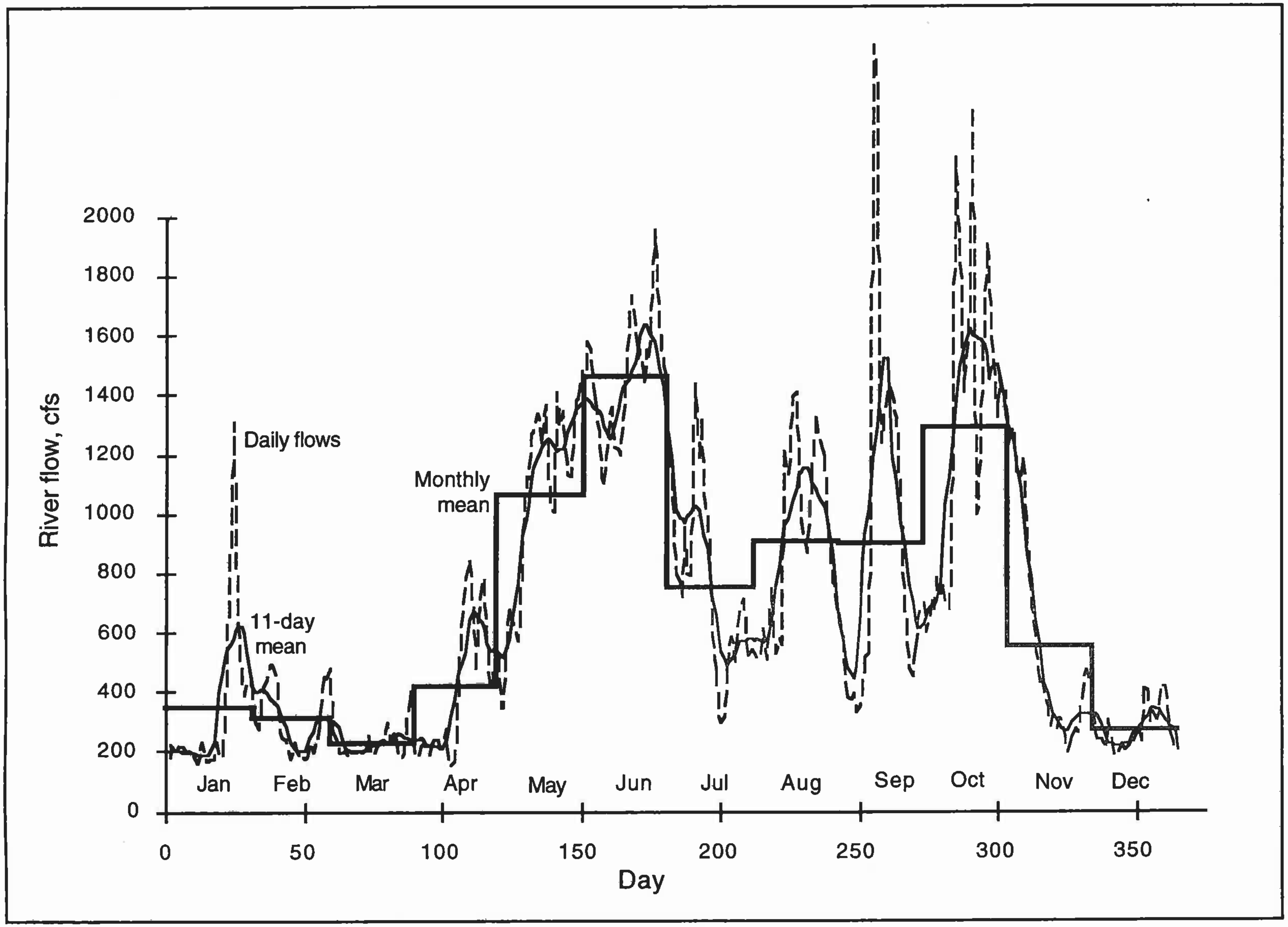
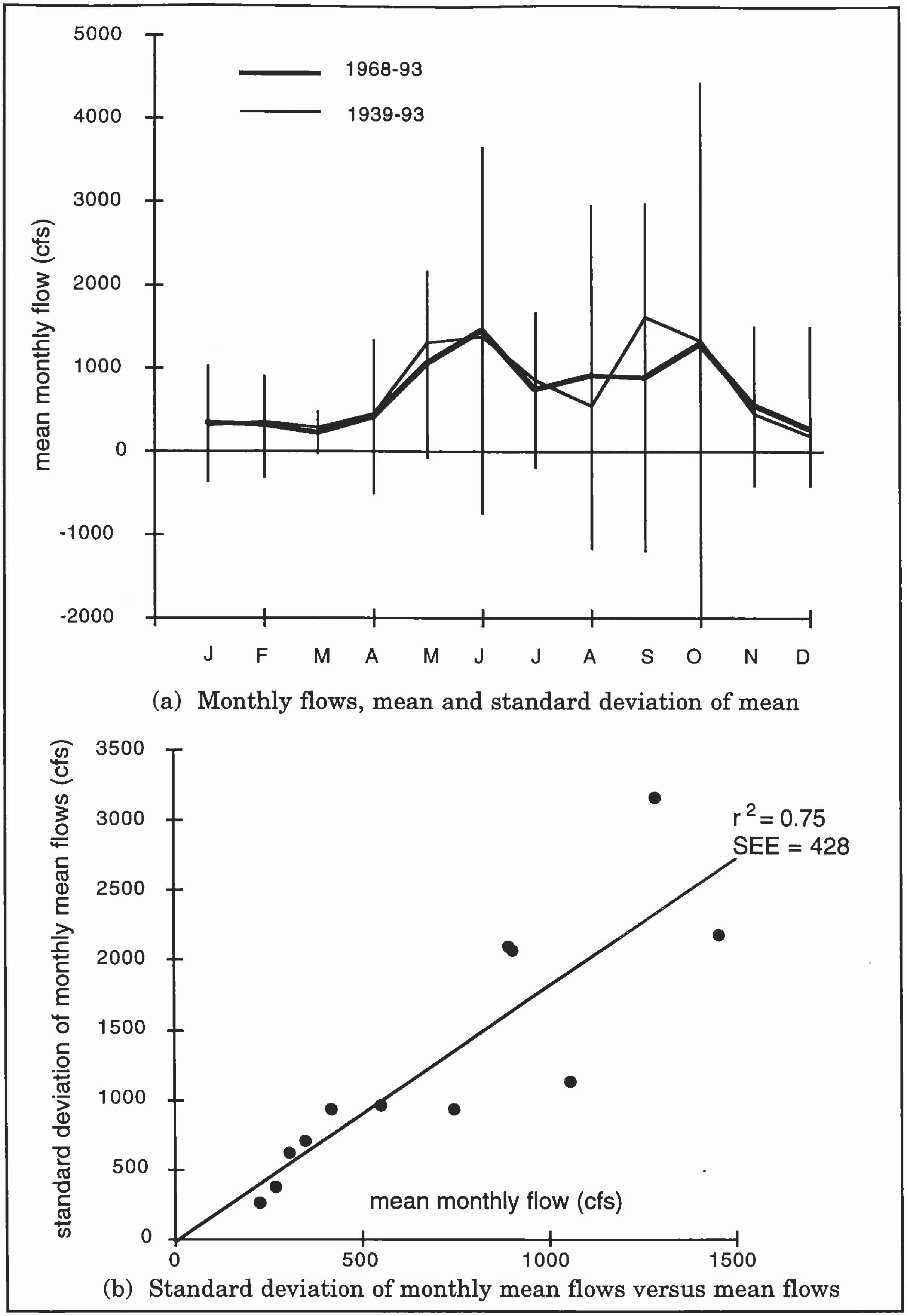


Figure 5-5. Nueces at Mathis, 1968-93, averaged daily flow and longer-period averages



(a) Monthly flows, mean and standard deviation of mean

(b) Standard deviation of monthly mean flows versus mean flows

Figure 5-6. Nueces at Mathis, monthly mean flows

Table 5-4

Monthly mean flows (cfs) for principal component watersheds in CCBNEP study area (1968-93)

	Baffin	*Upper Laguna*	*Corpus Christi*	*Nueces River**	*Redfish*	*Copano*	*St. Charles*	*Total*
J	141	4	150	347	15	791	113	1561
F	193	6	166	308	14	905	171	1763
M	46	4	95	227	9	441	66	888
A	29	2	80	419	9	279	29	847
M	73	5	180	1061	18	695	69	2101
J	242	12	338	1459	18	1513	97	3679
J	114	5	223	749	14	992	100	2197
A	108	6	169	905	13	479	40	1720
S	296	9	468	895	33	1988	224	3913
O	371	11	278	1288	21	1475	98	3542
N	76	4	124	551	13	690	118	1576
D	71	3	110	268	13	741	128	1334

Annual average flows

Baffin	*Upper Laguna*	*Corpus Christi*	*Nueces River**	*Redfish*	*Copano*	*St. Charles*	*Total*
147	6	198	706	16	916	104	2093
Runoff from watershed (10^{-3} ft/yr)							
56	110	370	48	521	496	577	
Fraction (percent) of total inflow to Study Area							
7	0	9	34	1	44	5	100
Fractions (percent) after correction for diversions and return flows							
7	0	10	31	1	46	5	

* At Mathis gauge, uncorrected for diversions and return flows

watershed of the Nueces. These same monthly flows are depicted graphically in Fig. 5-7 and 5-8, the former by individual watersheds and the latter by accumulated inflow from south to north. The application and interpretation of gauged flows of the Nueces are distorted somewhat by the water-supply operation of Lake Corpus Christi, especially at low flows. Since the river channel is the means of conveyance, the gauged flow at Mathis includes the releases earmarked for withdrawal from the river at Calallen, and therefore some of this flow will not enter Corpus Christi Bay other than by return flows. The USGS (Mosier et al., 1995) compiled TNRCC records of diversions and return flows, and addressed this aspect of bay hydrology. For present purposes, the data compiled by USGS was used to estimate a *net* reduction in inflow to the bay averaging about 83 cfs (i.e., average diversions less return flows). The 706 cfs average *gauged* flow in the Nueces in Table 5-4 represents about 623 cfs *net* inflow to Corpus Christi Bay.

The most important aspect of the year-to-year variation in annual discharge is how that is manifested in the occurrences of high flows. That is, the freshet is the central feature of the annual hydrograph. Some years exhibit a pronounced and extended freshet, while in other years freshets may be totally absent. Correspondingly, in some years the summer low-flow season may be shortened or even eliminated by unusual runoff, and in other years may be prolonged while the flows dwindle to nothing. To exhibit quantitatively the hydrologic behavior of inflows, the monthly-mean flow record for the 1968-93 period was analyzed for each of the component watersheds from the USGS simulations and the gauged flow of the Nueces. Figure 5-9 and Table 5-5 exhibit the annual inflow for each of the component watersheds over this period. As an approximate index to freshet behavior, it was postulated that a two-month sequence would capture the freshet in each of the watersheds, so for each year the highest two-month inflow was determined. This two-month average is also tabulated in Table 5-5. It is remarkable that for most of the inflow to the Study Area, these two months average half of the annual inflow, as shown in Table 5-5 and Fig. 5-10. The two-month average inflow for this maximal two-month sequence and the month in which it began are graphed in Figs. 5-11 and 5-12.

Several observations are noted from these analyses:

(1) The two most prolific sources of inflow are Copano Bay and the Nueces River, in that order. Corpus Christi Bay is a distant third. The small watersheds of Redfish Bay and the Upper Laguna render their inflows of negligible importance. However, there is considerable year-to-year variation in the magnitude and order of the annual inflow. The highest inflow of the 1968-93 period occurred in 1971.

(2) According to the results of the USGS HSPF simulation, the gauged flow of the Nueces comprises on average about 80% of the total flow to Corpus Christi Bay *per se* (i.e., the sum of the gauged flow at Mathis and the Corpus Christi ungauged watershed, which includes the Nueces ungauged). Especially during drought periods, the Nueces falls to about or even below 50%, see Fig. 5-9. (When the gauged Nueces flow is reduced to account for the diversion at Calallen, the Nueces is seen to represent in fact about 75% of the total inflow to Corpus Christi Bay.)

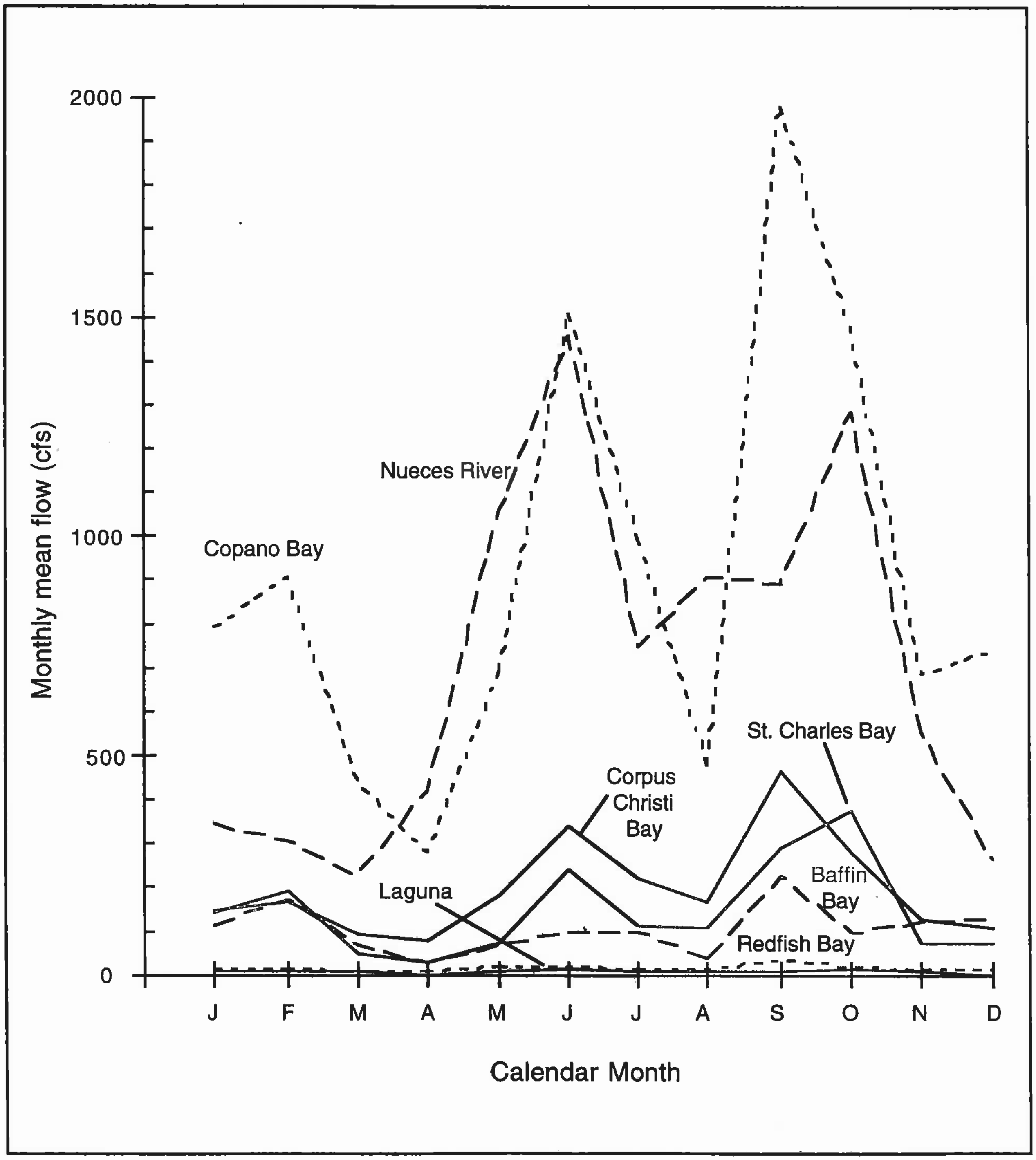


Figure 5-7. Monthly mean inflows (1968-93) for principal watersheds draining into Corpus Christi Bay Study Area

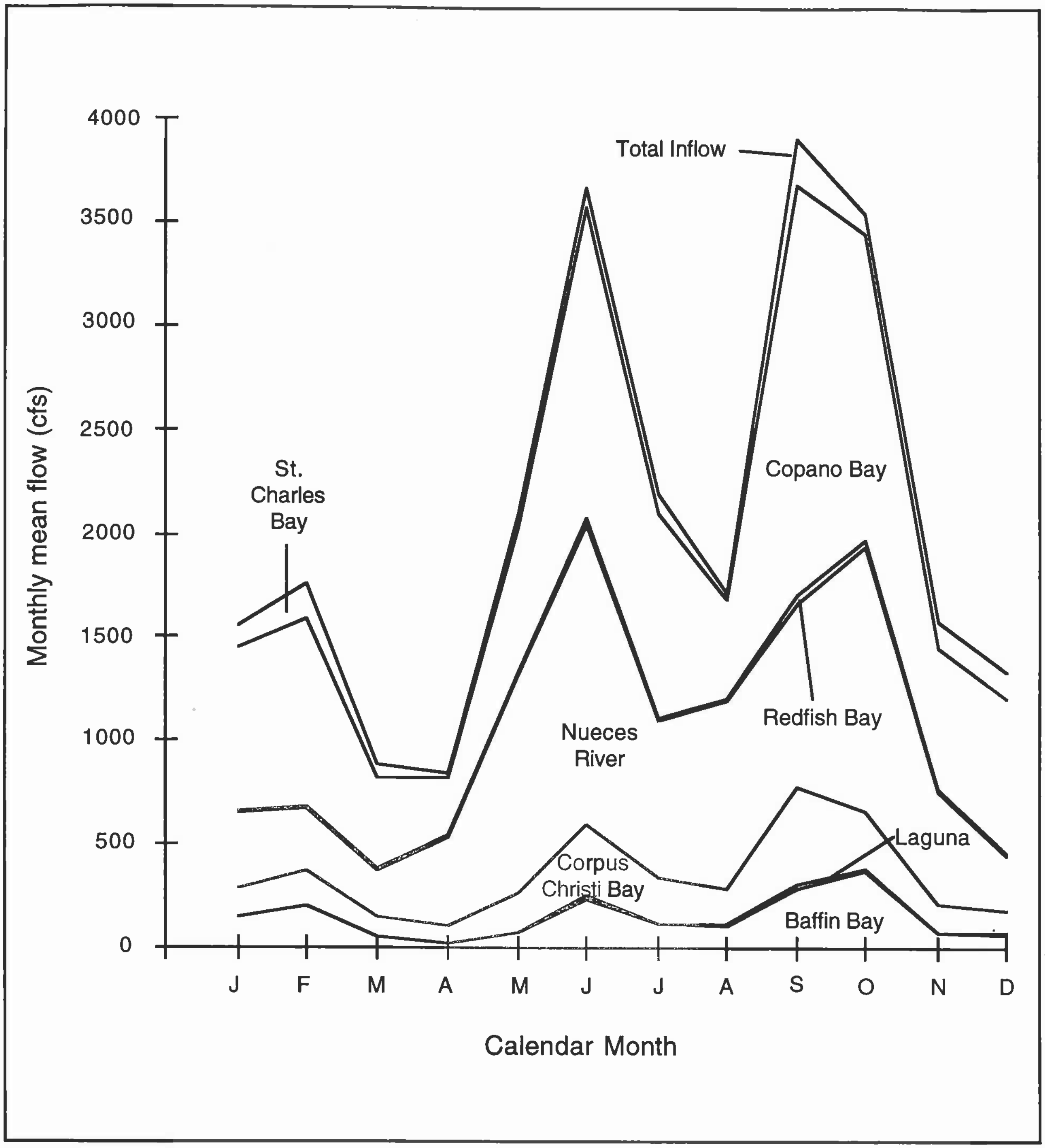


Figure 5-8. Monthly-mean inflows (1968-93) for principal watersheds draining into Corpus Christi Bay Study Area, accumulated from south to north.

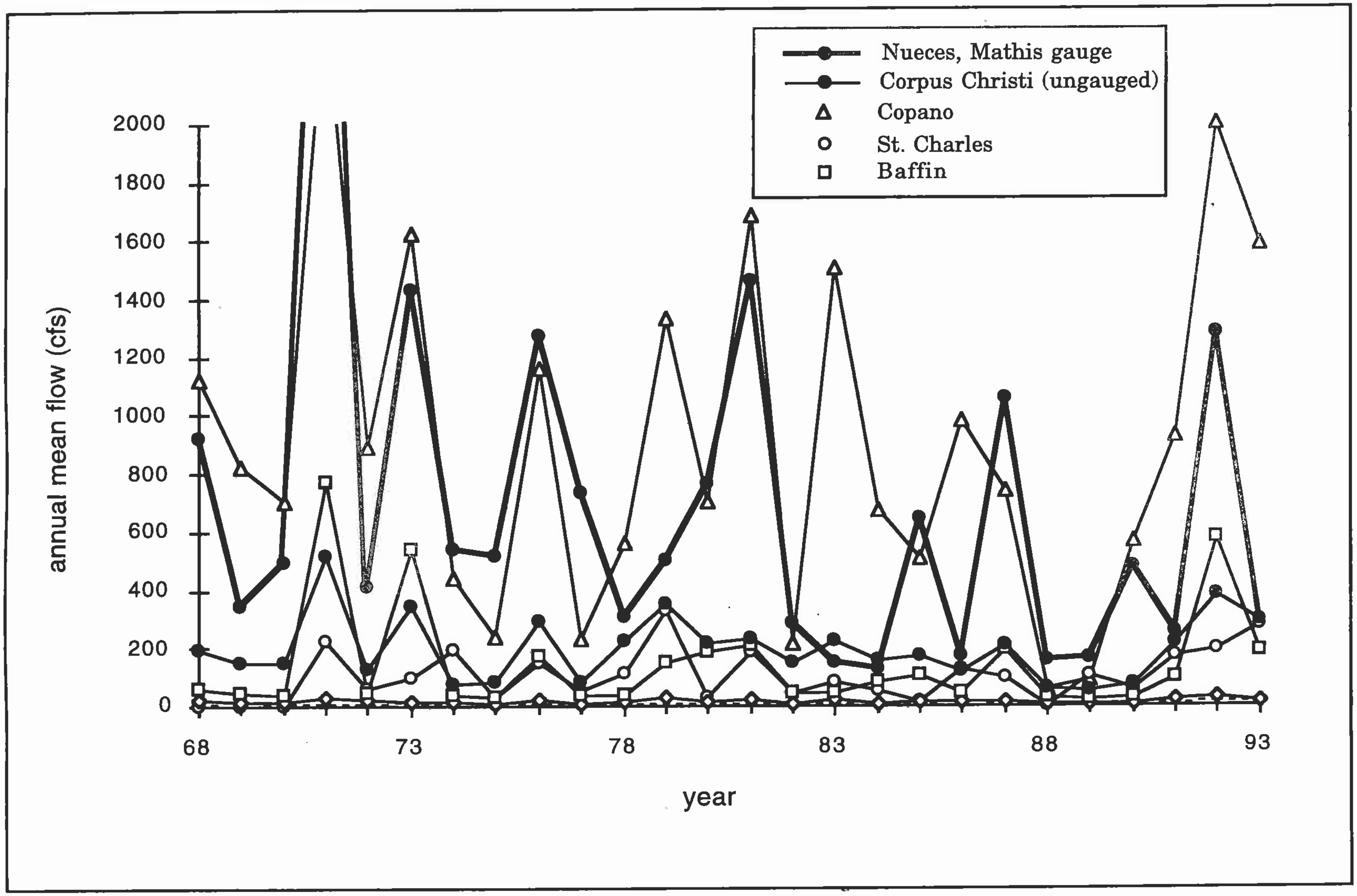


Figure 5-9. Annual mean flow for 1968-93 period by component watershed

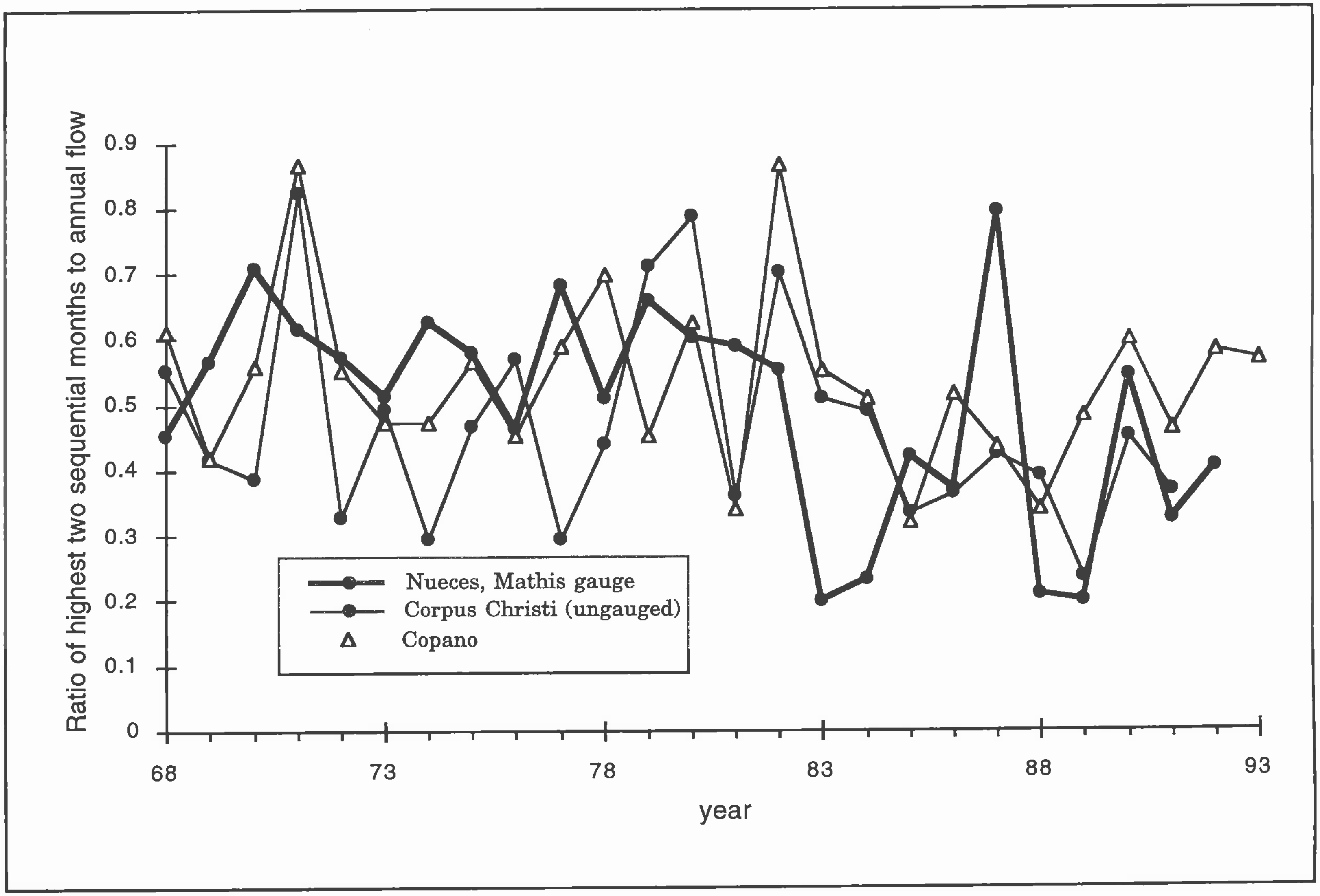


Figure 5-10. Proportion of annual flow in maximal two sequential months

Table 5-5
Annual inflow measures by component watershed, 1968-93, in cfs

	St Charles				Copano				Redfish			
year	mean	freshet mean	first month	ratio	mean	freshet mean	first month	ratio	mean	freshet mean	first month	ratio
68	1.2	7.1	4	1.00	1123	4118	5	0.61	19.7	45.7	5	0.39
69	0.1	0.5	11	1.00	827	2090	11	0.42	13.5	28.1	11	0.35
70	0.0	0.0	11	-	708	2377	9	0.56	18.3	66.0	9	0.60
71	226.8	597.0	11	0.44	2413	12558	9	0.87	31.7	120.5	9	0.63
72	63.3	195.1	4	0.51	895	2958	5	0.55	19.5	42.3	5	0.36
73	99.5	381.4	9	0.64	1625	4618	9	0.47	14.8	33.0	9	0.37
74	192.2	890.2	11	0.77	443	1255	9	0.47	13.6	31.3	5	0.38
75	26.9	127.4	8	0.79	240	813	9	0.57	10.1	20.5	8	0.34
76	148.0	515.7	11	0.58	1160	3159	11	0.45	22.1	40.7	11	0.31
77	51.8	149.6	5	0.48	230	813	1	0.59	9.9	16.0	4	0.27
78	115.5	532.2	9	0.77	562	2347	8	0.70	12.7	32.6	9	0.43
79	332.3	1189.2	8	0.60	1332	3617	8	0.45	27.8	71.2	8	0.43
80	29.1	130.5	8	0.75	705	2635	8	0.62	11.3	32.2	8	0.47
81	189.1	743.8	5	0.66	1687	3455	10	0.34	20.7	30.8	10	0.25
82	45.3	175.7	2	0.65	217	1129	2	0.87	6.1	13.6	2	0.37
83	85.2	250.3	9	0.49	1507	4984	9	0.55	19.4	44.0	6	0.38
84	52.3	225.7	10	0.72	671	2047	1	0.51	7.5	16.5	9	0.37
85	16.8	61.1	3	0.61	508	974	3	0.32	13.1	21.5	9	0.27
86	129.3	549.0	10	0.71	983	3038	10	0.51	12.4	23.2	9	0.31
87	96.1	219.4	6	0.38	742	1946	6	0.44	14.1	22.8	6	0.27
88	0.4	1.0	6	0.40	63	128	9	0.34	8.5	15.9	8	0.31
89	103.0	347.0	1	0.56	92	266	6	0.48	7.4	15.0	6	0.34
90	63.5	191.5	7	0.50	571	2051	7	0.60	10.1	15.5	2	0.26
91	175.9	435.4	11	0.41	927	2578	11	0.46	21.8	42.2	11	0.32
92	198.3	646.0	1	0.54	2001	6984	1	0.58	27.9	103.1	1	0.62
93	274.7	1297.7	2	0.79	1587	5412	5	0.57	15.3	35.9	2	0.39
mean	104.5	379.2	11*	0.63	916	3013	9*	0.54	15.7	37.7	9*	0.38

* Most frequent month

Table 5-5
(continued)

	Nueces River				Corpus Christi				Baffin			
year	*mean*	*freshet mean*	*first month*	*ratio*	*mean*	*freshet mean*	*first month*	*ratio*	*mean*	*freshet mean*	*first month*	*ratio*
68	920	2502	5	0.45	198.2	656.9	5	0.55	62.8	208.4	5	0.55
69	344	1167	10	0.57	153.4	382.8	11	0.42	45.4	95.7	8	0.35
70	496	2103	5	0.71	153.4	356.0	9	0.39	38.8	73.4	5	0.31
71	3487	12887	9	0.62	517.2	2550.1	9	0.82	770.8	4218.6	9	0.91
72	409	1406	5	0.57	126.2	247.3	5	0.33	45.2	94.5	5	0.35
73	1431	4405	9	0.51	345.8	1021.2	9	0.49	537.8	2333.4	9	0.72
74	540	2021	8	0.62	75.6	132.5	5	0.29	37.3	60.4	2	0.27
75	516	1795	5	0.58	82.3	230.4	8	0.47	33.2	75.0	7	0.38
76	1276	3545	10	0.46	293.3	1003.0	6	0.57	173.6	433.9	11	0.42
77	735	3008	4	0.68	83.1	146.5	4	0.29	33.9	62.1	5	0.31
78	308	940	8	0.51	222.0	585.5	6	0.44	37.5	80.9	9	0.36
79	505	1995	5	0.66	351.2	1498.5	8	0.71	147.2	563.5	9	0.64
80	767	2760	8	0.60	215.4	1015.8	8	0.79	187.3	808.8	8	0.72
81	1458	5148	5	0.59	229.7	494.8	6	0.36	206.4	927.6	6	0.75
82	287	947	5	0.55	148.6	623.6	2	0.70	46.1	156.2	2	0.56
83	148	176	5	0.20	226.0	688.7	6	0.51	43.9	73.4	6	0.28
84	129	178	4	0.23	154.7	453.7	10	0.49	81.3	341.6	10	0.70
85	646	1620	10	0.42	174.5	348.7	9	0.33	102.8	317.4	10	0.51
86	175	387	11	0.37	117.4	255.2	11	0.36	48.4	119.8	11	0.41
87	1053	5010	6	0.79	210.2	534.1	6	0.42	194.9	521.1	5	0.45
88	158	197	7	0.21	58.7	137.1	9	0.39	28.0	60.0	9	0.36
89	166	199	7	0.20	53.7	74.9	8	0.23	21.7	40.7	8	0.31
90	481	1562	7	0.54	77.8	208.8	3	0.45	30.3	54.5	3	0.30
91	252	487	5	0.32	215.7	476.2	11	0.37	94.9	356.5	11	0.63
92	1283	3094	5	0.40	379.3	1459.1	1	0.64	576.9	3144.0	1	0.91
93	296				292.6	1369.9	5	0.78	190.1	1009.0	6	0.88
mean	703	2382	5*	0.49	198.3	652.0	9*	0.48	146.8	624.3	5,9*	0.51

* Most frequent month

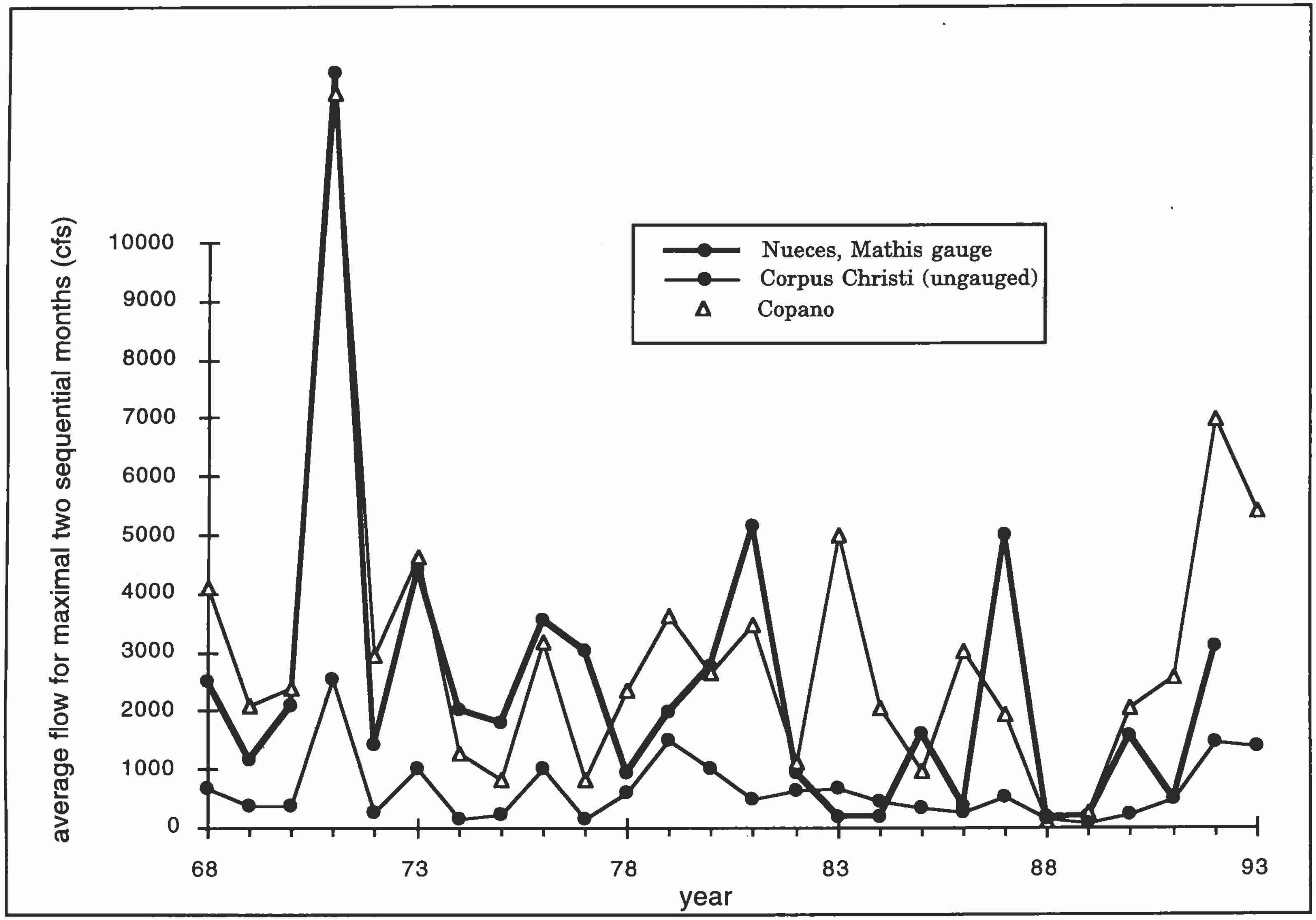


Figure 5-11. Historical variation of annual maximum flow in two sequential months

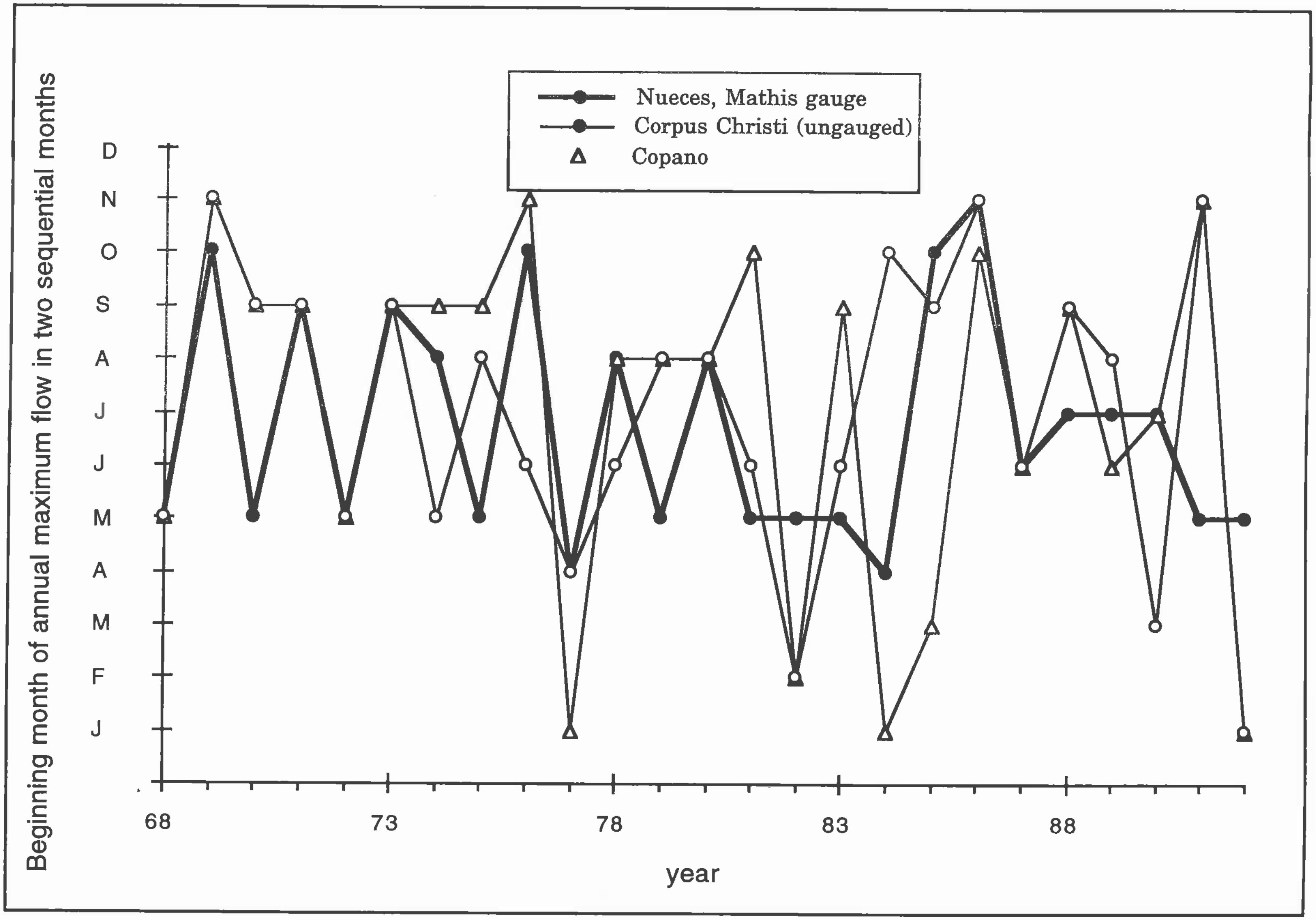


Figure 5-12. Historical variation of occurrence of annual maximum flow in two sequential months

(3) The hydroclimatology of the study area coastal zone is substantially different from the Nueces basin, which is more continental. This is evidenced by the runoff from the coastal watersheds of 263 x 10^{-3} ft/yr (average) compared to that of the Nueces at Mathis of 48 x 10^{-3} ft/yr, Tables 5-3 and 5-4.

(4) There is an order of magnitude decline in runoff across the study area from St. Charles Bay to Baffin Bay, see Table 5-3, indicative of the substantial gradient in aridity over this section of the Texas coastal zone.

(5) The fact that a two-month period is sufficient to "capture" the annual freshet demonstrates the flashy character of the inflows to the Corpus Christi Bay Study Area. (In contrast, for the Trinity River, Ward and Armstrong, 1992, found that a 3-month "freshet" period—as defined here—was necessary to represent just over *half* of the annual flow of the river.)

(6) The annual flow is highly correlated with the spring "freshet," r=0.91 for Copano and r=0.98 for Nueces. High correlation is not unexpected given (5), but to be this high is unexpected and further reinforces the domination of the annual hydrographic by the freshet.

(7) For the main contributors (Copano, Nueces and Corpus Christi) there is a interannual spread of nearly two orders-of-magnitude in the freshet volume.

(8) The first month of the 2-month freshet period is most commonly late summer (August or September). The exception is the Nueces, whose freshet most commonly begins in the late spring. This emphasizes the fact that the hydroclimatology of the Nueces watershed is fundamentally different from that of the coastal plain, and tracks more closely that of the upper Texas coast.

5.2.2 Nueces River

That the Nueces flow is flashy has already been emphasized. A cumulative frequency diagram of daily flows at the Mathis gauge is shown in Fig. 5-13. A simple statistic serves to characterize the extreme skew of this river. The average daily flow for the gauge at Mathis (1939-93) is 763 cfs; 86% of the daily flows are less than this value. On the other end of the spectrum, a reasonable estimate of the bankfull capacity of the Nueces is 4000 cfs. Less than 5% of the daily flows exceed this value. The *median* flow is approximately 150 cfs. Clearly, the flow regime of the Nueces is predominantly one of low flow. Floods, we conclude, are relatively rare occurrences. To complete this hydrological characterization, both the low flow and the flood events will be examined.

The prevalence of drought is a natural feature of the regional hydroclimatology, and has already been mentioned in recounting the history of development of the area. The Irish settlement at San Patricio was apparently frustrated with the vagaries of the Nueces. Almonte (1835) reported that, "The *empresario*, Juan [*sic*] McMullen, has a plan to make part of the waters of the Rio Bravo del Norte flow

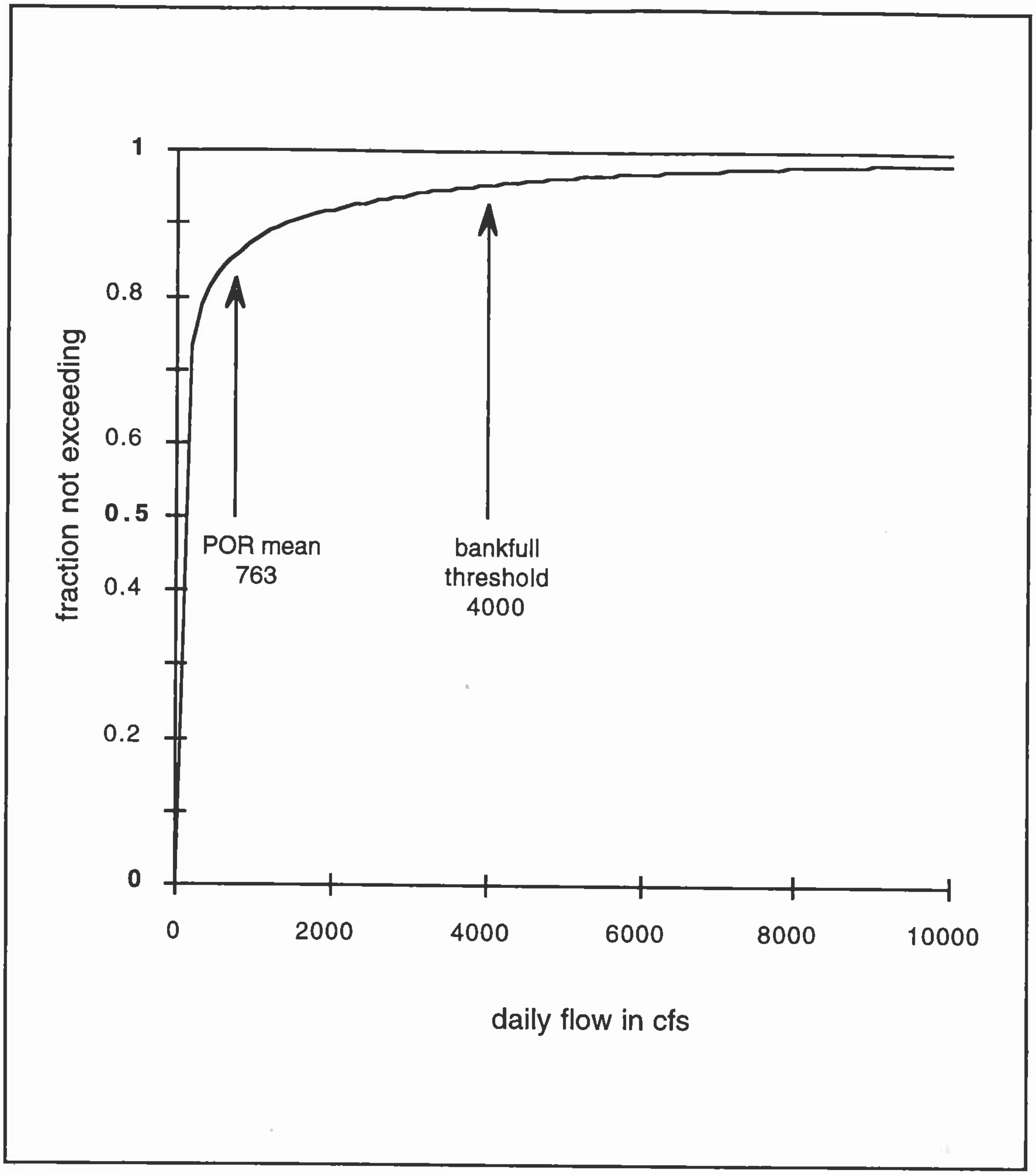


Figure 5-13. Ogive of daily flows (up to 10,000 cfs), Nueces River at Mathis

into the Nueces ...," which did not seem to him very practical. Bollaert (Hollon, 1956) reported in 1844 about the Nueces, "It has been known to almost cease running in parts and General Wavell, late of the Mexican Army, when he crossed there was only 5 inches in depth at ford." In commenting on the Coastal Bend bays, Collins (1878) stated, "The area of the back bays is very great *and for nine or ten months in the year no fresh water runs into them.*" (The emphasis was his.) In fact, the low flows indicated by Fig. 5-13 are distorted upward, because for almost the entirety of the period of record at Mathis, releases have been made from upstream storage for the purpose of downstream withdrawals, by far the most important being those of the city of Corpus Christi and its industries. The data of the USGS (see Section 5.2.1 above) indicate that since 1977 the average diversion is about 145 cfs, ranging 127-176 (winter to summer). (Henley and Rauschuber, 1981, state that the 1947-76 average diversion at Calallen is 80 cfs, or 58,000 ac-ft/yr.) It is apparent that for most of the daily flows below the median value, the excess of river flow over the diversion is practically zero. While it would be of interest to recover the "naturalized" flow into Nueces Bay, that task exceeds the scope of the present study and would require a comprehensive hydrological modeling exercise. What is important is that certainly since Wesley Seale Dam was built in 1958, for sustained periods perhaps as much as half of the time, the flow in the Nueces entering Nueces Bay is virtually nil.

Much study has been given the effects of river storage on flow downstream. One direct impact is that storage allows diversion of water from the river on a continuing basis; indeed, this is the purpose of a water-supply reservoir. The maximum such diversion under the usual zero-failure strategy of reservoir management in Texas is the firm yield of the reservoir, defined to be the constant drawdown that drives the reservoir contents exactly to zero under the drought of record. (The drought of record for the Nueces is the critical drawdown period of the early 1960's. See Ward and Proesmans, 1996, for treatment of the concept of firm yield and its application to the Nueces.) Firm-yield estimation for the reservoirs on the Nueces is something of a moving target, depending upon the period of record and details of the analytical methodology. As indicated in Section 3.3.1, in the early 1960's estimates of firm yield for Lake Corpus Christi ranged 130,000-140,000 ac-ft/yr, based upon the 1950's drought. Henley and Rauschuber (1981) give a value of 113,000 ac-ft/yr (156 cfs), evidently from Bureau of Reclamation work based on the 1960's drought. The early estimates of the combined yield from the Lake Corpus Christi-Choke Canyon (LCC-CC) system was 275,000 ac-ft/yr (HBA, 1968); the value used by Henley and Rauschuber (1981) taken from more recent Bureau of Reclamation analyses was reduced to 252,000 ac-ft/yr (350 cfs).

This firm yield flow can be used as an order of magnitude estimator for the long-term average impact of a water-supply reservoir on downstream flow. For Corpus Christi Bay, it is, on the one hand, an *upper bound* on the actual diversion. First, some of the diverted water will in fact reach the bay as return flows. The data of the USGS (see Section 5.2.1 above) indicate that since 1977 return flows have equalled approximately 45% of the average diversion. Henley and Rauschuber (1981) assumed a value of 60%. Second, long before the storage reservoir will be allowed to drop to zero contents, curtailment will be implemented (as evidenced in the present drought operation). On the other hand, creation of the reservoir imposes a water loss through the increased evaporation from storage, bank losses and infiltration. This is why long term reservoir simulations provide a more accurate indication of the impacts of a reservoir on downstream flow than merely firm yield numbers. Henley and Rauschuber (1981) report that the additional yield from Choke Canyon of 139,000 ac-ft/yr will result in a net reduction of freshwater inflow to Corpus Christi Bay of 163,000 ac-ft/yr. This includes the assumed 60% return flow.

Another of the consequences of the imposition of a storage dam on a flashy river such as the Nueces is that the extremes of variation in the river hydrograph are smoothed out; in particular, the peak of a flood event is reduced and its duration is increased. This will occur even if there is no flood control capability of the reservoir. First, the reservoir will be drawn down during drought periods, and when a flood event occurs, this deficit will be filled before any spill can occur. Second, the large volume and surface area of the reservoir will act as a time integrator, even if the reservoir contents are at capacity, so the extremes of inflows entering the reservoir are attenuated in the spills leaving the reservoir. Therefore, evaluation of the effects of the reservoir must include flood events. This may seem paradoxical, in that for a purely storage (water-supply) reservoir, the volume of water in a flood event is not altered, but is simply spilled downstream, so the long-term influx to the estuary at high flows is not affected. As will be seen, the distribution of that flood volume over time is also important in how it influences the estuary.

The flood of record on the Nueces (at Three Rivers) stood as the September 1919 storm (peak flow 85,000 cfs, see also USCE, 1944) until the occurrence of Beulah in 1967 (peak flow 141,000 cfs), which remains the all-time frog strangler on this river, at least since the beginning of the Three Rivers record in 1915. However, it is not these extreme events that are important to the circulation of the estuary system, but rather the smaller floods that occur on a more regular basis. Ward (1985a) reports a statistical analysis of flood, i.e. rise, events on the Nueces based upon the 1940-80 period of record, drawn from EH&A (1981). In this study, individual storm events were isolated in the hydrological record, from which the long-term frequency, expressed as a return period, was determined, summarized in Table 5-6. We emphasize that this is the return period for the entire storm event whose peak flow (after scalping the base flow) is the indicated value, not the return period for a daily flow, and not the return period for an annual peak. (These are the more usual statistics employed in hydrological analyses, but these provide little insight into the time-series behavior of the river flow.) The threshold for what would be considered a storm, or rise, event was taken to be a surge and recession with peak of at least 400 cfs (11 m^3/s). This is clearly a modest storm. Yet, the average frequency of events equaling or exceeding this value was found to be only 6.7 per year. On a seasonal basis the occurrence of rise events is directly associated with the normal annual pattern of streamflow as exemplified in Figs. 5-5 through 5-7. The return period for a given size event is very different for May, say, versus December. Table 5-7 provides an example of return period by calendar month for a 7,000-cfs event.

Table 5-6
Peak flows of river-rise events on Nueces River at Calallen as a function of return period, from Ward (1985a) and EH&A (1981)

Return period	*Peak flow (cfs) of rise event (above baseflow)*	
(years)	*Gauged data (1940-80) (without Choke Canyon)*	*Model results (1940-80) (with Choke Canyon)*
1	11,000	4,400
2	18,000	13,000
3	22,000	20,000
4	28,000	24,000
5	30,000	28,000
10	40,000	44,000
20	60,000	55,000
40	74,000	72,000

Because Lake Corpus Christi (or its predecessor) has been in existence for virtually the entirety of the period of record at Mathis, the only way to establish its impact on the peaks and frequencies of storm-hydrograph events would be to synthesize the "natural" flows of the Nueces, which has not been done and would be beyond the scope of the present study. However, a daily-flow model simulation of Choke Canyon and Lake Corpus Christi together has been carried out to determine the same flood statistics following the above methodology. This was done in EH&A (1981), and the resulting return periods are shown as the last column in Table 5-6. These can be compared to the analyses based upon gauged data with Lake Corpus Christi, to infer the impact that Choke Canyon would have on flood events. Clearly, the additional upstream storage significantly reduces the peak flows of the smaller, more frequent events, and this impact diminishes for larger, less frequent flood events.

The practical importance of these smaller flood events derives from the hydromechanics of the lower Nueces. As shown in Fig. 3-10, the present channel of the Nueces follows the southern periphery of the delta and the river debouches into Nueces Bay along its south shore, completely circumventing its delta. If the river stage is sufficiently high in the channel below Calallen, the river can overbank into Rincon Bayou, an abandoned river channel and the principal distributary to the Nueces delta. These overbank events are the primary mechanisms for freshwater influxes into the upper delta, and, if sufficiently large, can inundate large areas of the delta. Freshwater inundation is widely considered to be beneficial to the delta and to enhance its value in the biological functioning of the estuary (see, e.g., TDWR, 1981 and references cited therein).

Table 5-7
Return period (years) for 7,000-cfs peak flow event,
Nueces River at Calallen, 1940-80, from Ward (1985a) and EH&A (1981)

Month:	J	F	M	A	M	J	J	A	S	O	N	D
Return Period:	28	40	32	22	4.5	7.3	7.7	56	4.0	5.5	45	>100

Without commenting on the various ecological processes conceived to be operating during these inundation events, we observe that the benefits are considered to increase with duration of inundation, depth of water over the delta, and the area of the delta inundated, all of which generally increase as a function of the peak flow of the storm hydrograph. The key parameters are the stage—and corresponding flow Q_t—at which the river overbanks into Rincon delta, and the flow Q_d necessary to begin to accomplish biologically beneficial inundation.

HDR (1980) used a value for Q_t of 3,000 cfs for the river flow at which overbanking into Rincon Bayou occurs. Later, the Corps of Engineers carried out bankfull capacity studies of the Nueces below Calallen (reported in EH&A, 1981) and determined Q_t to be about 4,000 cfs, which seems better founded than the HDR estimate. We note that whatever the correct value may be, it is of importance in evaluating the effects of historical rise events on the delta, but no longer applies to the present system, since the recent overbank diversion constructions of the U.S. Bureau of Reclamation have altered this threshold.

Mere overbanking of the river flow into Rincon Bayou does not guarantee inundation of the delta, because the Rincon channel is capable of containing a range of higher flows. So the second parameter above, Q_d, must also be determined, and this one is more difficult to establish. HDR (1980) assumed that $Q_d = Q_t$, that the same flow of 3,000 cfs that results in overbanking also inundates the delta, so determination of "inundation" events amounted to determining the number of days per year with flows exceeding 3,000 cfs. The Corps of Engineers (see EH&A, 1981) acted upon a statement of TDWR (apparently undocumented), that a rise event required a duration of at least 6 days to "flush the marsh," to define an inundation event as one exceeding bankfull capacity (4,000 cfs) for at least 6 days. TDWR (1981) stated that, "based upon field observations," a flow exceeding 5,000 cfs at Mathis was necessary to achieve "appreciable inundation" of Nueces marsh, and that a duration of at least two days was necessary. EH&A (1981) evaluated historical aerial photography and the corresponding gauged flow records and inferred that a flow of *at least* 6,000 cfs at Calallen was needed for inundation "involvement of the upper areas adjacent to Rincon." A numerical hydrodynamic model (Hauck and Ward, 1980) was applied to the Nueces delta, summarized by Ward (1985a), and operated with flood events of various peak flows; the model indicated that out-of-bank flows in Rincon Bayou began to occur when the Calallen flow was at about 7,000 cfs. Direct field confirmation that Q_d = 7,000 cfs was a reasonable estimate was made in two floods in May and June, 1981, described in Ward (1985a) and documented in EH&A (1981). As was the case with Q_t, this value of Q_d is important for evaluating the historical behavior of the delta, but has been altered in the present system by the diversion project of the Bureau of Reclamation.

With Q_d quantified, the frequency of such events can be evaluated. HDR (1981) constructed a "daily flow record" from the monthly flow simulations of Bureau of Reclamation (by assuming fixed ratios of the flow on each day to the total monthly flow, based on the actual gauge record), and evaluated this for the occurrence of flows ≥ 3,000 cfs. For the 1958-79 period they found 2.3 such "inundation events" per year of average duration 9.8 days under Lake Corpus Christi operation, and that this would be reduced to 1.2 events per year of average duration 13 days with Choke Canyon on line. The TDWR (1981) analyzed the 1939-79 record at Mathis for the occurrence of flood events exceeding 5,000 cfs for at least two days, and found that a median of two such events per year had occurred historically. The hydrodynamically based value of Q_d = 7,000 cfs is more exacting, and Ward (1985a) reports a return period of 0.9 years, i.e. 1.1 events per year. The return periods by month are given in Table 5-7. We emphasize that the TDWR (1981) and Ward (1985a) computations are for the period before Choke Canyon began operation. The return period for any subset of months, e.g. a season, can be computed from $T = 1/\Sigma(T_m)^{-1}$, where T_m are the individual monthly return periods from Table 5-7. For example, the return period for such an event in the biologically important May-July period is 2.0 years. Of course this represents an "infinitesimally brief inundation." To accomplish prolonged inundation or a specific water depth would necessitate even greater (and less frequent) peak flows.

To summarize, several conclusions about the Nueces River flow can be drawn:

(1) The river is in a chronic low-flow, drought-prone state: its hydrology can be described as transient, widely spaced flood impulses superposed on a low base flow.

(2) Most of the normal low flow measured at the Mathis gauge is in fact withdrawn for water supply at Calallen.

(3) The order of magnitude of net reduction of mean inflow to the system due to water-supply diversion associated with Lake Corpus Christi is about 150 cfs. With Choke Canyon fully developed this number for the combined LCC-CC system will increase to about 350 cfs. (During drought, conservation and curtailment will reduce this number.)

(4) The Nueces delta is freshwater-starved: significant inundation of the delta occurs only when the peak flows *substantially* exceed 7,000 cfs; considered independent of the month or season, such events had a return period of at least 2 years prior to Choke Canyon.

(5) The effect of Choke Canyon on these smaller flood events was to add about a year to the return period.

(6) The present overbank diversion works constructed by Bureau of Reclamation have the potential for enhancing inundation of the delta during flood events. There appears to have been little quantitative hydrological evaluation.

5.3 Water budgets

On the intertidal time scale there are operating long-term transports of water volume through the system. These can be conveniently subdivided into throughflow and exchanges, the former referring to a unidirectional flux of water through the system, and the latter referring to the bidirectional volume forced into or from the system by hydrographic or hydrometeorological processes that is later compensated by a return in the opposite direction. Both of these accomplish a replacement of water in the estuary, either locally or systemwide. This replacement may be beneficial in diluting degraded water or moderating salinities; it may be detrimental in moving contaminants, or degraded or "non-native" water to other sections of the estuary where they can have harmful impacts on a nonacclimated biological community. From the viewpoint of system circulation, our purpose is to quantify these transports.

5.3.1 Throughflow budgets

Among the throughflow fluxes, the most important systemwide is the influx of freshwater through rivers and drainageways into the bay. The data assembled in the preceding sections can be combined in a freshwater budget of the study area. The mean budget for the period 1968-90 is summarized in Table 5-8 for three large components of the study area: the Aransas-Copano system, Corpus Christi Bay including Nueces Bay, and the Baffin Bay/Upper Laguna system. Areas given in Table 2-1 were combined with the monthly surface *net* precipitation data of Section 2.2.2 to determine the surface volume flux. For Corpus Christi Bay, the average of the Rockport and Kingsville net precipitation data was used. Runoff inflows for the component watersheds described in Section 5.2.1 were combined with diversions and return flow data provided by USGS. The net inflows for each component and the total Corpus Christi Bay system are given in the last two columns of Table 5-8, as both total monthly flow volume and as a fraction of the volume of the bay (see Table 2-1). For the purposes of this budget, a total system volume of 3080 Mm^3 was used.

Throughflow budgets are also provided for Nueces Bay (Table 5-9) and the Upper Laguna (Table 5-10), in which the power-plant circulations are included. For Nueces Bay, the freshwater inflow is subdivided into that due to the Nueces River as gauged (included water-supply releases), the net diversion at Calallen, and the inflow from the ungauged periphery of Nueces Bay (provided to this project by USGS from its HSPF model operation). The power plant throughflow is an inflow to Nueces from the adjacent Corpus Christi Bay that operates continuously.

Table 5-8
Freshwater throughflows, 1968-90, for Corpus Christi Bay system

Component bay		*watershed inflow Mm³/mo*	*surface P-E Mm³/mo*	*Net Mm³/mo*	*as fraction of volume % per mo*
Aransas-Copano	mean	62.5	-18.0	44.9	4.7
	range	0.1	-80.1	-78.4	-8.2
		1431.9	138.8	1570.7	165.0
	st dev	129.5	31.3	150.8	15.8
Corpus Christi (including Nueces Bay)	mean	62.5	-26.8	35.7	2.2
	range	-0.5	-97.8	-91.7	-5.7
		1238.3	111.2	1250.7	77.4
	st dev	142.4	33.3	159.4	9.9
Upper Laguna/ Baffin Bay	mean	9.6	-31.2	-21.7	-4.2
	range	0.1	-102.5	-100.6	-19.7
		347.8	126.9	400.1	78.3
	st dev	34.9	35.5	58.8	11.5
Total system	mean	134.6	-76.0	59.0	1.9

Table 5-9
Throughflow water budget for Nueces Bay, 1968-90

	Watershed ungauged (Mm³/mo)	*River gauged (Mm³/mo)*	*Net diversion (Mm³/mo)*	*surface P-E (Mm³/mo)*	*Net (Mm³/mo)*	*as fraction of volume (%/mo)*
mean	4.9	53.2	4.7	-3.0	50.6	103.3
range	0.0	4.0	1.8	-13.5	-10.3	-21.0
	182.2	1105.3	12.9	23.5	1198.0	2444.9
st dev	14.9	122.7	2.5	5.3	136.0	277.6
Power-plant inflow from Corpus Christi Bay via Inner Harbor					48.5	99.0

Table 5-10
Throughflow water budget for Upper Laguna Madre, 1968-90

	Baffin Bay deficit (Mm^3/mo)	*surface P-E (Mm^3/mo)*	*Net (Mm^3/mo)*	*as fraction of volume (%/mo)*
mean	-5.6	-16.1	-21.2	-28.1
range	-48.3	-52.9	-100.6	-130.5
	373.1	65.5	400.1	519.0
st dev	44.7	18.3	58.3	76.3
Power-plant inflow from Corpus Christi Bay via LBJ Causeway			49.9	64.7

For the Upper Laguna, for practical purposes the only source of freshwater inflow that needs to be considered is from the streams and drainageways entering Baffin Bay. A freshwater budget on the Baffin system indicates the 1968-90 average inflow of 9.6 Mm^3/mo to be less than the average net surface evaporation of 15.1 Mm^3/mo implying an average deficit of 5.6 Mm^3/mo for Baffin Bay. This is the source of the "Baffin deficit" entry in Table 5-10. The power plant throughflow is a continuous inflow to the Upper Laguna from lower Corpus Christi Bay through the inlets in the Causeway.

These results are illuminating. Over the long term, the average freshwater throughflow is small, by estuarine standards. To replace the volume of the system by this freshwater throughput would require 53 months. (This is the so-called "flushing time" of the estuary, for those who believe in such twaddle, see remarks of Ward and Montague, 1996.) The importance of the gradient in hydroclimatology of southward-increasing surface deficit is demonstrated clearly by comparing the positive net throughflow for Aransas with the negative for the Upper Laguna. As discussed earlier, there is another potential source of throughflow not accounted for, the freshwater influx from the San Antonio Bay system through Ayres Bay, so the hydroclimatological gradient, if anything, is understated.

These results are also misleading. The high variability in these numbers is as important as their long-term means. There are points in the record when components of the system lose as much as 20% of their volume per month to evaporation, and there are occurrences when the monthly inflow is great enough to replace the entire volume of the system. For smaller components, such as Nueces Bay, the volume can be replaced as much as 25 times in a month. Figure 5-14 displays the cumulative net inflow to the entire CCBNEP study area over the

1968-90 period, and the cumulative departure from the mean, in units of total bay volume. The inflow history of the system can be succinctly described as widely spaced influx events on the order of the volume of the system, superposed on a chronic continuing inflow deficit. In Fig. 5-15, the 1968-90 cumulative freshwater throughflow is subdivided into the three principal component bays.

Another way in which the data of Tables 5-9 and 5-10 can be misleading is in the interpretation of the power-plant throughflows. For Nueces Bay, while this volume is equivalent to recirculating the volume of the bay once a month, it would be incorrect to infer that the entire bay volume is replaced. The power-plant outfall is located in the southeast corner of the bay, relatively near Nueces Entrance, Fig. 3-10, so that the volume transport is largely confined to this section of the bay (see Ward, 1982a). The number given in Table 5-9 means simply that this *portion* of Nueces Bay is replaced at a proportionately greater frequency; if this is one-fifth of the bay's volume, say, then this volume is replaced five times per month. Similarly, Table 5-10 gives the rate of volume circulation by Barney Davis to be 65% of the volume of the Upper Laguna, but this does not mean that 65% of the entire Upper Laguna system is affected. The recirculation can be expected to have much more effect on the volume between the Causeway and Pita Island, than the volume farther south.

5.3.2 Exchanges

In Section 5.1 two intertidal-scale water exchanges with the Gulf of Mexico were identified, the fortnightly increase and decrease of water levels associated with the changing lunar declination and long-term meteorological systems, and the seasonal secular rise and fall of waters in the northwestern Gulf of Mexico. Both of these processes have a direct effect on Aransas Bay and Corpus Christi Bay, since these systems are in communication with the Gulf through Aransas Pass inlet. For the outer systems, i.e. the Laguna Madre, Nueces Bay and Copano Bay, the water entering or leaving these systems does not communicate directly with the Gulf but rather with Corpus Christi or Aransas Bays. There is, therefore, an exchange between the component bays.

Table 5-11, drawn from the data of Tables 5-1 and 5-2, summarizes the magnitudes of both of these exchanges and the systems affected. For comparative purposes, a time frame is assigned to each of these. The fortnightly prism is assumed to enter and leave the bay over a 0.5-month period, and the seasonal prism over a 6-month period. Moreover, the average values for each of these analyses are used as characteristic of the phenomenon. Since the period of record for each is rather short, especially compared to the 22-year period upon which the freshwater throughflows were based, some bias is no doubt incurred. The full range of lunar declinations were not encountered in the 2-3 year periods of tidal data analyzed. Moreover, as noted earlier, the objective analysis techniques for determining fortnightly prisms does not differentiate between astronomical influences and longer-term meteorological responses, such as recovery of water levels after a polar outbreak. Therefore, these data on fortnightly prisms include both processes. With respect to the seasonal variation, certainly the 4-5 years

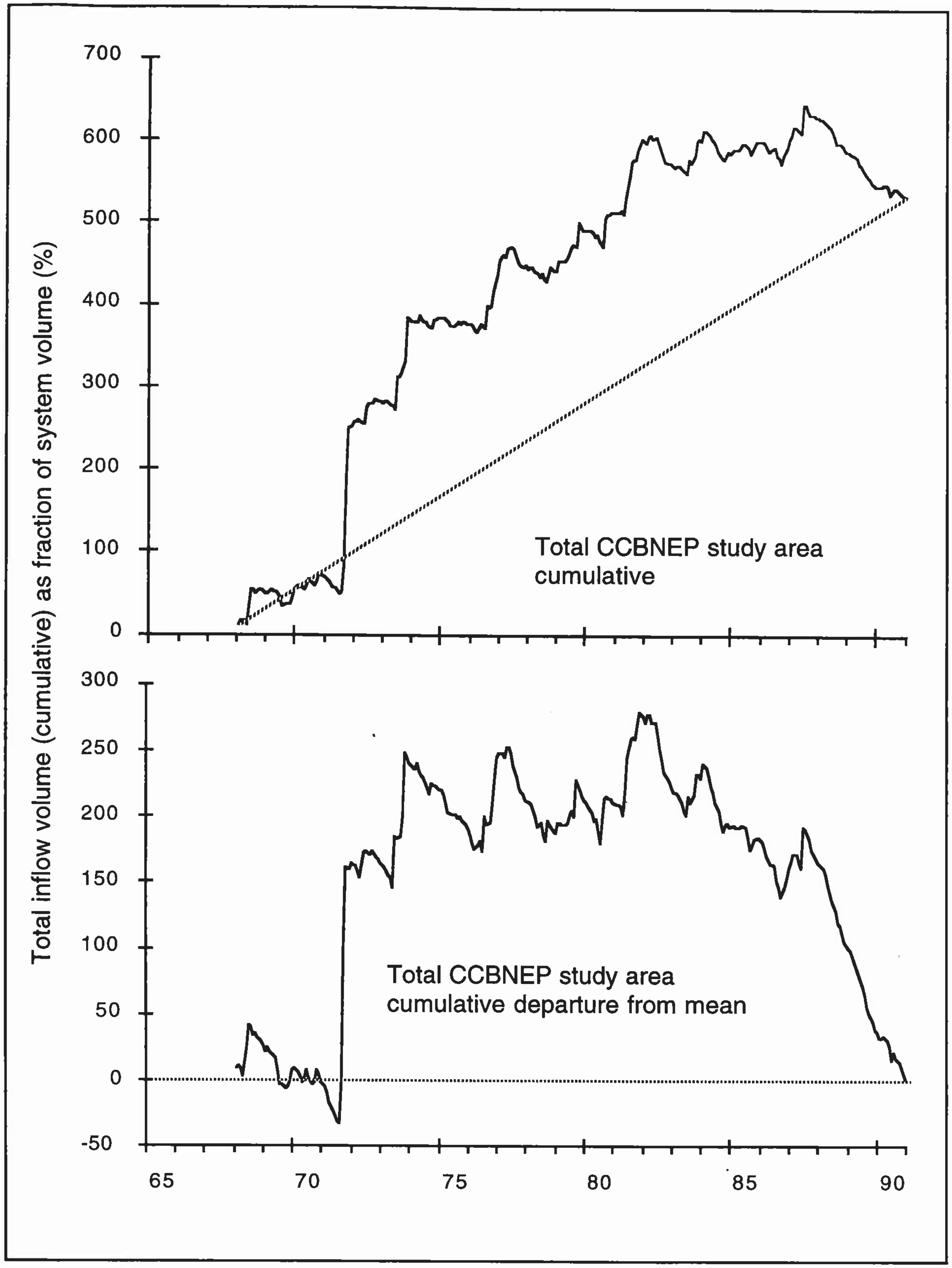


Figure 5-14. Net freshwater inflow relative to bay volume for entire system, cumulative flows (above), cumulative flows above 1968-90 mean (below)

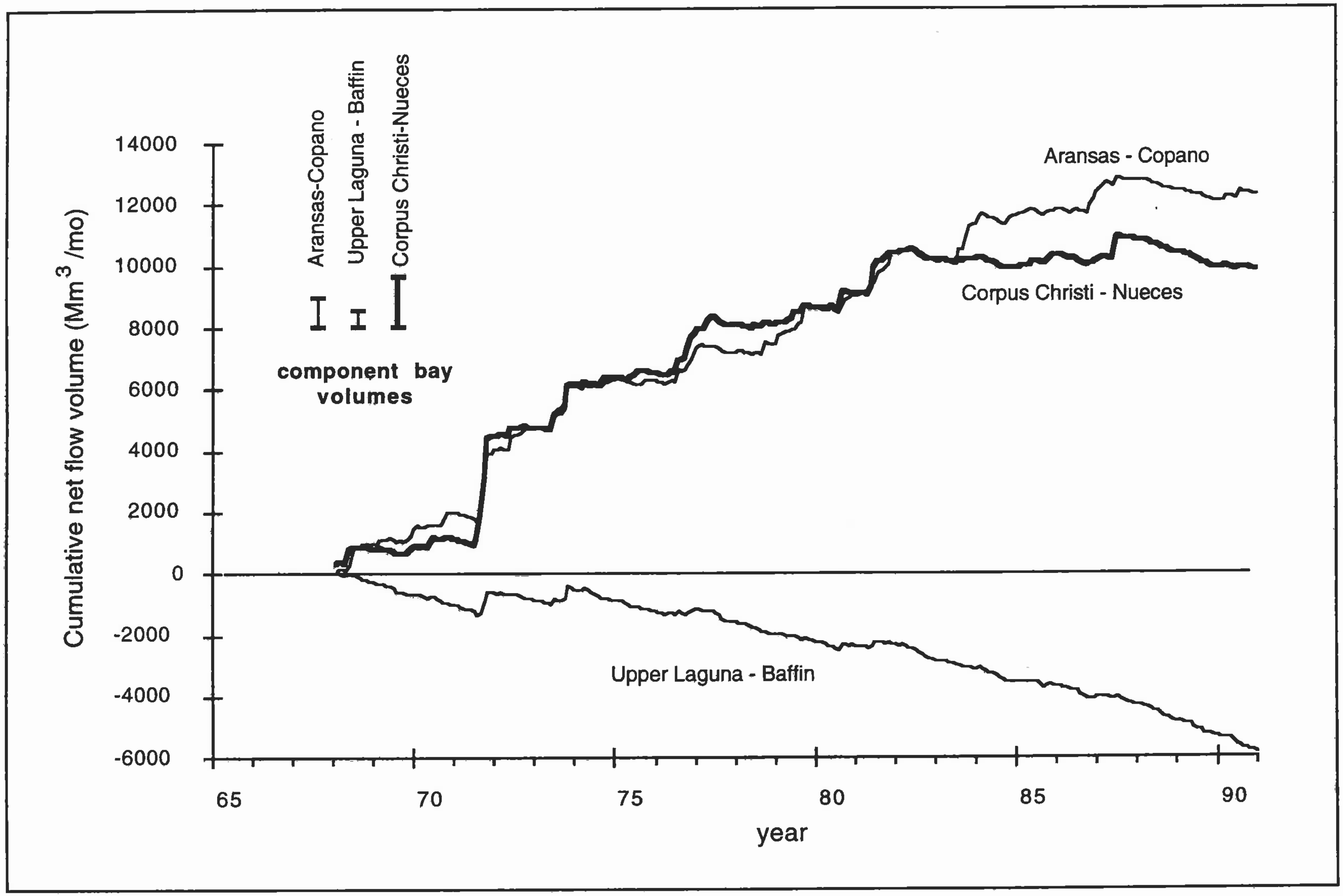


Figure 5-15. Cumulative net freshwater inflow by component bay

Table 5-11
Summary of intertidal exchanges in Corpus Christi Bay system

Component	*volume*	SEASONAL *prism*	SEASONAL *exchange per month*		FORTNIGHTLY *prism*	FORTNIGHTLY *exchange per month*	
	Mm^3	Mm^3	Mm^3	% vol†	Mm^3	Mm^3	% vol†
Total system	2647	348	58	2	118	236	9
Corpus system*	1692	227	38	2	76	151	9
Aransas system	955	120	20	2	42	84	8
Laguna	77	79	13	8	24	47	47
Nueces	49	19	3	5	6	11	21
Copano	429	54	9	2	20	41	9

† as fraction of low-tide volume + prism   *includes Nueces Bay and Upper Laguna

analyzed of the seasonal rise does not entirely capture its range of variability (especially in view of the drought-dominated meteorological regimes of the last few years, cf. Fig. 5-14). With these necessary qualifications, the results of Table 5-11 are considered to quantify the relative magnitudes of these exchanges.

The most fundamental exchange is the influx of water from the Gulf of Mexico and the subsequent evacuation of water out of the bays. This is represented by the first line of Table 5-11, the Total System exchanges. In this computation, the volumes of Ayres, Carlos and Mesquite Bays are excluded from the area/volume of the Aransas system on the assumption this part of the study area will exchange with San Antonio Bay to the north. Similarly Baffin Bay is excluded on the assumption that its long-term exchange will take place largely with the Lower Laguna Madre, through the GIWW landcut and hydraulic continuity established over the Mudflats at high water. The Total System is intended to approximate the water volume passing through Aransas Pass. While the total seasonal prism is much larger than the fortnightly, the fact that the fortnightly prism is exchanged six times more frequently makes it the larger of the two in terms of *rate* of exchange. On a monthly basis, the seasonal prism represents an exchange of approximately 2% of the total system volume, while the fortnightly exchange is equivalent to 9% of the total system volume. Inspection of Figs. 5-3 and 5-4 will aid in differentiating the time scales of these two exchanges.

This water volume transiting Aransas Pass is further subdivided into the upper bay component, *viz.* the Aransas system including Copano and St. Charles bays, and the southern bay component, *viz.* the main body of Corpus Christi Bay, including Nueces Bay and the Upper Laguna. Within each of these there will be further exchange between the main bay and the secondary bays, given as the last entries of Table 5-11. The fortnightly exchange is particularly important to the shallow bays of Nueces and the Upper Laguna, not in volume *per se*, but in the proportion of the water exchanged. EXHIBIT2 should be activated for Area 5 (Upper Laguna), and initiated at 94160. Note the long-period variation of water level at Bird Island, for a system whose mean depth is a fraction of a metre (at MLT). (Recall, also, that Nueces Bay prisms are probably underestimated because the White Point gauge pegs at low waters.)

5.4 Salinity as a hydrographic tracer

Salinity is the quintessential parameter of estuarine waters, being determined by the intermixing of fresh and oceanic waters and quantifying therefore the relative influences of riverine and marine processes. Salinity is easily measured by a variety of techniques. Since there are large spatial gradients in salinity and it exhibits high temporal variability, for work in estuaries a lower degree of precision in salinity determination can be accepted than is the case either in totally fresh or oceanic systems (Head, 1985, Ward and Montague, 1996). This means that data can be employed from a variety of protocols and parameters, such as specific gravity, conductivity, titration of chlorides, and light refraction, and converted to equivalent salinity. Because, in most estuaries, salinity behaves as a virtually conservative parameter, it is an excellent watermass tracer. It is also a key ecological indicator, as it affects the suitability of habitat due to varying osmoregulation capabilities of organisms. Salinity further affects sedimentation and many chemical reactions. Any direct impact on salinity has the potential of indirect consequences for ecosystem structure and function.

5.4.1 Salinity data base

It would be extremely desirable to have a record of salinity antedating the major modifications made to the Corpus Christi Bay system in this century. Galtsoff (1931) reports a handful of measurements made in Corpus Christi Bay, Nueces Bay, Aransas Bay and Mesquite Bay in summer of 1926. A much more extensive set of salinity data was collected by the Texas Game Fish & Oyster Commission in 1936-37, by the state Marine Biologist A.W. Collier (summarized in Collier and Hedgpeth, 1950). Since then until the 1950's, TGFOC has been the only agency to regular survey salinities in the study area, but this older data has apparently not survived. The oldest salinity data that could be located by this project is due to a nationwide research project on marine borers conducted by the Committee on Marine Piling Investigations of the National Research Council, which logged daily measurements from November 1922 through October 1923 at Corpus Christi Harbor (then on the bayfront) and Port Aransas, see Atwood and Johnson (1924). Unfortunately, these measurements do not afford the space and time density necessary to be able to extract statistically sound judgments about any alterations in salinity which may have taken place since the turn of the century.

Ward and Armstrong (1997a) compiled data on salinity throughout the Corpus Christi Bay system from numerous historical and ongoing data-collection programs, and analyzed this data in the context of characterizing the water quality of the system. Their data base extends from the 1950's until the early 1990's. Some of their results are summarized here. Their data was subjected to additional analyses directly relevant to circulation. There are approximately 60,000 independent measurements of salinity in this data base. But when it is considered that this data base is distributed over 1700 km^2 of area (including the nearshore Gulf of Mexico), and over at least three decades, the sampling density is seen to be less than a dozen measurements per ten km^2 per year. Of course, the actual sampling activity is quite nonhomogeneous: some areas are sampled more densely, and others are rarely sampled at all. Moreover, this sampling rate does not take cognizance of multiple measurements in the vertical. Given the great spatial and temporal variability of salinity in the system, this parameter is clearly undersampled.

It is not surprising therefore that this data base does not generally permit analysis of time scales of variation shorter than a few days. The use of automatic data logging and electrometric sensing now permits the recovery of nearly continuous, fine-scale time signals of salinity. In the study area, there are three sources for this kind of data. The Bays and Estuaries Program of TWDB was the first agency in the Corpus Christi Bay study area to employ such robot observation systems, referred to generically as "sondes," and has operated such equipment since the early 1980's. Several researchers at the Marine Science Institute of the University of Texas have deployed such systems experimentally in a few locations in the system. Most important is the Conrad Blucher Institute of Texas A&M–Corpus Christi which has incorporated conductivity sensors into its program of automatic gauging at a few selected stations. These data sets are valuable in providing insight into a element of variation of Corpus Christi Bay salinity that is virtually unsampled, and the surface has only been scratched in the analysis of the data. However, no sonde data were included in the data base of Ward and Armstrong (1997a). The reason is that the data are presently either untrustworthy or uncorrected. The keys to developing a reliable record of data from a robot sonde are frequent maintenance, careful pre-deployment and post-deployment calibration, and diligent data scrubbing (i.e., review of the sonde records and detection of aberrancies). The electrometric probes are prone to fouling and degradation, especially in the saline environment, and can exhibit substantial drift in time due to these effects. Self-contained sondes with a built-in data logger can also be subject to timing errors. Ward and Armstrong (1997b) report that present maintenance and data-scrubbing activities of these agencies are inadequate, and provide examples of data corruption that led to the decision to exclude them from the data base.

As in most estuaries, there are substantial spatial gradients in salinity across the Corpus Christi Bay system, not only because of the great range in hydroclimatology, but also because of the location of the river drainages and the variable influence of the sea. Before the combined salinity data base can be analyzed, this variability in space must be separated. This was accomplished in Ward and Armstrong (1997a) by subdividing the study area into 178 Hydrographic Areas (or Segments), including 18 in the nearshore Gulf of Mexico. Any such segmentation is based implicitly upon an assumption of data aggregation: that in many areas of the bay, *to within a certain level of confidence* (in the statistical sense), there is no difference between measurements taken at one position and those from another, perhaps even several kilometers removed. This assumption can be better assured by identifying regions of homogeneity (within some statistical threshold), and zones or loci of sharp gradients in properties. The former corresponds to the interior regions of segments and the latter to boundaries between segments. The Hydrographic Areas were defined to take into account what is known about transports, bathymetry, freshwater inflow points, barriers to flow, and in general the distribution of physicochemical factors which will either homogenize the parameter (to define the region encompassed by a water quality segment) or create steep gradients (to define the boundary between segments). These Hydrographic Areas are shown in Fig. 5-16, except for those in the Gulf of Mexico and the Corpus Christi Inner Harbor.

5.4.2 Spatial variation of salinity

Historically, even before quantitative determinations of salinity were made, the importance of salt in the Coastal Bend Bays was evident from accumulation of evaporites, especially in the Laguna Madre. In his comment on the low inflow to the area bays, Collins (1878) added, "The evaporation is so great that salt is formed in the shoal water far back from the Gulf, and in Laguna Madre... ." Around this time, the Laguna, in particular, served as an importance source of salt for beef packers in the area (Howell, 1879). Because of its relative isolation and the very high negative net precipitation, the Laguna acts as a great evaporation basin, and has become the classic example of a hypersaline estuary (e.g., Pritchard, 1952, Hedgpeth, 1967, Dyer, 1973). However, salinities well in excess of seawater have been measured in all of the study area bays.

This is exemplified by Table 5-12, listing the range of salinity as reflected in the data of Ward and Armstrong (1997a) for a selection of hydrographic segments, see Fig. 5-16. The minimum and maximum occurring in each hydrographic segment along with the date of the record, coded as YYMMDD, are given. (This table also exemplifies another aspect of this data base, extensively discussed in that report, that most of the historical data could not be verified against a paper record, and include some suspicious values. For example, the maximum value in Oso Bay of 78 ppt may have been 7.8 ppt with the decimal omitted through a keyboard area. But since 78 ppt is within the range of possibility there is no *a priori* reason to expunge it.) What is significant about the data in Table 5-12 is that almost all sections of the system have recorded values in the 30's, and most

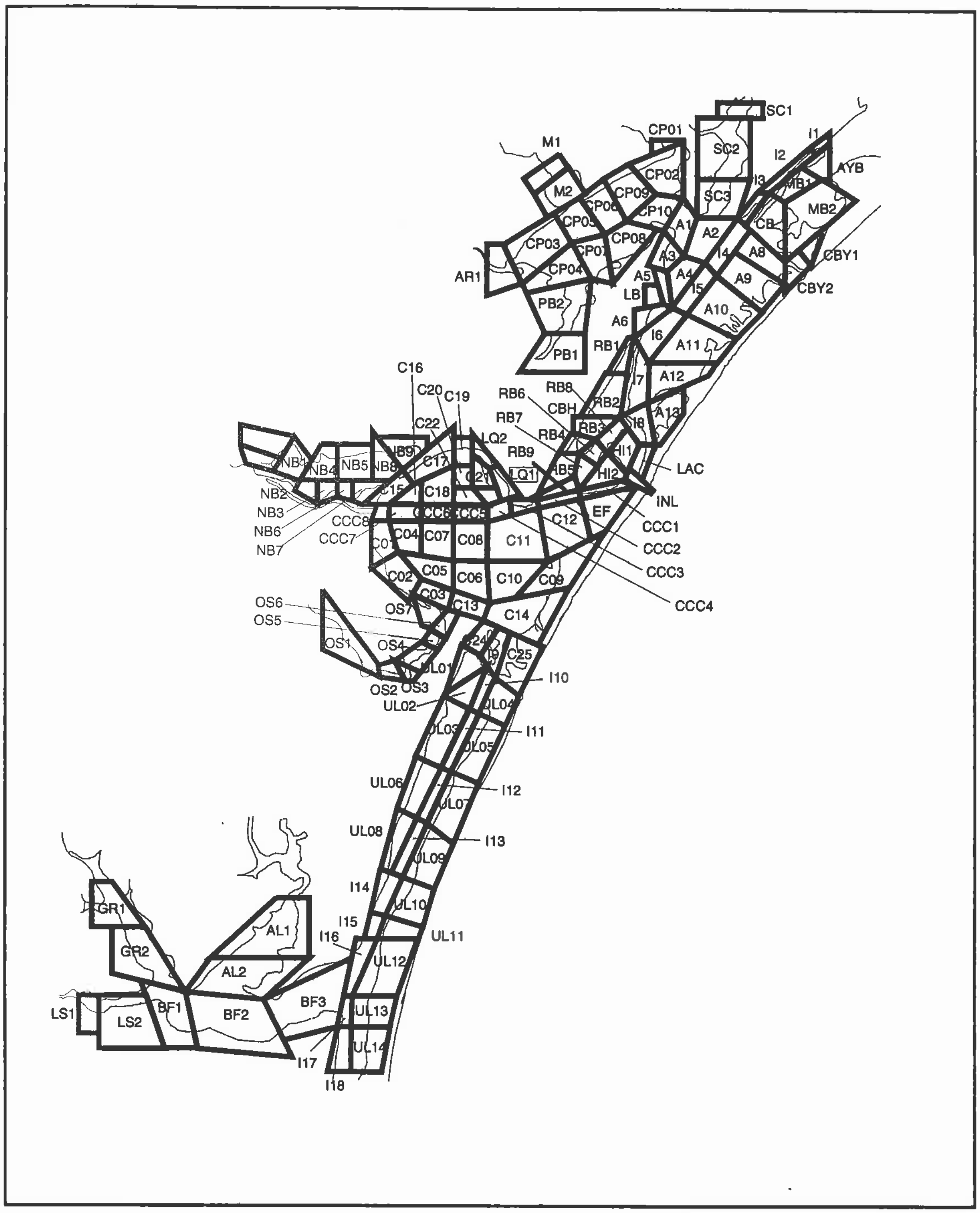


Figure 5-16. Hydrographic areas for water/sediment quality analysis from Ward and Armstrong (1997).

Table 5-12
Salinity range (ppt), in upper 1 m, by Hydrographic Area

Segmt	*No. of obs*	*Minimum value*	*Minimum date*	*Maximum value*	*Maximum date*
Copano Bay					
AR1	174	0.0	811118	38	891017
CP02	342	0.3	811208	35	890928
CP03	467	0.0	730615	42	641201
CP05	289	0.0	680615	50	690801
CP08	241	0.0	920408	40	890918
CP10	501	0.0	680715	39	641201
PB2	201	0.0	790928	40	890918
M2	101	0.0	831101	39	891024
Mesquite-Carlos-Ayres Bays					
MB1	294	0.0	920414	39	900123
CB	323	1.0	920312	39	850911
AYB	34	12.0	690515	34	890620
Aransas Bay & St. Charles Bay					
A1	463	0.3	680715	44	630828
A2	270	1.0	920226	36	890828
A3	364	1.0	920421	34	641130
A5	168	1.9	920421	36	641130
A6	189	3.1	760720	37	641130
A8	108	1.0	920226	36	840913
A10	269	1.2	831026	37	641130
A11	144	3.0	920609	40	891009
A12	307	3.0	880427	40	890919
I8	82	5.0	920210	38	890710
SC3	543	0.3	680715	35	890717
Aransas Pass, Cedar Bayou & Lydia Ann Channel					
INL	47	12.0	780509	40	881114
LAC	100	5.0	920608	36	770629
CBY2	45	10.0	920113	38	670815
Redfish Bay					
RB3	189	5.0	920608	40	851107
RB8	275	4.2	760720	41	890227
Corpus Christi Bay &Corpus Christi Ship Channel					
C03	320	1.3	710914	70	670816
C05	149	1.1	671002	45	520824
C07	186	0.0	860927	43	710618
C12	689	0.0	860927	46	880323
C14	855	0.0	860927	54	800715
C17	411	0.0	870706	47	841220
C18	101	2.5	670930	42	520824
C19	119	10.0	810713	51	630807
C24	221	0.0	890122	47	880717
CCC2	101	5.9	760720	39	870605
CCC3	370	0.0	860927	43	710702
CCC6	161	6.4	710916	54	910116
CCC7	291	0.0	870716	42	520824
Nueces Bay & delta					
NB1	211	0.0	870611	49	890907
NB4	357	0.0	800826	41	890729
NB6	457	0.2	710914	41	880922
NB7	572	0.0	870706	62	670816
ND4	327	0.0	920331	50	891008
Inner Harbor & La Quinta Channel					
LQ1	264	8.5	711020	43	710727
LQ2	181	15.0	731024	39	860814
IH1	161	0.0	920728	60	670816
IH5	200	0.6	710720	61	670816
IH7	265	3.8	710922	77	610628
Oso Bay					
OS6	89	0.6	900806	52	880809
OS7	217	0.6	900806	78	850722
Upper Laguna Madre					
I9	222	0.0	860927	54	880712
I10	118	6.0	760809	51	690815
I12	141	0.5	900807	55	910408
I13	447	0.0	860921	64	641115
I14	109	23.0	920722	55	901212
I15	143	0.0	860921	53	901009
I17	154	0.5	900807	58	900212
I18	170	12.0	870622	59	641015
UL03	339	8.9	671015	60	630826
UL06	234	11.0	671015	63	640915
UL09	104	19.0	920608	54	900925
UL10	203	18.0	680115	64	641115
Baffin Bay					
BF1	402	0.0	860921	65	910408
BF2	294	2.8	731017	63	891106
BF3	531	0.6	900807	61	641115
LS2	254	1.1	731017	68	901220
GR2	283	0.5	731017	64	910117
AL1	167	0.0	870616	77	890828
AL2	260	0.0	860921	90	900830
Gulf of Mexico					
GMI6	214	3.0	930429	40	881114
GMI7	348	18.0	910604	40	880726
GMO5	47	24.0	870318	41	920817
GMO7	75	24.0	870302	40	870903

sections in the 40's and 50's. Moreover, many segments, especially in the lower bays, have logged the maximum value (in this data set at least) in recent years.

These hypersaline values (i.e., exceeding oceanic values of ca. 35 ppt) are clearly the result of evaporation at the water surface exceeding the combined influxes of precipitation and runoff, and to a considerable extent undermine the utility of salinity as a watermass tracer in these bays. The effect of evaporation is to create a virtual surface flux of salinity (since the salts are left behind in the water column as water is evaporated to the atmosphere). With a substantial surface flux, salinity no longer behaves conservatively: evaporation creates, in effect, a first-order-kinetics source of salinity in the water column. This means that even in other sections of the system, such as Corpus Christi Bay, in which the mean salinities are intermediate between oceanic and fresh, there are no *a priori* means of determining how much of the resultant salinity value is due to dilution by fresh water because an indeterminate increase is also made due to evaporation. In principle, the procedures of Appendix F (see also Section 2.2.2) could be used to estimate the evaporative-flux increment in salinity, and this could be subtracted from the mean salinity to produce a quasi-conservative residual. The present study did not have the resources to carry out such an analysis, but this would need to be done in any study using salinity as a quantitative measure of freshwater impacts. For present purposes, the distribution of salinity is used as a qualitative measure of freshwater inflow influences, subject to the caveat that high evaporation renders it nonconservative.

The long-term average salinities for each of the Hydrographic Segments are depicted in Figs. 5-17 through 5-21, showing the overall horizontal variation of salinity throughout the study area. For this purpose, the data from which these averages were computed were restricted to near-surface measurements, taken to be the upper 1 meter (3.3 feet) of the water column. Even though vertical stratification is small, as will be seen, this screening was necessary to eliminate any spurious weighting of stations where profile data, and therefore more measurements, were taken. What is striking about the distributions in these figures is that the overall gradient in salinity runs from north to south across the study area, from lowest salinities in the Aransas-Copano system to highest salinities in Baffin Bay, but without clear association with points of major inflow. In the upper section of Corpus Christi Bay, in particular, the gradient to the Nueces River inflow is quite flat.

Within Corpus Christi Bay *per se*, Fig. 5-18, the highest average salinities occur dead center in the bay and (as might be expected) near the entrance to the Laguna Madre. In the Gulf, mean salinities are higher nearshore than offshore, and are depressed slightly around Aransas Pass. However, comparison of the average salinities interior to Corpus Christi Bay to those in the Gulf (the figures indicate the former to be less than the latter) should be done warily since the period of record for the Gulf data is considerably shorter than for the bay, and is biased by more recent data from a rainfall-deficient period. It should be noted that there is no evidence of systematically higher salinities in the open-bay reach of the Corpus Christi Ship Channel. Oso Bay, Fig. 5-19, exhibits a landward decline in salinity, but in its open areas exceeds substantially the salinity of the adjacent Corpus

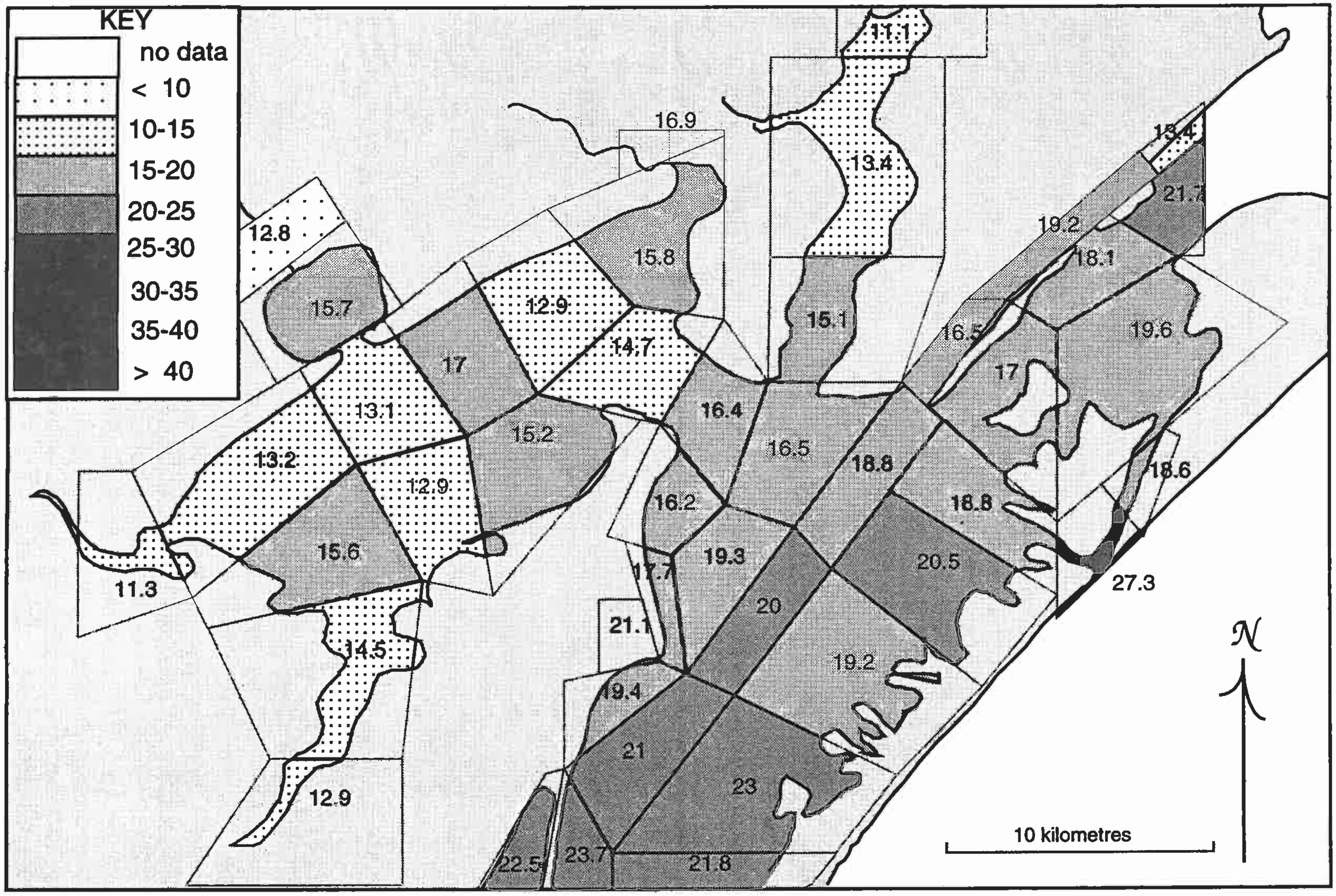


Figure 5-17. Period-of-record mean salinity, upper 1 m, for Aransas-Copano system

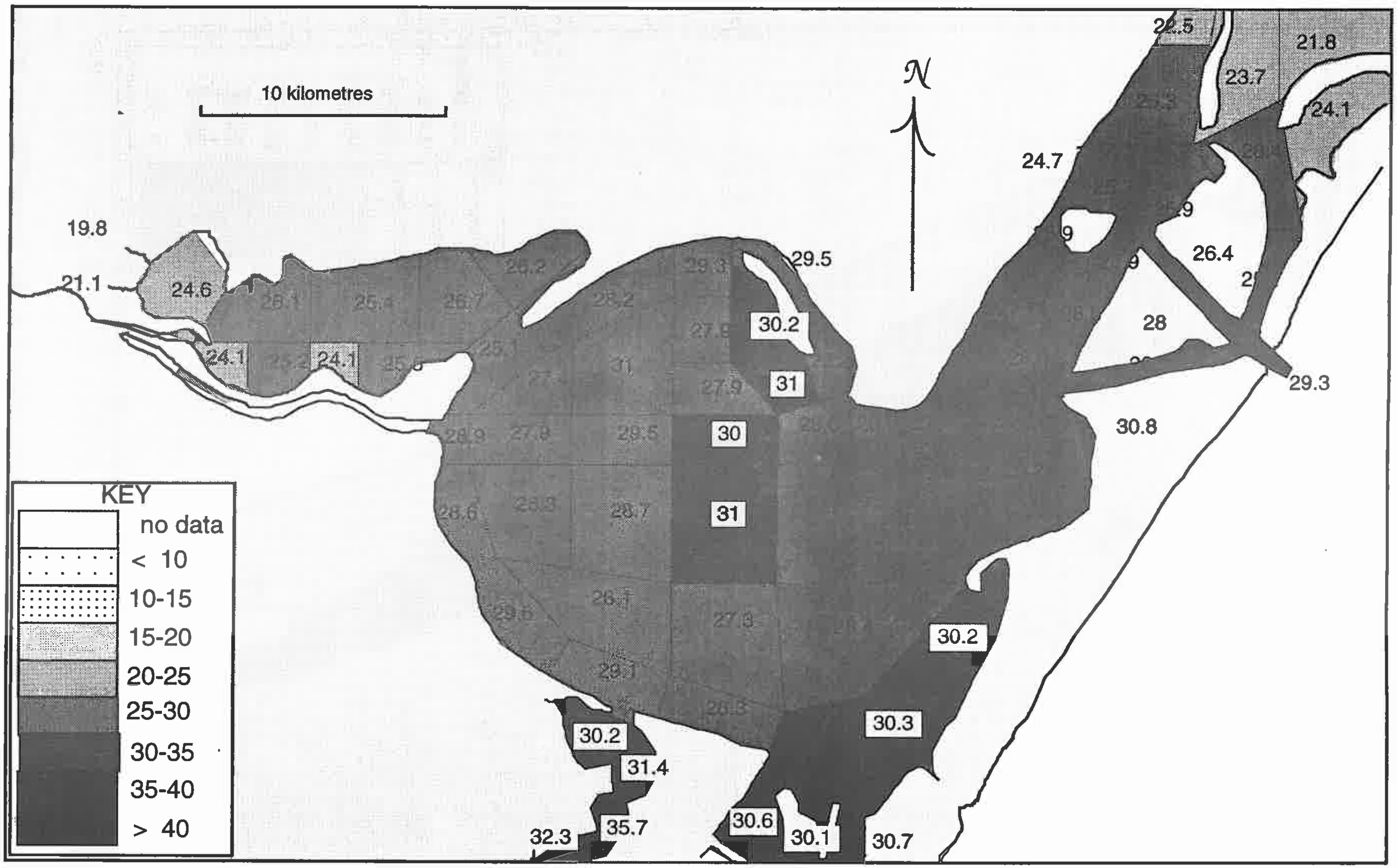


Figure 5-18. Period-of-record mean salinity, upper 1 m, for Corpus Christi system

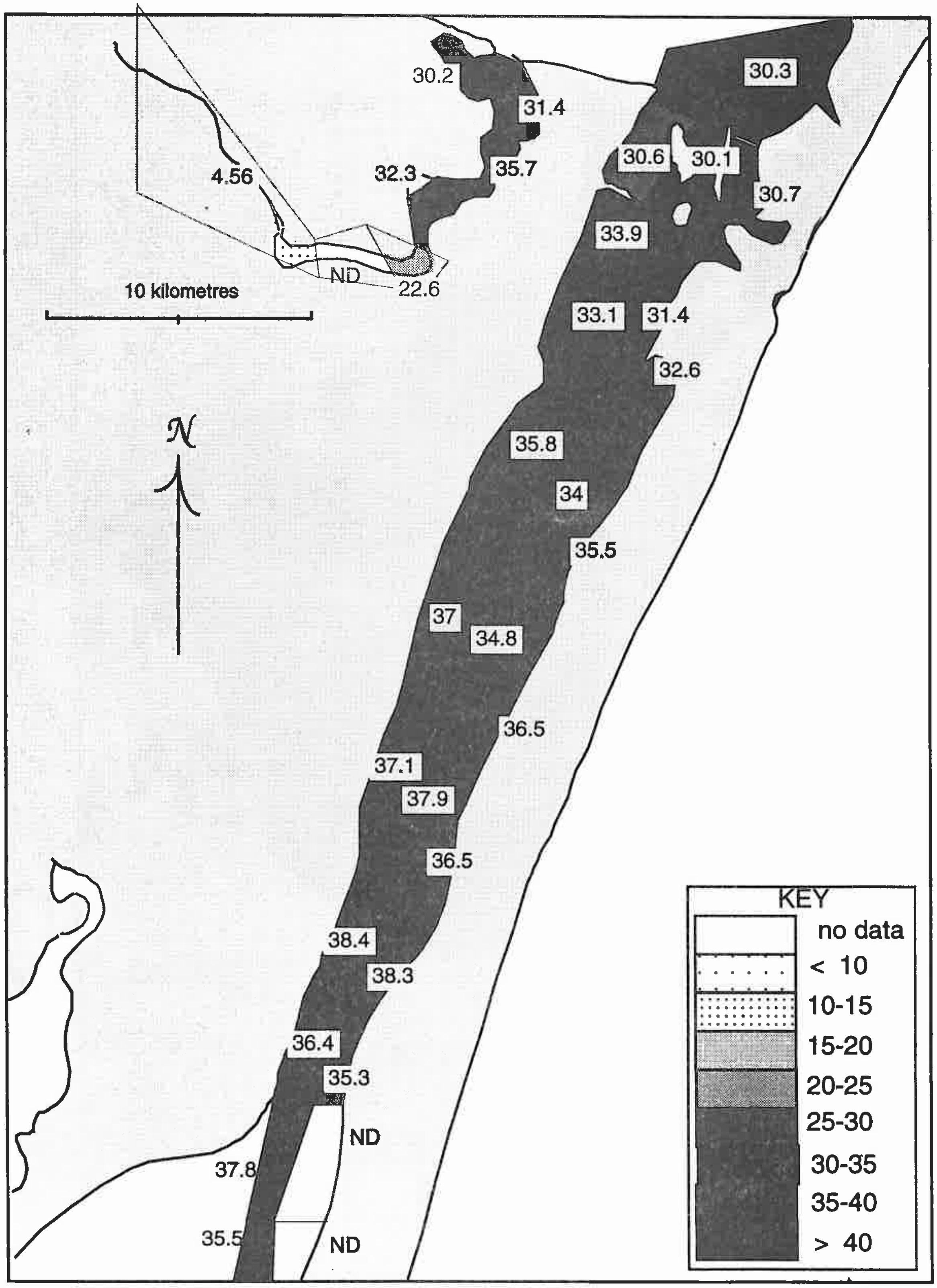


Figure 5-19. Period-of-record mean salinity, upper 1 m, for Upper Laguna Madre

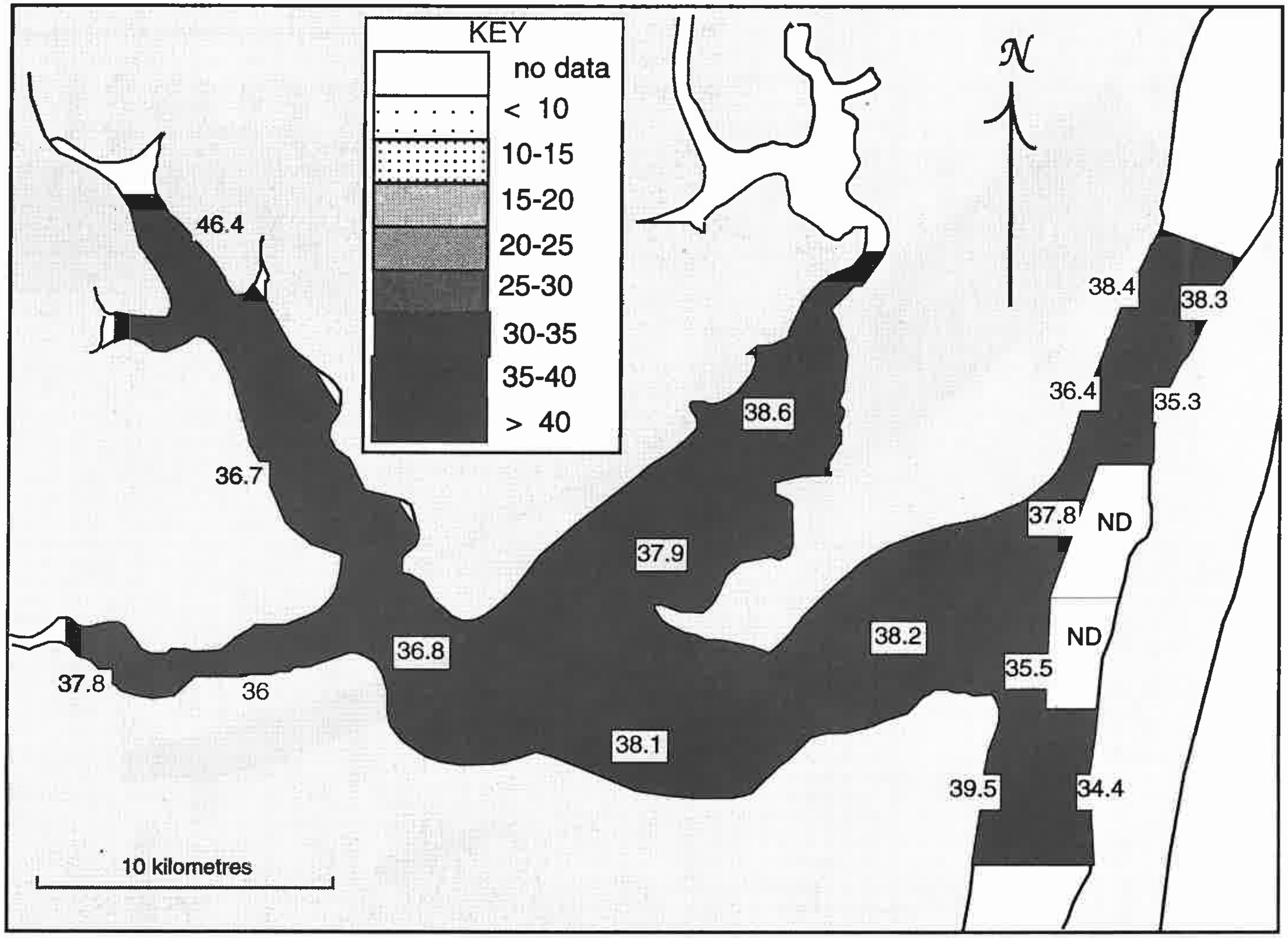


Figure 5-20. Period-of-record mean salinity, upper 1m, for Baffin Bay region

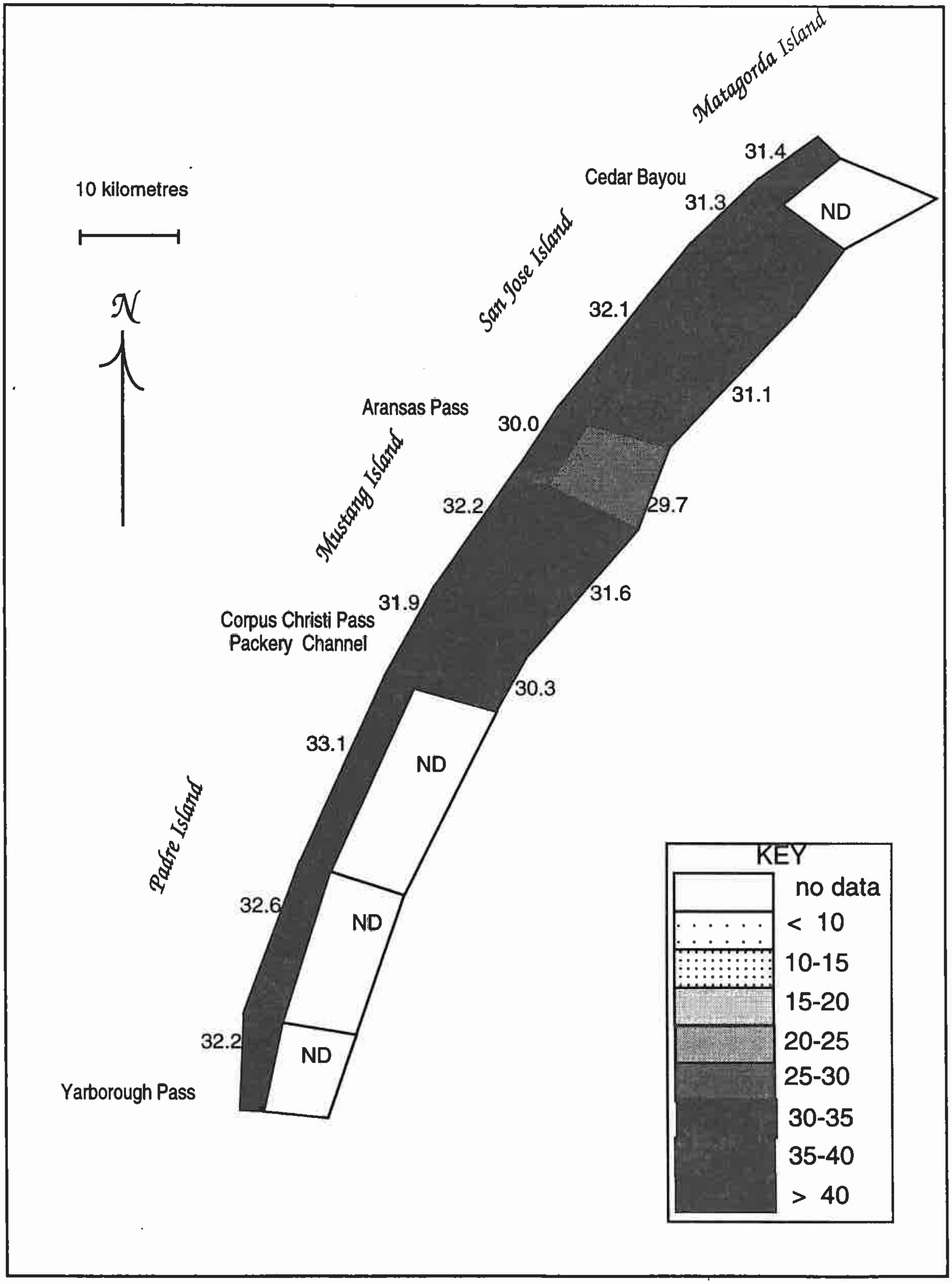


Figure 5-21. Period-of-record mean salinity, upper 1 m, for Gulf of Mexico

Christi Bay. Salinities in the Laguna and Baffin Bay generally exceed those of the adjacent Gulf by several ppt, and in the upper Laguna the GIWW seems to exhibit systematically lower salinities than those of the adjacent shallows. Baffin Bay, the most saline component of the study area, exhibits *increasing* mean salinity landward up the principal tributary arms of the estuary, Fig. 5-20.

The variability of salinity is as important as its mean value. This is measured by the period of record standard deviation for each Hydrographic Segment (again, restricted to measurements in the upper 1 m), shown in Figs. 5-22 through 5-26. The variance of salinity is clearly quite large in the Corpus Christi Bay system. There appear to be two controlling factors governing the spatial distribution of variance: proximity to a source of freshwater inflow and range of variation of salinity. The former refers to the zone of maximum interplay between freshwater inflows and intrusion of higher salinity water, not only the mouths of rivers, but the passes to brackish secondary bays, such as Nueces. The greatest range of salinity is in the Baffin system, due to the high evaporation rates, and therefore the variance is greatest here. The smallest variances are found in the nearshore Gulf of Mexico.

The extent of vertical stratification in salinity is an important parameter of any estuarine environment. First, salinity, as a tracer, provides a direct measure of the intensity of vertical mixing. Second, salinity in fact is a prime control on vertical mixing, since it in effect governs density stratification. Water density is in general governed by both temperature and salinity, but in an estuary, the wide range of salinity coupled with the small range of temperature means that salinity, for practical purposes, determines density. This is illustrated by Fig. 5-27, showing contours of density versus salinity and temperature for estuarine ranges. The intensity of vertical mixing in the Texas bays, and the resulting vertical homogeneity of the water column has been frequently remarked. The Corpus Christi Bay data base was used by Ward and Armstrong (1997a) to quantify vertical stratification in several important parameters, substantiating their near-homogeneity in the water column. Vertical stratification VS is computed as the vertical gradient in concentration between the two most widely separated measurements in the vertical (for a specific sample station and date):

$$VS = \Delta c/\Delta z$$

where Δc is the upper-to-lower difference in concentration, and Δz is the difference in elevation of the two measurements with z positive upwards. It must be emphasized that *stratification* is treated in its fluid dynamics sense, and does not imply any "layering" of the water (which entails quantum changes in parameter values at an interface). Such "layering" and associated concepts, such as the notorious "salt wedge," are rare and evanescent phenomena in Corpus Christi Bay. The units of stratification are parameter units per unit depth, e.g. for salinity, ppt per meter, and VS is positive if concentration increases upward. Therefore, a normal stable density stratification would imply a stratification in salinity that is negative.

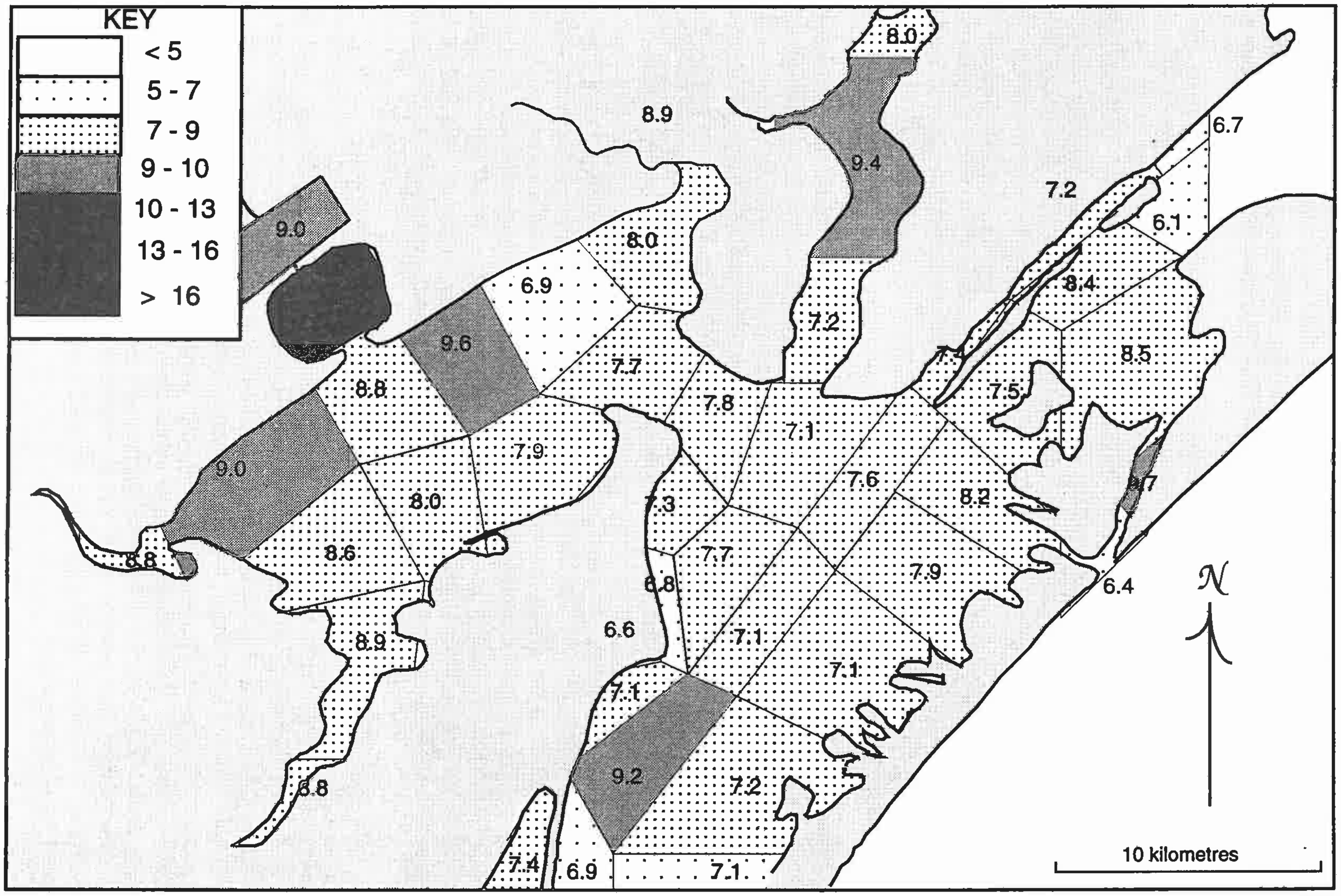


Figure 5-22. Standard deviation (ppt) of near-surface salinities, Aransas-Copano Bay

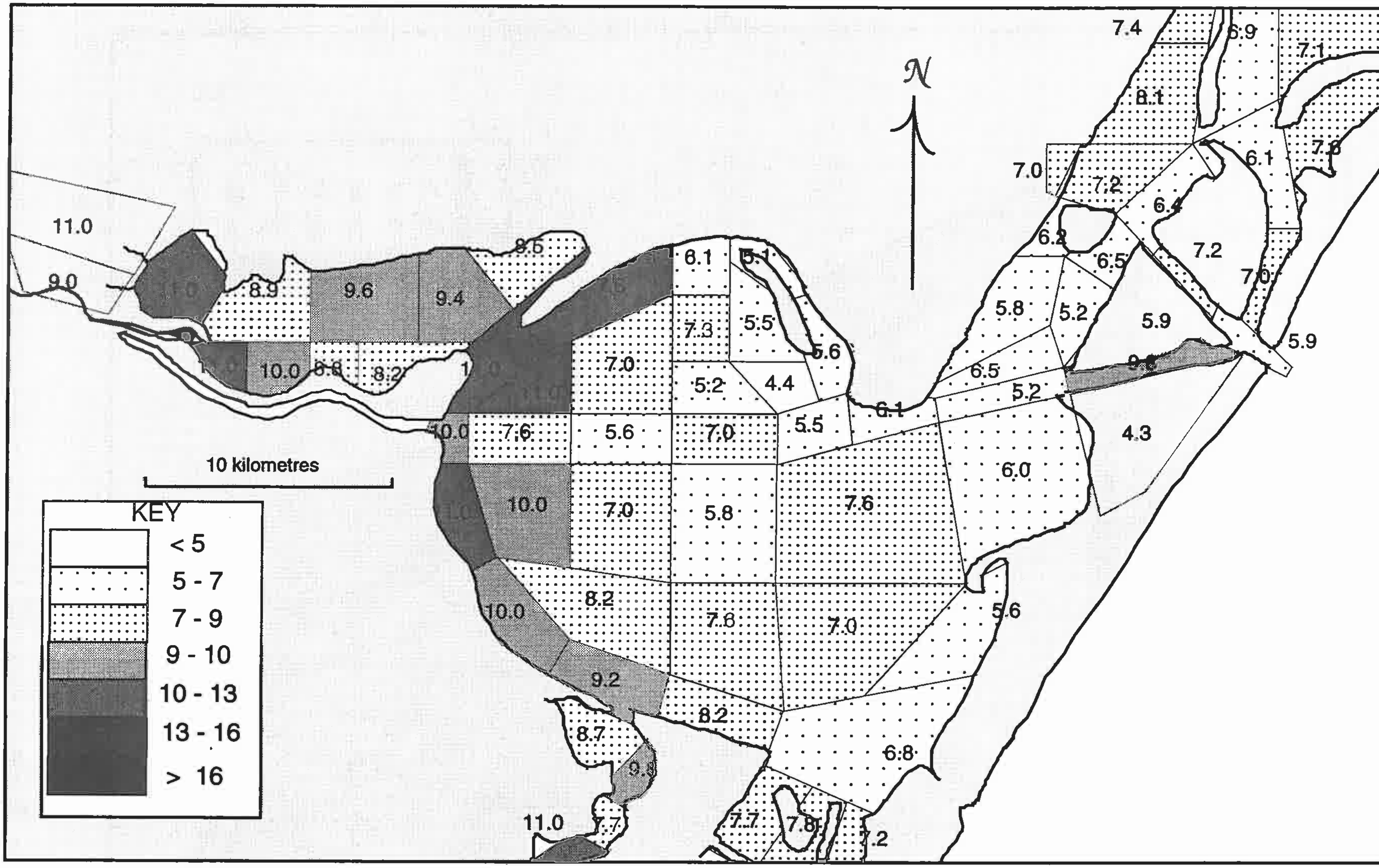


Figure 5-23. Standard deviation (ppt) of near-surface salinities, Corpus Christi Bay

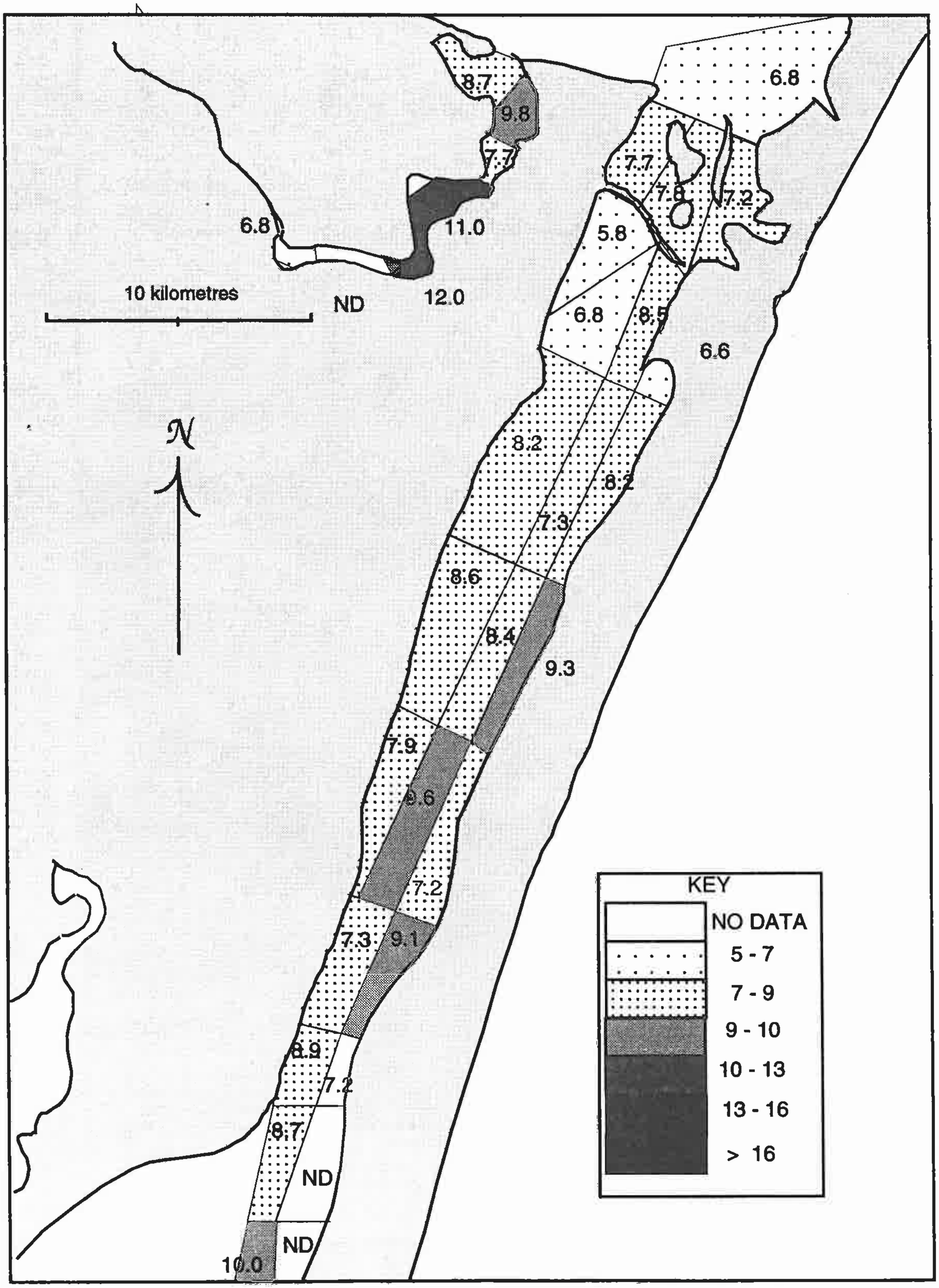


Figure 5-24. Standard deviation (ppt) of near-surface salinities, Upper Laguna Madre

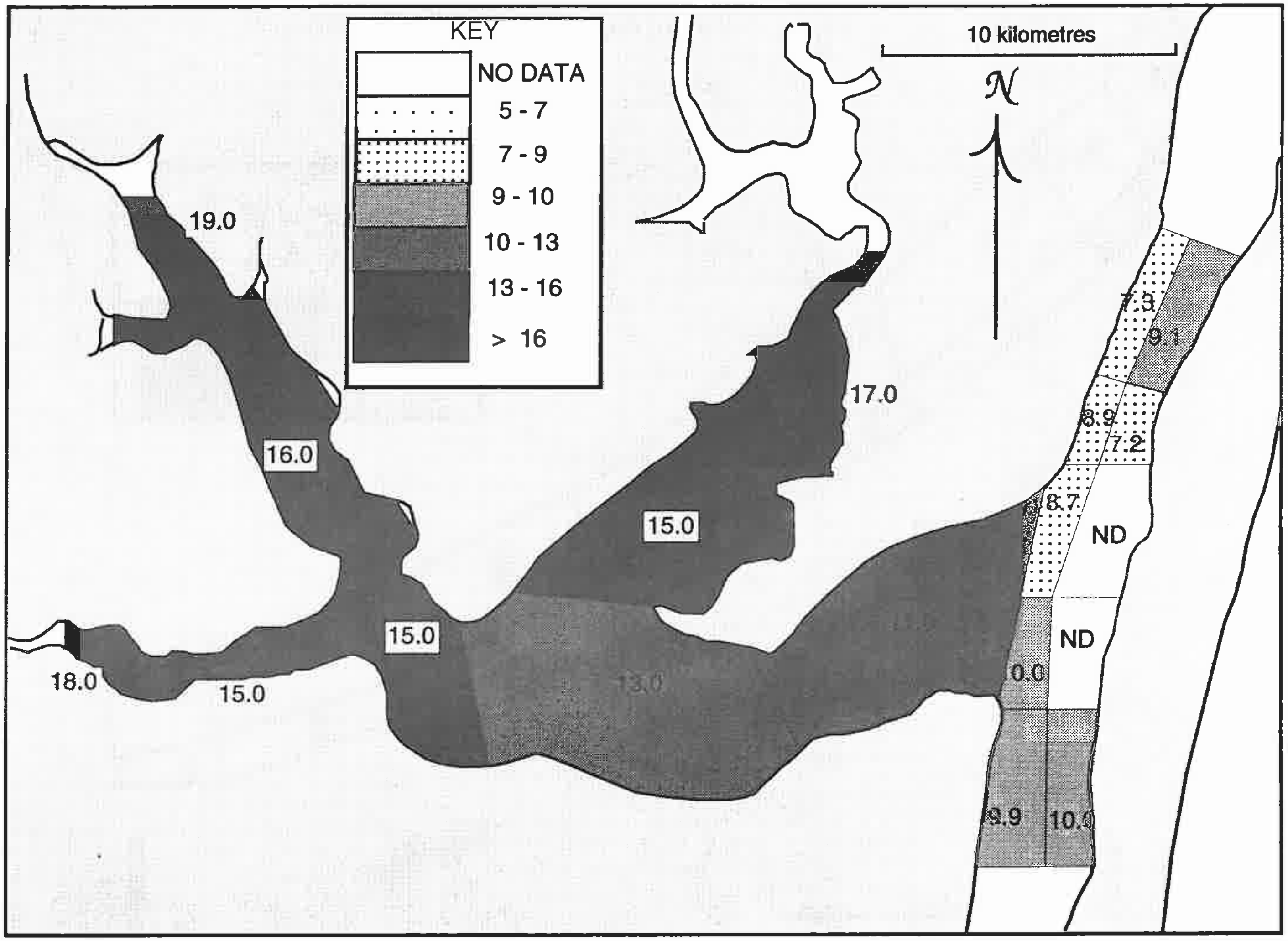


Figure 5-25. Standard deviation (ppt) of near-surface salinities, Baffin Bay

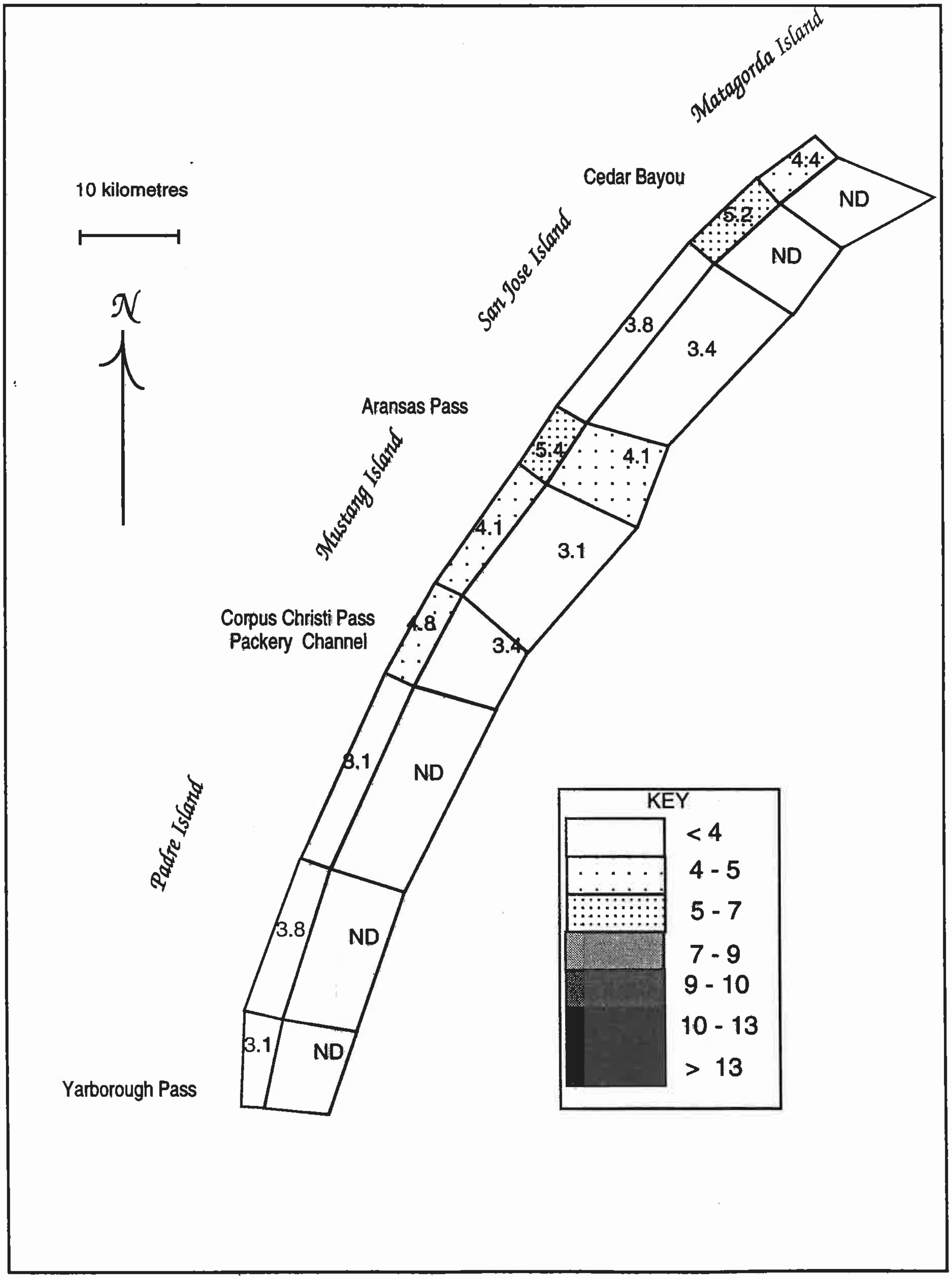


Figure 5-26. Standard deviation (ppt) of near-surface salinities, Gulf of Mexico

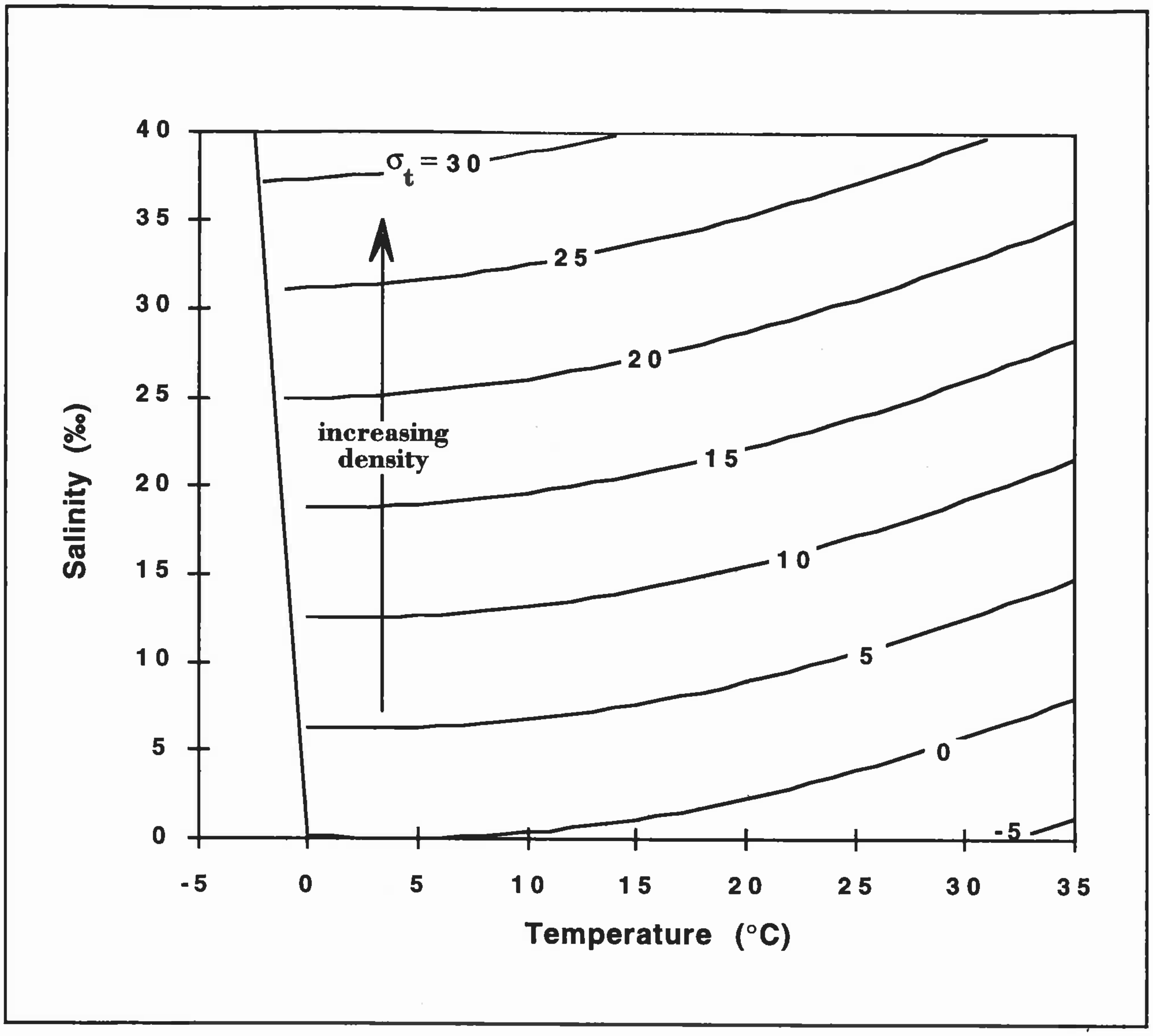


Figure 5-27. Water density as a function of temperature and salinity, based upon the International Equation of State 1980 for seawater. Density ρ (kg m^{-3}) = $\sigma_t + 1000$.

The distribution of salinity stratification as a function of space is depicted by Hydrographic Area in Fig. 5-28 through 5-31. The Gulf of Mexico is not shown separately because the available profile data allowed calculation of stratification in only two segments, both out from Aransas Pass. Mean salinity stratification at the inshore segment is -0.13 ppt/m, and at the offshore segment -0.06 ppt/m. The average salinity stratification by component bay is summarized in Table 5-13. In this table, Bulkhead Flats refers to the shoal area through which the JFK Causeway is constructed, the part in Corpus Christi Bay referred to as "North" and in the Laguna Madre as "South," relative to the Causeway.

Average salinity stratification is remarkably uniform through the bay, given its noisy character, and is almost exclusively negative, as would be expected given the effect of salinity on buoyancy. In magnitude, the vertical (negative) salinity gradient is less than 0.5 ppt/m nearly everywhere, and less than 0.3 ppt/m throughout about half of the study area. Thus, the long-term average data support the general statement that the system is practically homogeneous in the vertical. The largest values of this (small) vertical gradient occur primarily in regions affected by inflow. There is no dependence of stratification on water depth evidenced in the long-term averages; in particular the deepdraft Corpus Christi Ship Channel does not exhibit a rate of stratification different from the adjacent water. Reversed stratification does occur in the system (i.e., stratification in

Table 5-13
Stratification in salinity by component bay

Component Bay	*no. of obs*	*strat ppt/m*	*st dev ppt/m*	*percent positive*
Aransas Bay	538	-0.40	1.24	14
Copano Bay	486	-0.35	1.12	10
St Charles Bay	75	-0.37	1.24	12
Mesquite Bay	161	0.29	2.63	22
Redfish Bay	263	-0.62	1.29	16
Corpus Christi Bay	1719	-0.32	1.06	14
CCSC (bay reach)	430	-0.25	0.52	13
Inner Harbor	487	-0.21	0.50	23
Nueces Bay	404	-0.46	3.31	21
Aransas Pass	245	-0.13	0.87	14
Bulkhead Flats N	223	-0.16	0.67	16
Bulkhead Flats S	132	-0.14	1.06	33
Laguna (King Ranch Reach)	310	-0.12	1.27	24
Laguna (Baffin Bay Reach)	106	-0.01	2.10	42
Baffin Bay	451	0.05	3.07	33

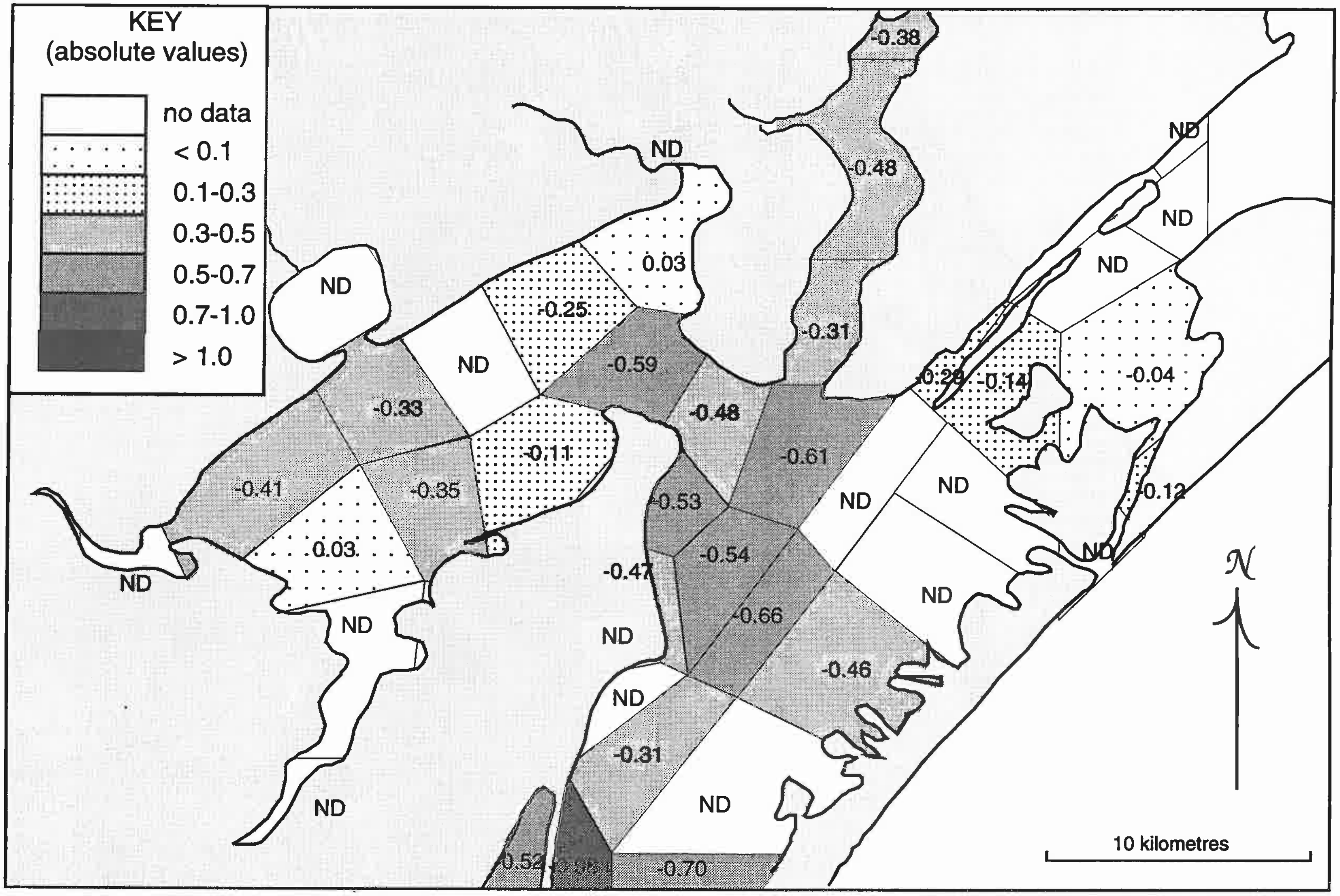


Figure 5-28. Vertical stratification in salinity (ppt/m), Aransas-Copano Bay

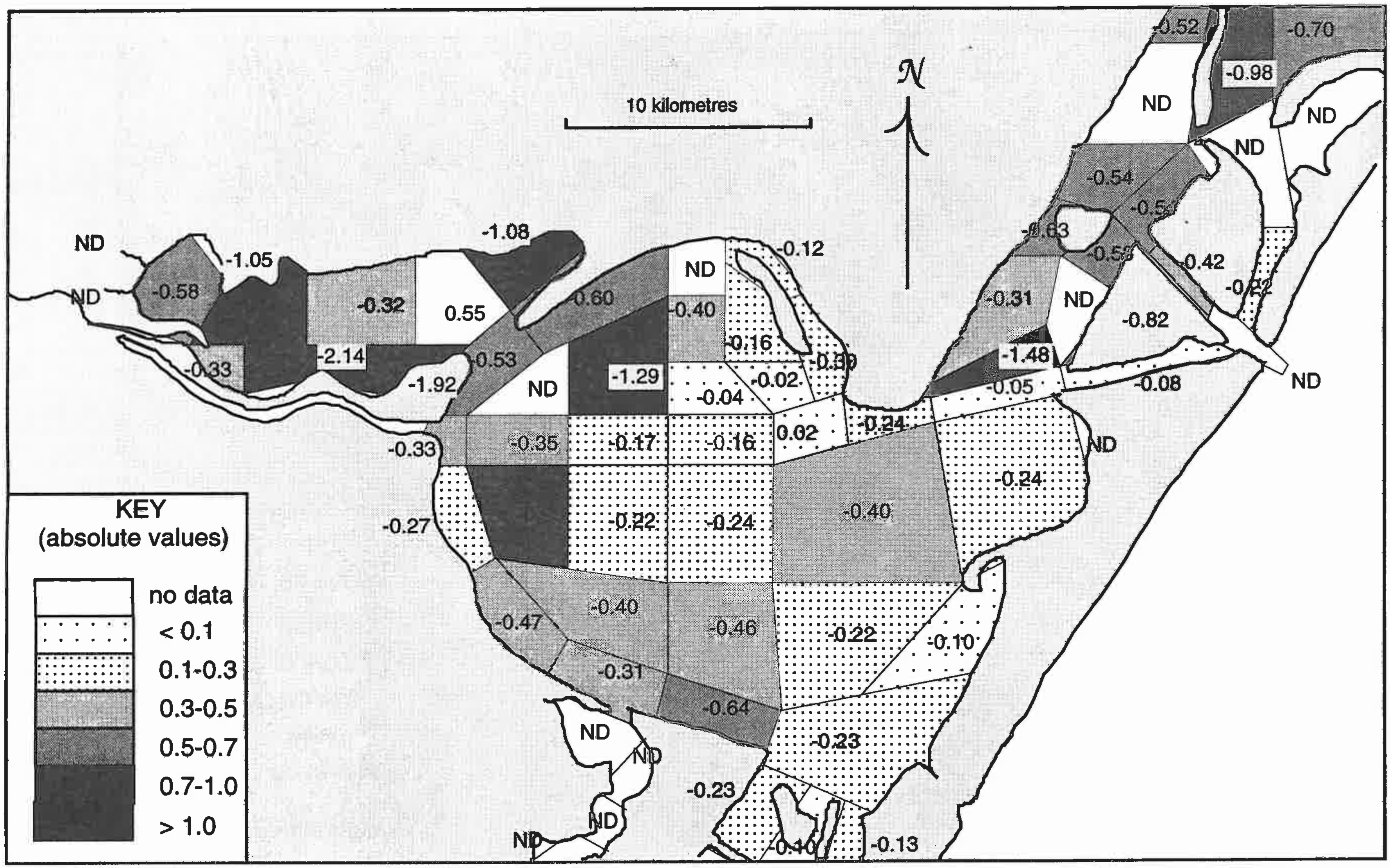


Figure 5-29. Vertical stratification in salinity (ppt/m), Corpus Christi Bay

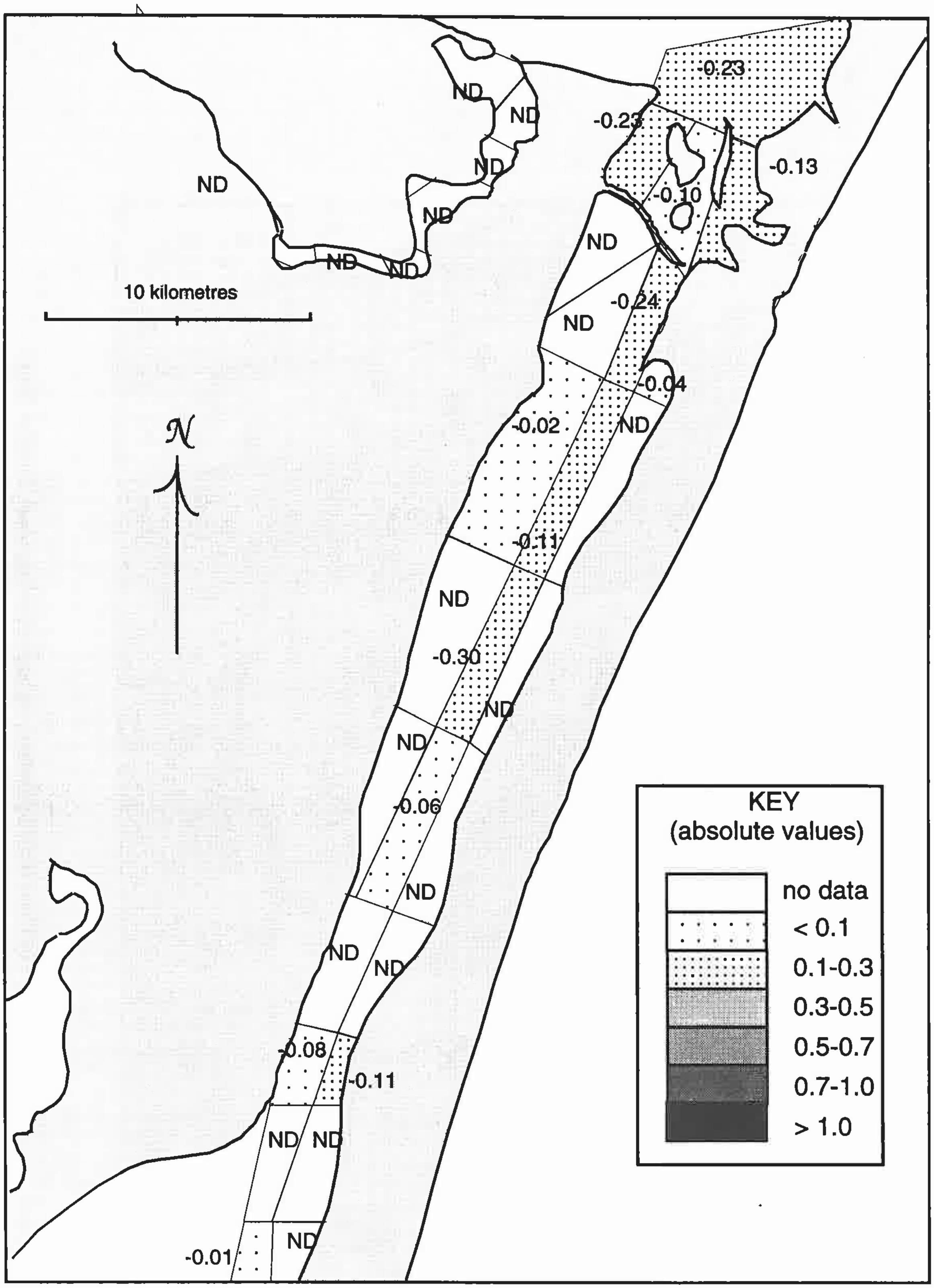


Figure 5-30. Vertical stratification in salinity (ppt/m), Upper Laguna Madre

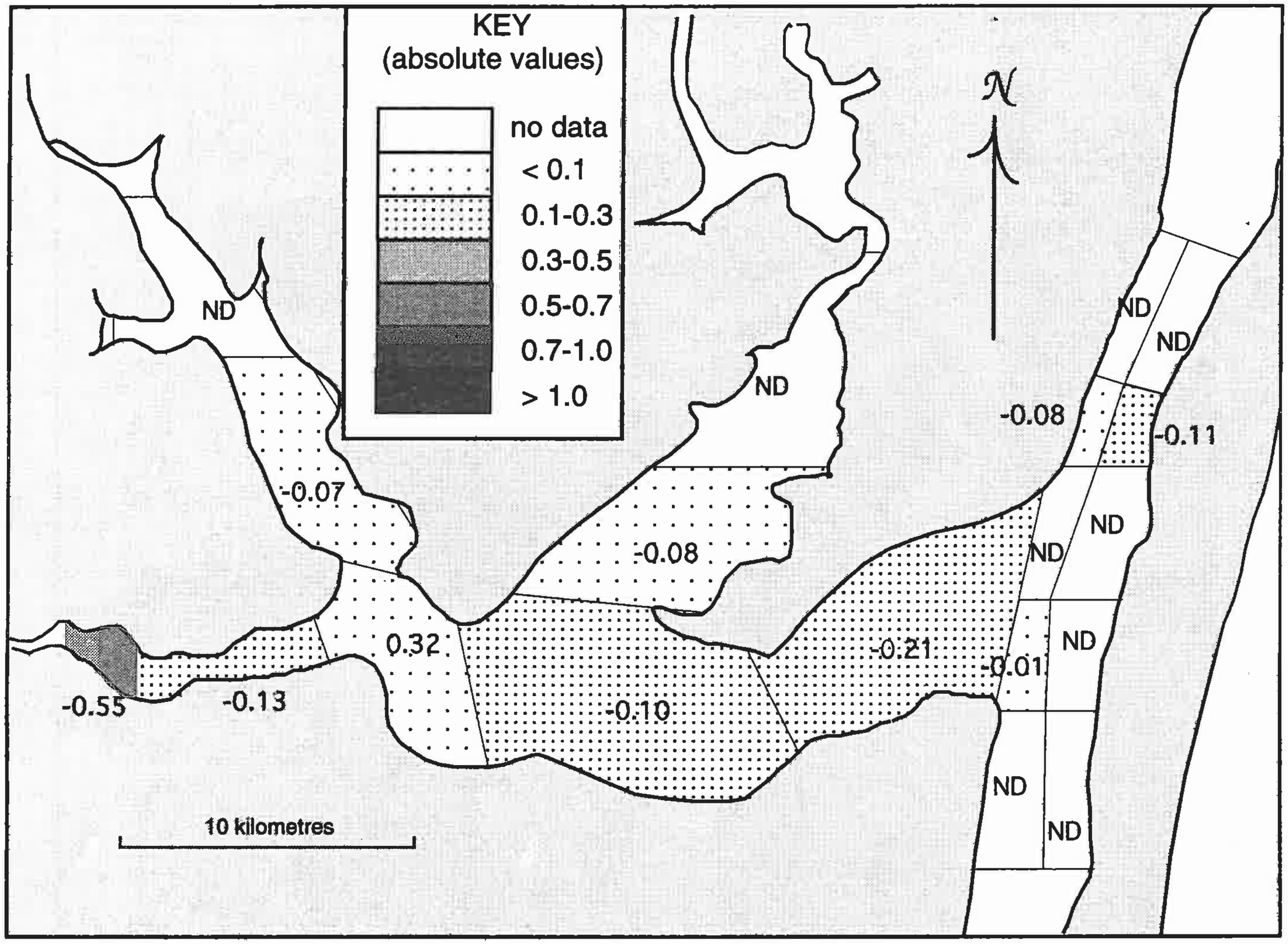


Figure 5-31. Vertical stratification in salinity (ppt/m), Baffin Bay

which the upper salinities exceed the lower), especially in the regions whose salinities exceed seawater. For the period of record, 10-20% of the time, stratification is positive in the upper bays. This does not represent a violation of gravity, but rather the vigor of vertical mixing processes in comparison to the weak density stratification. This is yet another illustration of the natural hydrographic variability of the Corpus Christi Bay environment.

5.4.3 Time variation of salinity

Variability of salinity with time is implicit in the mapping of segment standard deviations of Figs. 5-22 *et seq.*, in that the principal source of this high variability is salinity variation with time. In order to explore the causes of this time variability, it is examined in more detail. Presuming that the main source of variation in salinity is hydroclimatological, we would expect to find a more-or-less regular seasonal variation of salinity, as is the case for the estuaries on the upper Texas coast. In Figs. 5-32 and 5-33 are shown the monthly-mean salinities for, respectively, the component bays and specific subareas of the system. Perhaps surprisingly, there is no clear seasonal variation in salinity in the Coastal Bend bays other than a proclivity for slightly higher salinities in the summer months. Only Nueces Bay exhibits a depression that could be characterized as an average freshet response, and this is a depression of only 7 ppt in June.

Time trend analysis was performed by Ward and Armstrong (1997a) by a linear least-squares regression of the measurements in each Hydrographic Segment versus time. Reference is made to that report for details of analysis, and complete tabulations of the results. For the purposes of the present study, the most important regression parameter is the slope of the trend line, as it is the key indicator of a systematic change in salinity. This is the average (in the least-squares sense) rate of increase (if positive) or decrease (if negative) in the magnitude of salinity, in ppt per year. Not only is the magnitude of the computed trend important, but also its "reality," which can be judged by the signs of the upper and lower confidence bounds. The confidence bounds for a specified level of probability quantifies how likely the computed trend is to agree with the *real* trend. A *probable trend* is defined to be one for which *both* of the 95% confidence bounds have the same sign. This means there will be a 1/40 failure rate (i.e., Type-I error, slope judged as significant when it is not), so this is a very stringent definition of "probable." A *possible* trend is similarly defined as one in which both of the 80% confidence bounds have the same sign, i.e. a 1/10 risk of misjudging the sign of the trend. It should also be noted, however, that a least-squares trend line is not judged by its explained variance (or linear correlation coefficient) because we are not seeking to *explain* the observed variability in a parameter *only* in terms of the passage of time. Indeed, considering the many sources of variation in the Corpus Christi system, we expect time to be a relatively minor contributor to systematic variation in salinity. Even if such a trend line "explains" only, say, 1 per cent of the variance of salinity in a given Hydrographic Segment, it can still provide insight into long-term alterations in the salinity.

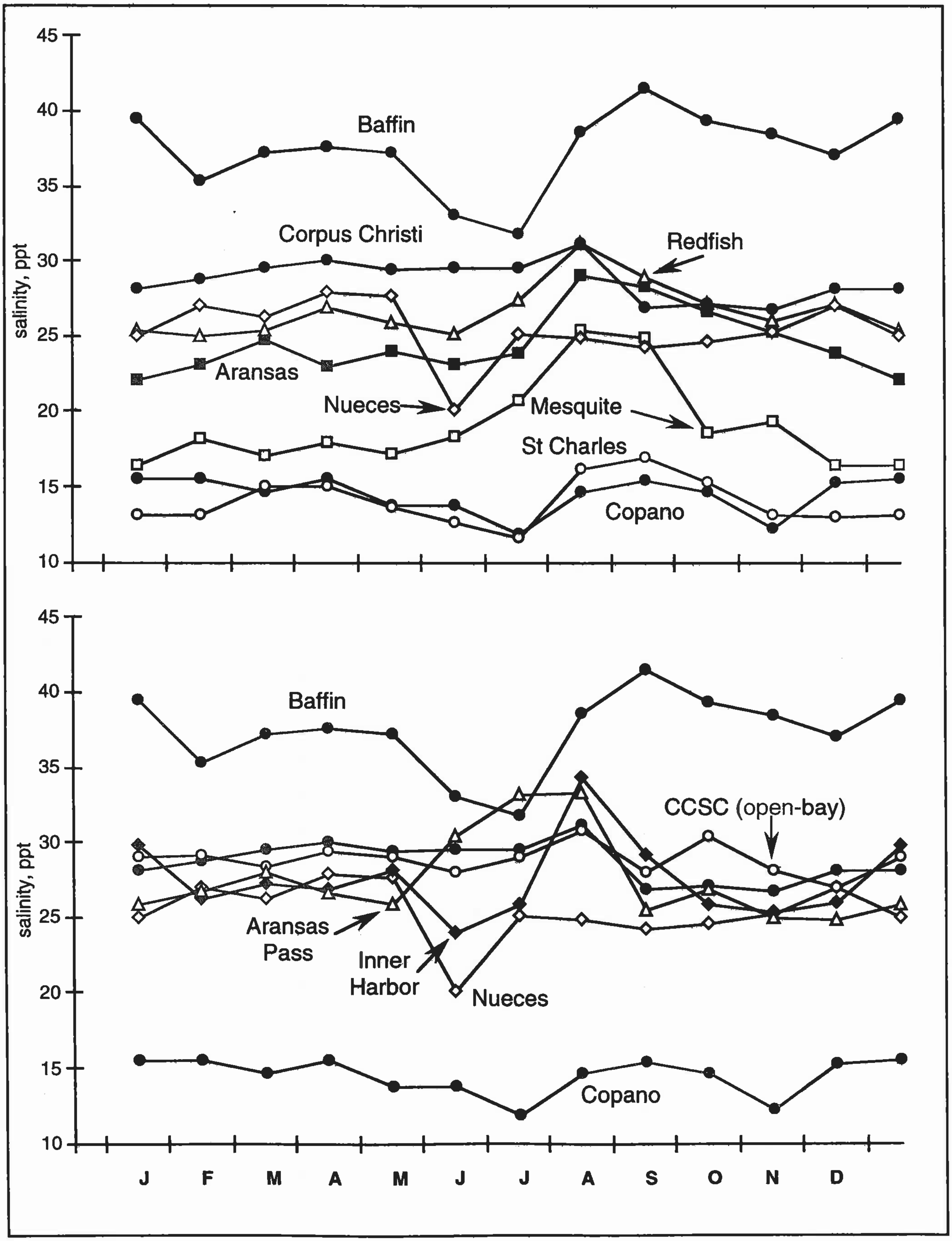


Figure 5-32. Period-of-record monthly-mean salinity, upper 1 m, principal bays (above) and Corpus Christi Bay region (below)

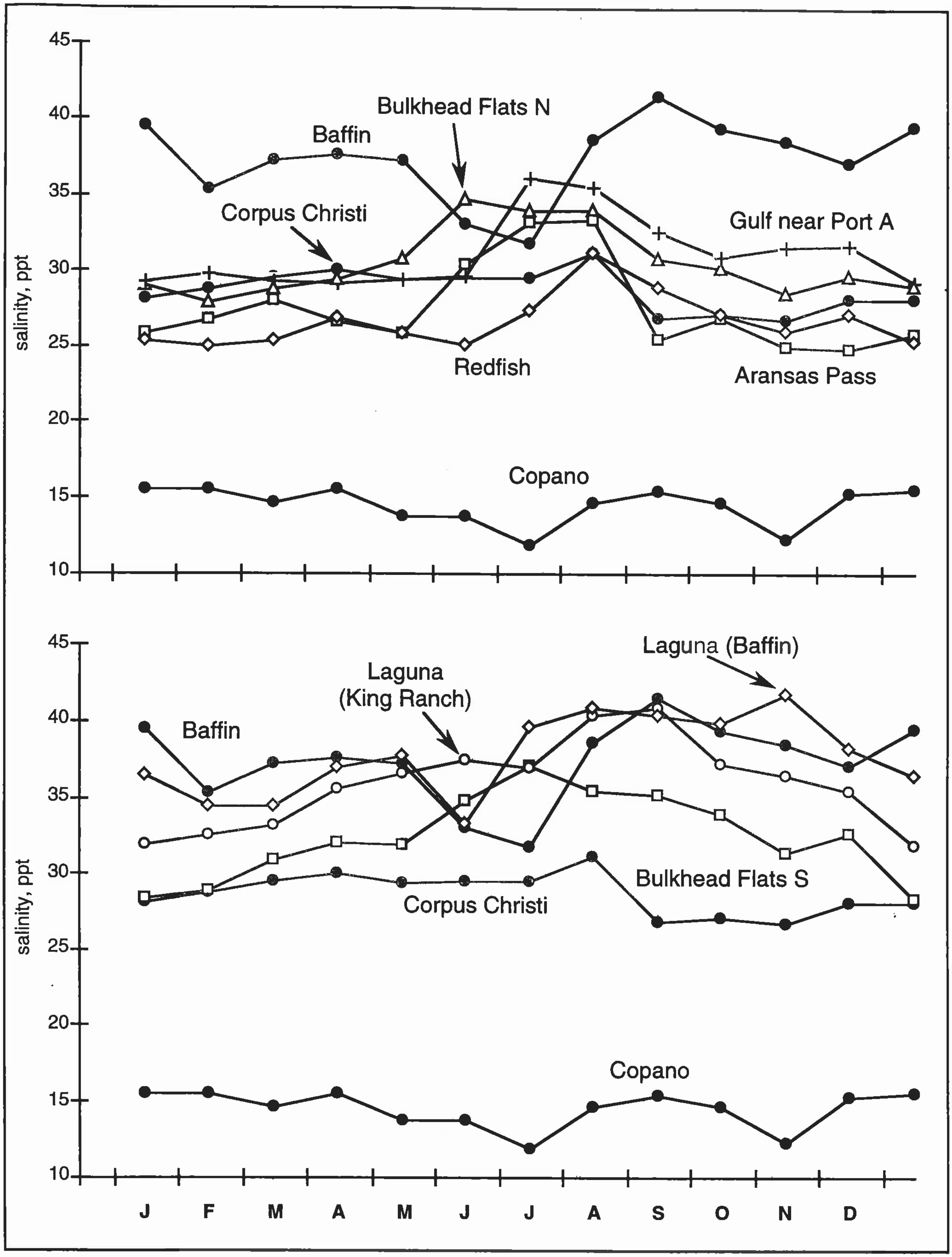


Figure 5-33. Period-of-record monthly-mean salinity, upper 1 m, barrier island region (above) and Upper Laguna region (below)

As in any statistical inference, establishing the slope and intercept of a linear trend line is subject to the assumption that the available data are an adequate sampling of the population. We note also that this analysis does not distinguish between a statistically unresolvable trend and a trend of zero. In this respect, the behavior of salinity in neighboring areas of the bay should be used in determining whether to accept the statistical calculation of trend. The present analysis has a distinct advantage in statistical interpretation compared to the usual problem of interpreting a trend analysis of a set of data, namely that here the data has been sorted into separate geographical segments, each one of which represents an *independent* data set for trend analysis. This not only provides insight into spatial variation in salinity in Corpus Christi Bay, but also uses the regional coherence of trends as a strong indicator of whether the trends are real or are some statistical artifact (including the 1/40 chance of occurring by random variation).

In Figs. 5-34 through 5-38, from Ward and Armstrong (1997a), the distribution of long-term changes in salinity is depicted graphically by zones of "probable" and "possible" trends. For example, in Copano Bay, Fig. 5-34, each of segments except one displays an *increasing* trend in salinity, either possible or probable. The data set for each segment is drawn from different projects at different times, and the periods of analysis differ. One might be tempted to dismiss the fitted trend for any one of these segments as a statistical artifact. But taken together, the trends in these eight segments argue for the reality that salinity is increasing in Copano Bay, an inference that is further supported by the probable increasing trends in Port Bay, St. Charles Bay, and the inlet cove of the Aransas. In other cases, the spatial distribution of trends has no obvious coherence, and one must carefully inspect the data base for each segment to determine which is probably more reliable. An example is near-surface salinity in Baffin Bay, Fig. 5-37, which trends upward in some segments, downward in others. The periods of record are long, dating back to the 1950's, and the number of samples per year are about equal. One is forced to the conclusion that either one or more of these trends is an artifact, improbable though that may be, or there are local or regional influences on salinity that affect areas of the bay in different ways. The reduction of oil-well brine disposal activities in the upper tributaries of Baffin may account for the declining trends in these areas, and the main-axis increases may be due to declining precipitation and runoff.

A summary of the statistical trends is given in Table 5-14 by component bays, including mean magnitudes of trends in declining or increasing salinity. Clearly, regions of the study area exhibit well-defined trends in salinity, notably Copano Bay, St. Charles Bay, Nueces Bay and most of the open areas of Corpus Christi Bay. The average rates of increase for these bays given in Table 5-14 are not trivial. Over two decades (say), these would translate to increases in average salinity of: Copano Bay, 1.6 ppt; Corpus Christi Bay, 1 ppt; and Nueces Bay, 5 ppt.

In seeking a possible explanation for these trends, the obvious control to examine is freshwater inflow. With respect to the gauged flow of the Nueces, a linear decreasing trend in the monthly mean flows is indeed disclosed, with rate 29 cfs per year. This trend line superposed on the time series of monthly flows is shown

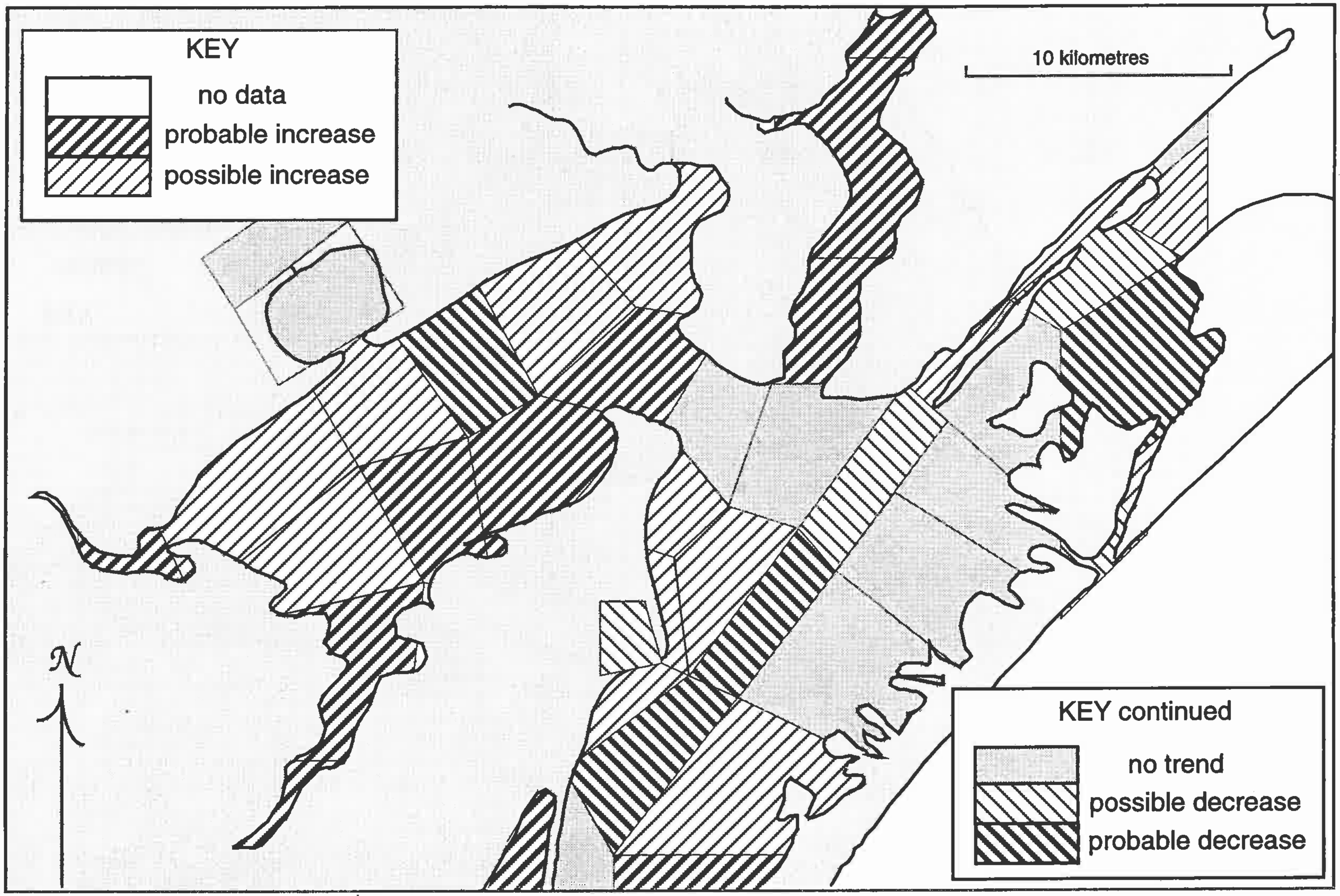


Figure 5-34. Period-of-record time trends in salinity, upper 1 m, for Aransas-Copano system

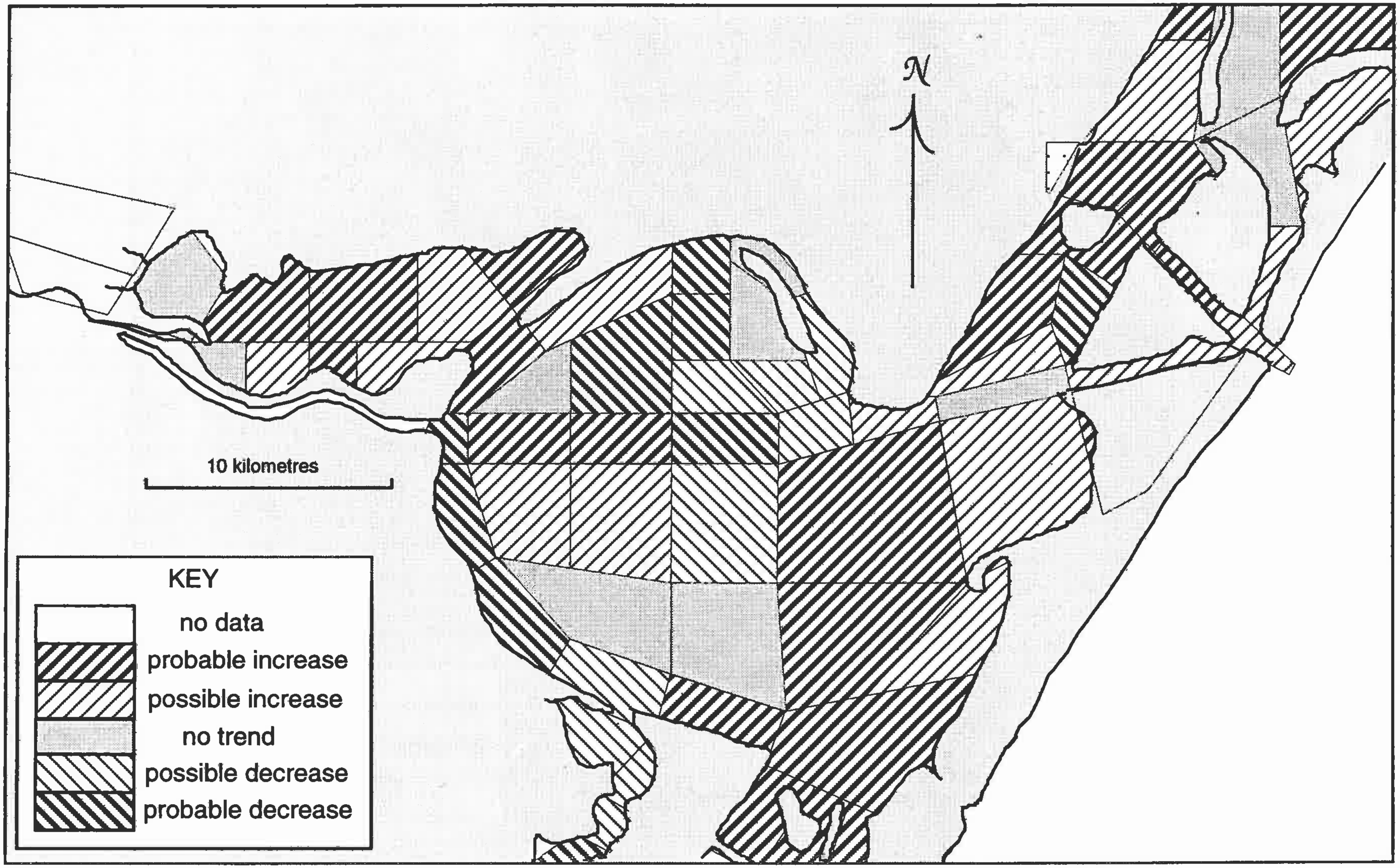


Figure 5-35. Period-of-record time trends in salinity, upper 1 m, for Corpus Christi system

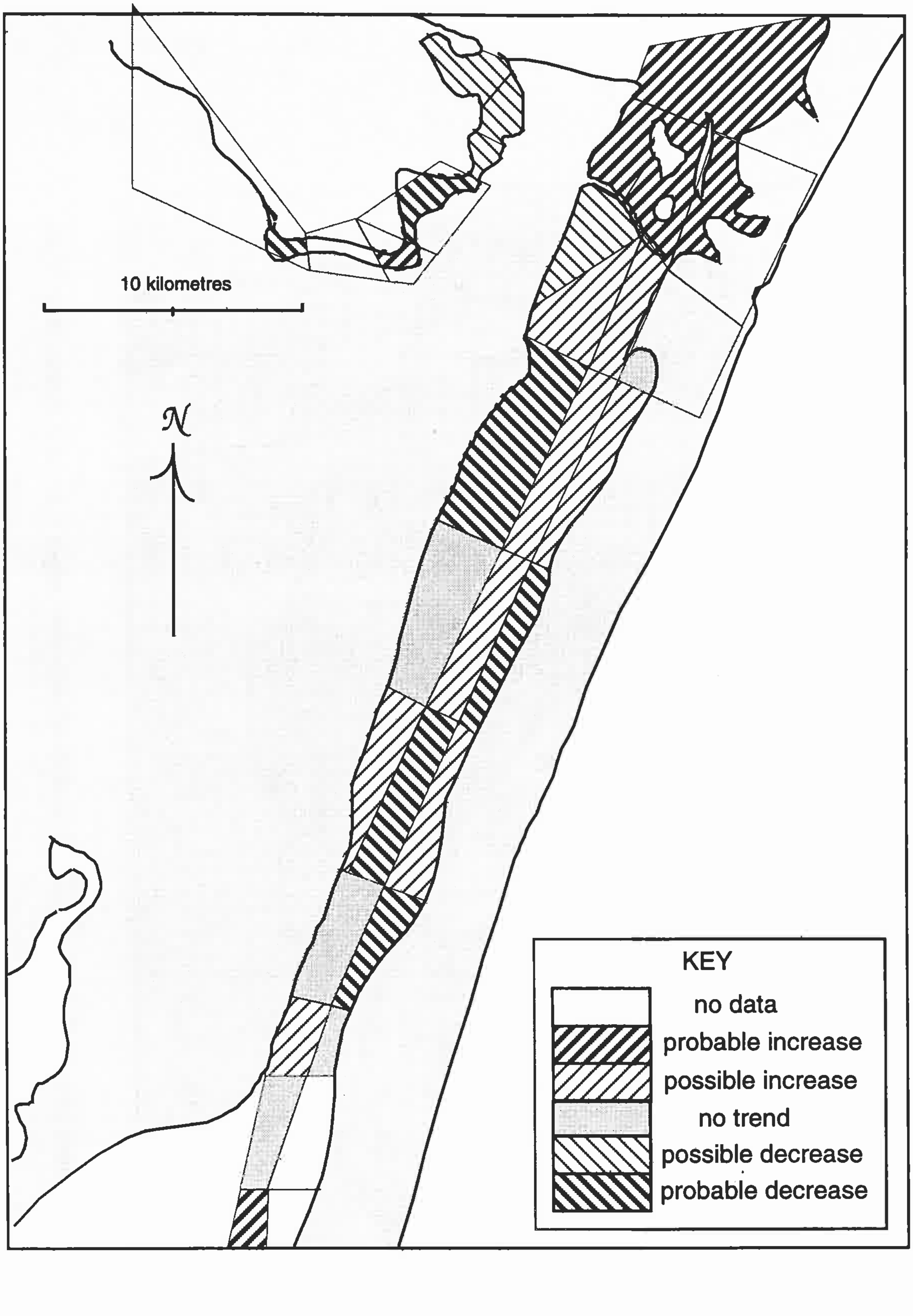


Figure 5-36. Period-of-record trends in salinity, upper 1 m, for Upper Laguna Madre

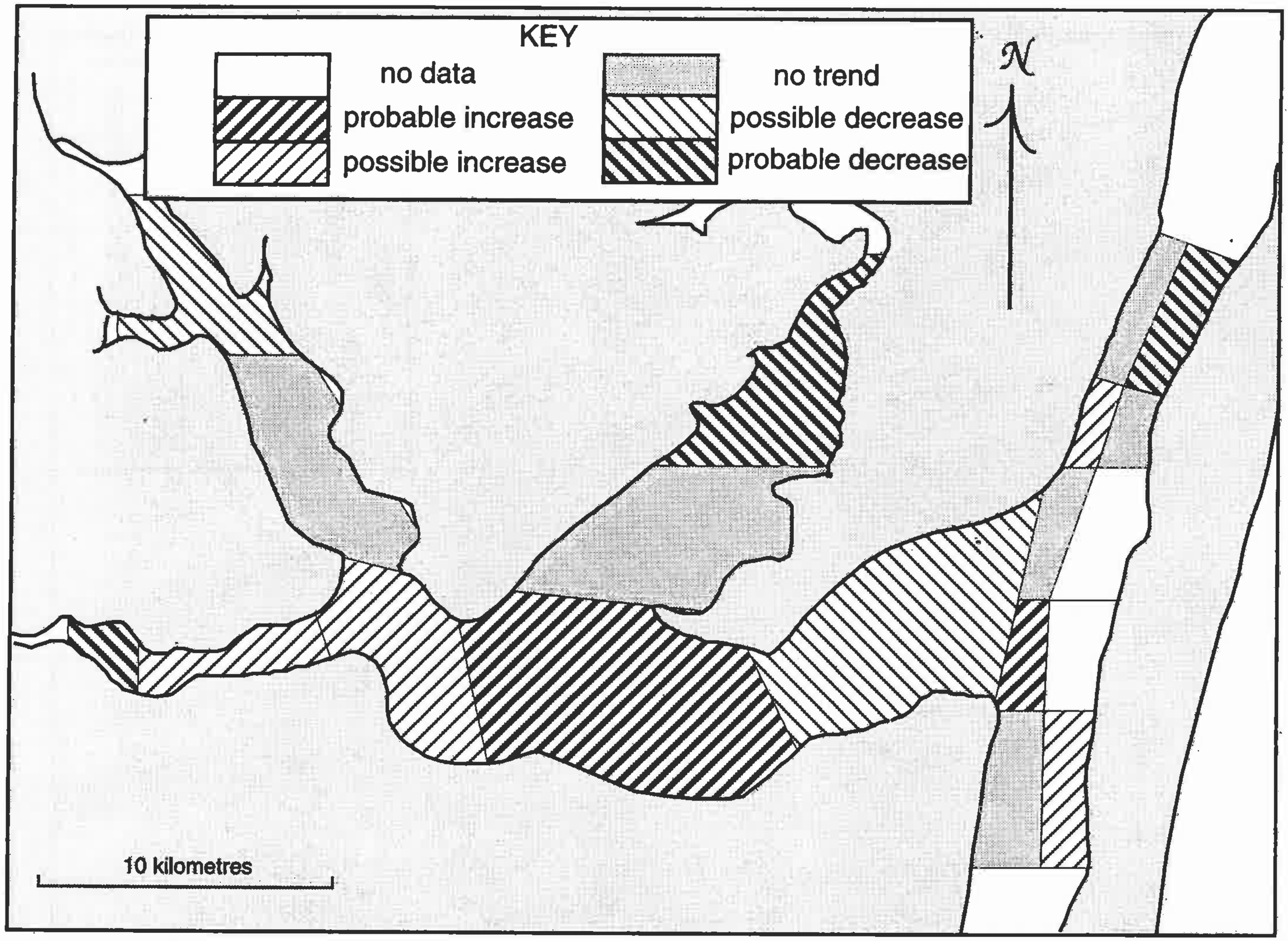


Figure 5-37. Period-of-record time trends in salinity, upper 1 m , for Baffin Bay region

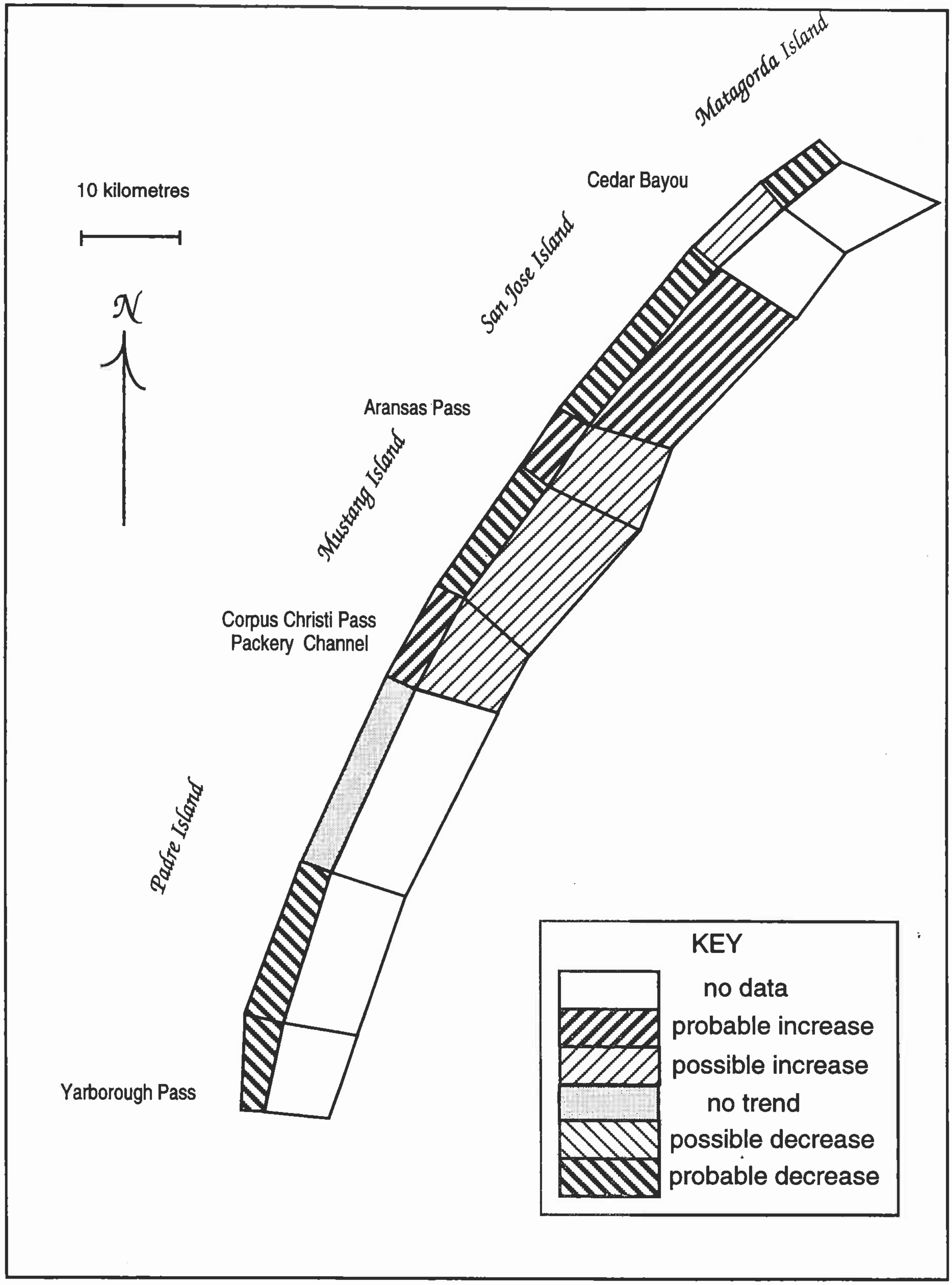


Figure 5-38. Period-of-record trends in salinity, upper 1 m, for Gulf of Mexico

Table 5-14
Trend analyses for salinity, upper 1 metre, from Ward and Armstrong (1997a)
Summary by component bay:
Fraction of Hydrographic Segments with data exhibiting indicated trend and average value of slope for segments with probable trends

component bay	*Percent of segments with trend*					*mean slope of trend (ppt per year)*	
	prob <0	*poss <0*	*none*	*poss >0*	*prob >0*	*mean prob<0*	*mean prob>0*
Aransas Bay	0	7.7	53.8	23.1	15.4		4.17×10^{-2}
Copano Bay	11.1	0	0	55.6	33.3	-3.56×10^{-2}	8.11×10^{-2}
St Charles	0	0	0	0	100		2.62×10^{-1}
Mesquite	25	25	25	25	0	-5.25×10^{-2}	
Redfish	12.5	0	0	25	62.5	-1.66×10^{-2}	1.63×10^{-1}
Corpus Christi	25	20	20	15	20	-5.25×10^{-2}	4.66×10^{-2}
CCSC (bay)	20	20	0	20	40	-2.54×10^{-2}	9.54×10^{-2}
Inner Harbor	14.3	14.3	0	14.3	42.9	-8.04×10^{-2}	2.19×10^{-1}
Nueces Bay	0	0	40	20	40		2.52×10^{-1}
Aransas Pass	0	0	0	75	25		1.31×10^{-1}
Causeway N	0	0	0	0	100		3.75×10^{-1}
Causeway S	0	25	25	50	0		
Laguna (King)	30.8	0	23.1	46.2	0	-4.28×10^{-2}	
Laguna (Baffin)	0	0	66.7	0	33.3		4.08×10^{-2}
Baffin Bay	0	20	40	20	20		9.18×10^{-2}
GOM inlet	33.3	0	0	33.3	33.3	-1.52×10^{-1}	1.37×10^{-1}

in Fig. 5-39. Inspection of the data indicates that the greatest contributor to the declining trend is the reduced frequency of occurrence of high-inflow events. A similar trend analysis was carried out for the synthetic flows developed by USGS for Copano-Aransas Bay (see Section 5.2.1 above), averaged by month. For Copano a barely resolvable declining trend emerged, of 5.1 cfs/yr, shown in Fig. 5-40. To determine whether such a declining trend in inflow could be responsible for the increasing trend in salinity would require a detailed salt budget for the system, manifestly beyond the scope of the present study. By comparison of these inflow trends to their initial values in 1968, the respective reduction in annual inflow over the 1968-93 period would be about 14% for Copano Bay and 69% for the Nueces River (at Mathis). This is substantial, and is the likely explanation of the increasing trends in salinity, though Ward and Armstrong (1997a) offer some alternative hypotheses.

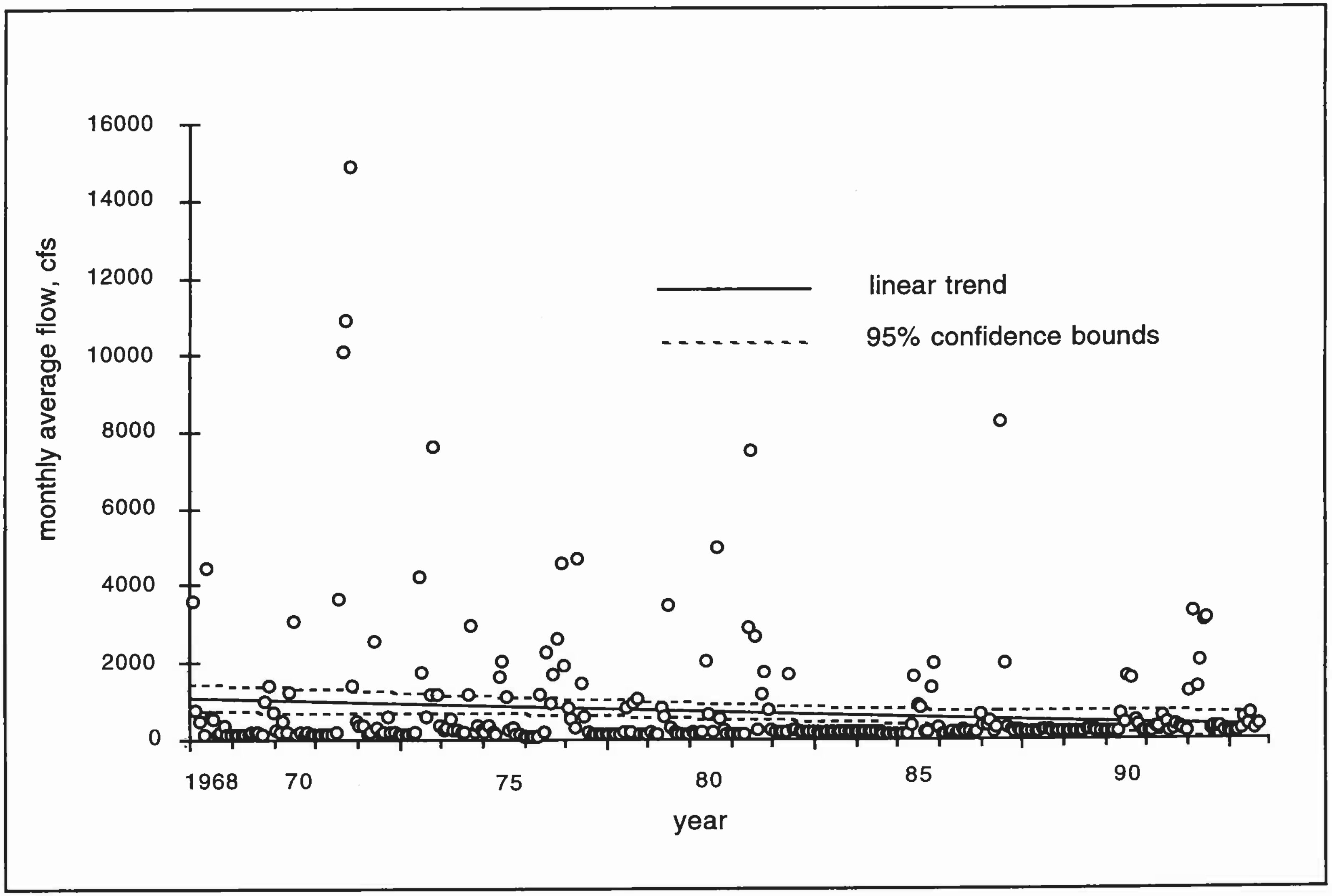


Figure 5-39. Monthly mean flow of Nueces at Mathis and linear trend line

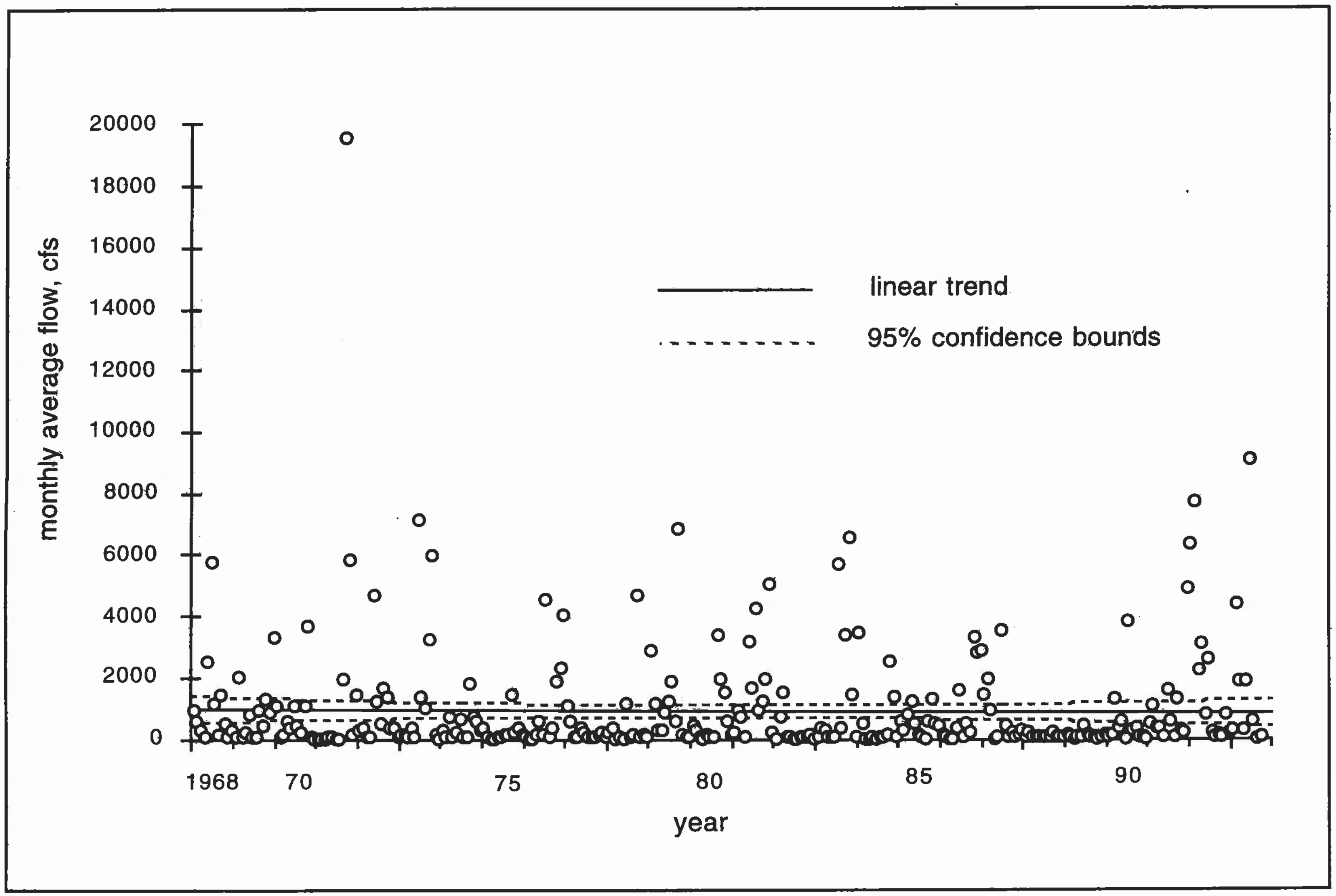


Figure 5-40. Monthly mean flow of Copano Bay watershed and linear trend line

5.4.4 Intrusion and extrusion

The long-term statistical depictions of salinity variation in time suppress the vacillation of salinity structure in response to water-mass changes, which in fact are a major feature of salinity behavior in the study area, as indicated by the magnitudes of standard deviation in Figs. 5-22 through 5-26. One of the most common and important contributors to this vacillation is the response of salinity to an influx of freshwater ("extrusion") and the subsequent recovery of salinity as the inflow diminishes ("intrusion"). The two involve different physical processes and therefore are not symmetric events. Extrusion is effected by a replacement of water due to the rapid influx of the inflow hydrograph. Intrusion is accomplished by the internal circulations gradually returning higher salinity water to the upper reaches of the bay. These processes are dictated by the hydroclimatology of the area, i.e. the sharply rising freshet hydrographs followed by long recessions, that are widely spaced in time. Extrusion typically occurs quickly, within a few days to several weeks (depending upon the region and the size of the freshet event), while intrusion typically requires weeks to months. Because the synoptic events producing the runoff are also frequently accompanied by a frontal passage and regional rainfall, the freshwater displacement is assisted by both frontal cross-bay transports and efflux to the Gulf (see Section 4.4.4) and salinities are further reduced by the surface precipitation surfeit. Intrusion, occurring over a longer time frame, is assisted by the more usual evaporation deficit at the surface.

Examples of salinity extrusion and intrusion events, drawn from the salinity data base of Ward and Armstrong (1997a) are presented in Figs. 5-41 through 5-43, for the Aransas-Copano system, the main body of Corpus Christi Bay, and Nueces Bay, respectively. The differing time scales of extrusion and intrusion should be especially noted. One factor of the regional hydroclimatology that facilitates identification of these kinds of events is that the largest freshets (which therefore have the potential for the greatest salinity response) are very widely spaced in time. Occasionally several such freshets occur closely enough in time that intrusion from one is superposed on extrusion from the other, making interpretation of the salinity response quite complicated. For example, the salinity recovery of the Copano system from the Beulah freshet (Fig. 5-41) was affected by the freshets of April 1968 and February 1969, the former, driving the salinities to zero. But generally these events are isolated, and the system response is easy to interpret.

Two immediate inferences from these figures are that the freshet responses of Corpus Christi Bay are much smaller than those for the upper bays, and the landward regions seem to exhibit a much smoother response and recovery than those in the interior of the bays. From a physical viewpoint, extrusion is an advective process, involving the wholesale displacement of water from the upper bay to the lower, or (for extreme events) into the Gulf of Mexico. Intrusion, on the other hand, is the combined effect of smaller watermass transfers, such tidal exchanges and internal transports (discussed in the next section), whose cumulative behavior is more of a diffusive process, operating to mix out and

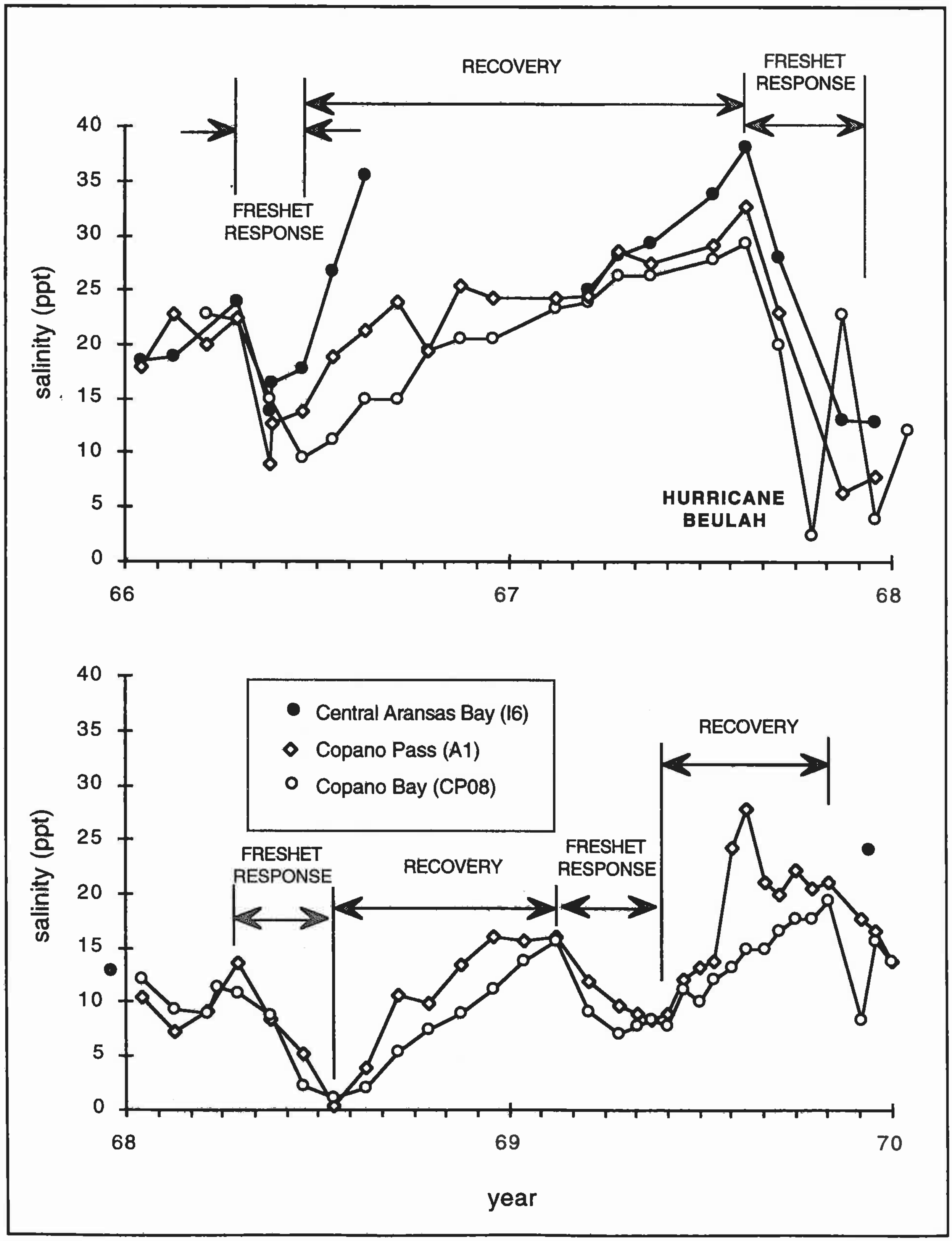


Figure 5-41. Aransas-Copano salinity extrusion and intrusion examples

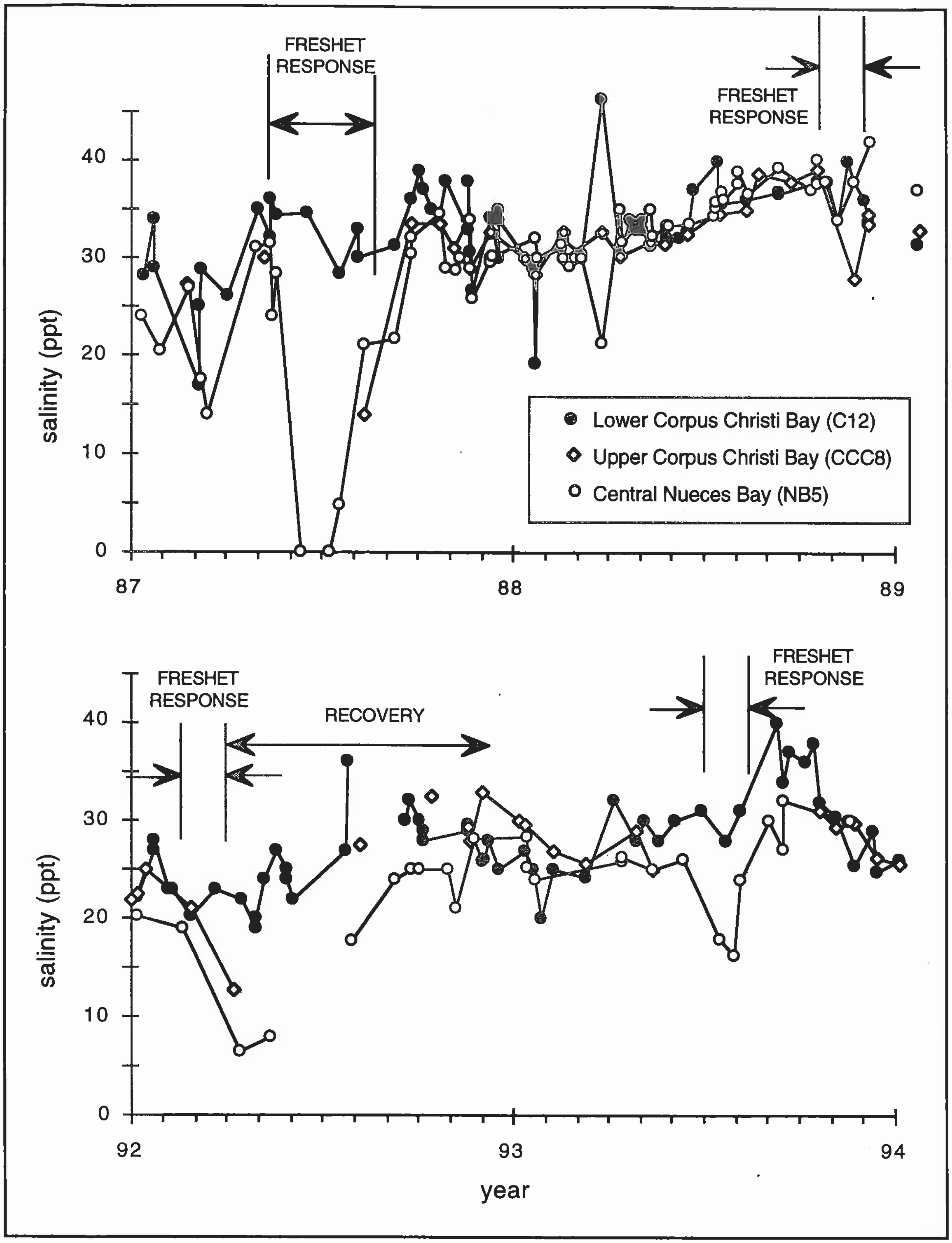


Figure 5-42. Corpus Christi Bay salinity extrusion and intrusion examples

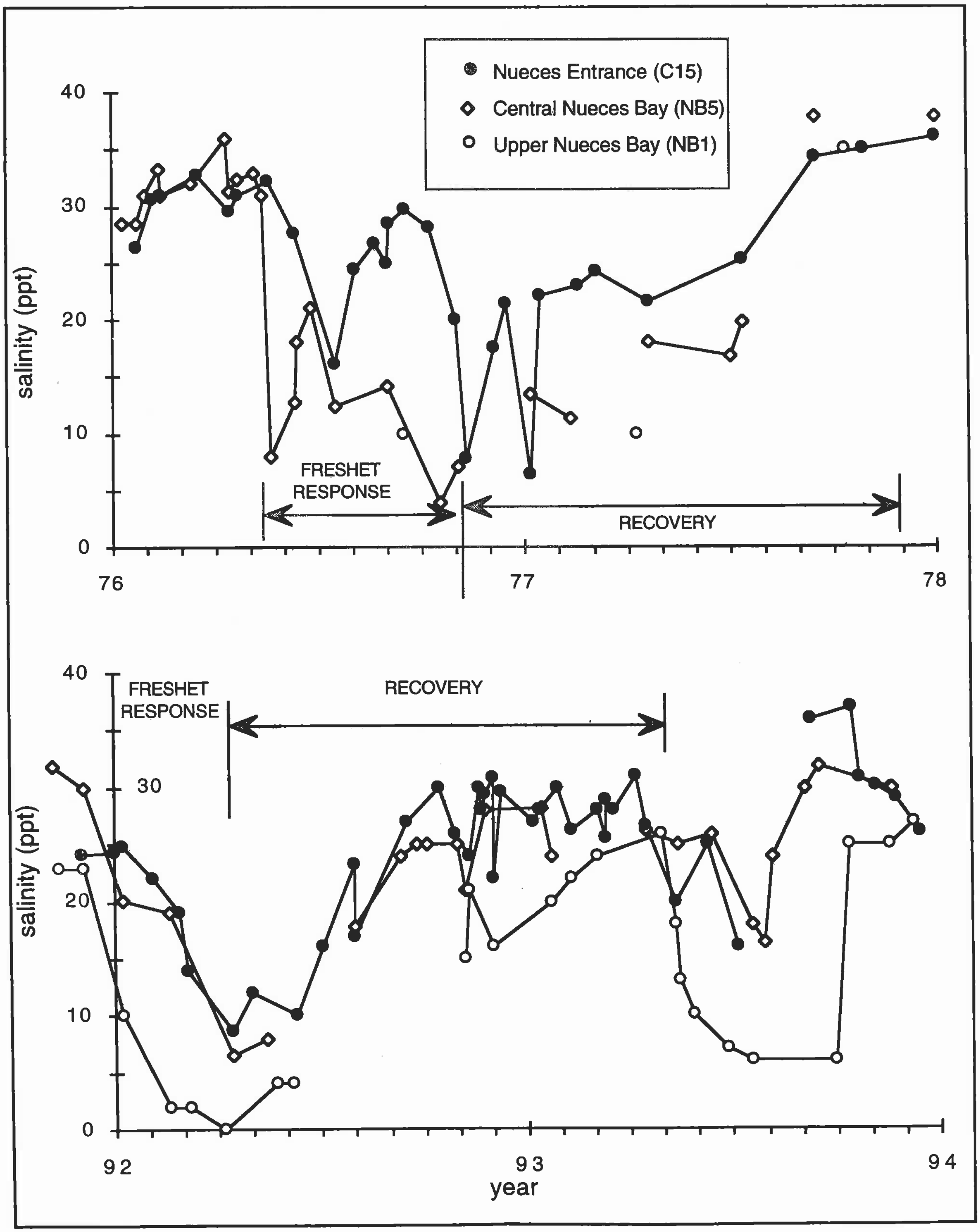


Figure 5-43. Nueces Bay salinity extrusion and intrusion examples

reduce the overall salinity gradient. At any point in time, the salinity is a result of the combined effects of the two types of processes, but their relative importance depends upon the freshet response.

This is illustrated by Fig. 5-44, showing theoretical longitudinal profiles of salinity in an idealized estuary composed of a broad wide bay up to x = 33, connected to a narrower bay for x > 33. Salinity at the mouth (x = 0) is fixed at 35 ppt, and the figure shows two profiles at the end of a freshet for two different levels of inflow, Q = 300 and Q = 1500, and the profile under a steady inflow of 30. (One can think of these as m^3/s, and the linear dimension as measured in km, for specificity, but the units are really arbitrary.) Under this theoretical and highly idealized model, the intrusion of salinity during the recovery would evolve back through these same longitudinal shapes to the initial steady (Q = 30) profile. In Zone I, the wide bay, the greater cross section of the bay compared to the volume of inflow makes the depression of salinity much smaller. That is, the greater volume of the large bay reduces the salinity response effect of a given freshet. This is the reason that Corpus Christi Bay exhibits such a minimal response to freshets: the volume of the freshets from the watershed are generally not large enough to produce a substantial reduction in salinity. Zone II is the primary salinity gradient region, and during both the extrusion and the subsequent intrusion recovery, the salinity changes are greatest both in time and in space in this region. Zone III exhibits a

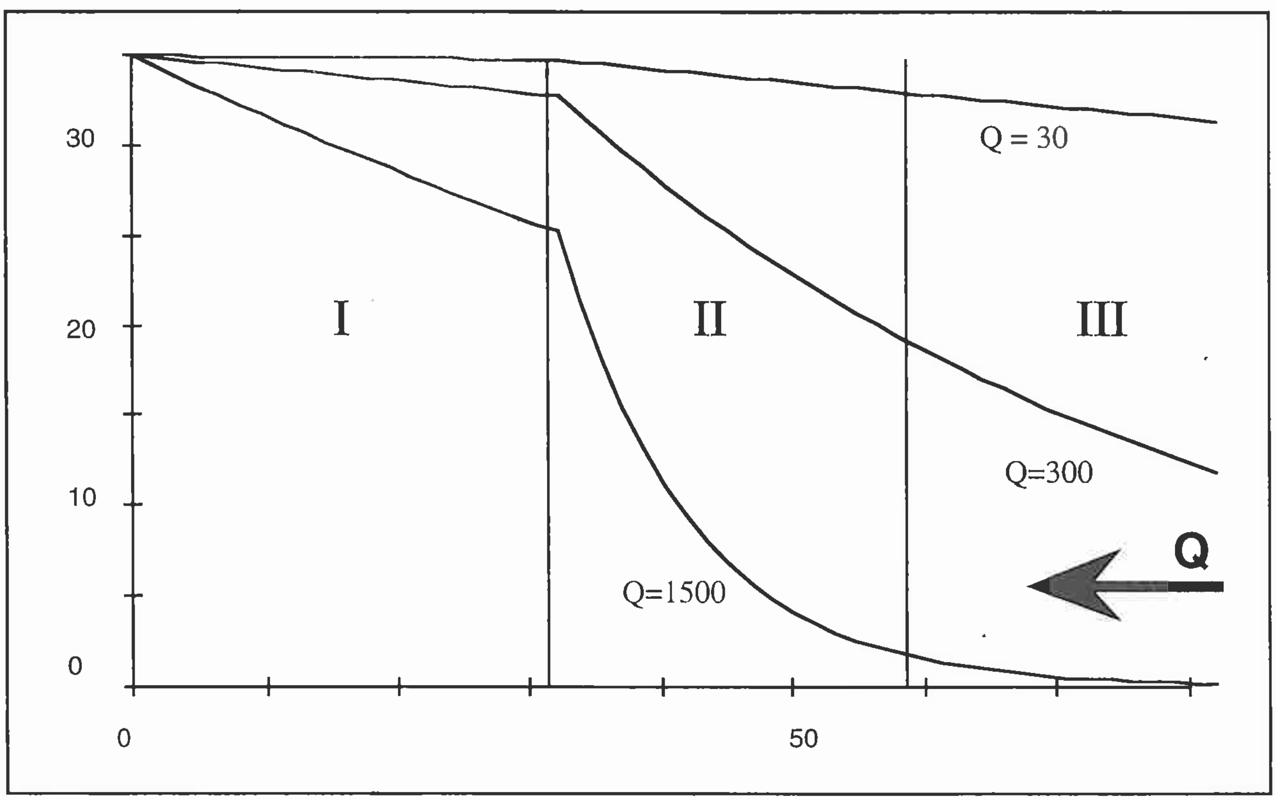


Figure 5-44. Schematic of salinity profile during intrusion event

general upward or downward shift in salinity, but the gradient across the system is small, compared to Zone II. In the real Corpus Christi Bay system, the central to lower section of Aransas Bay (Fig 5-17) and the area outside of Nueces Entrance in Corpus Christi Bay (Fig. 5-18) are where the high-gradient zones are located on average. (These areas also manifest the higher standard deviations, see Figs. 5-22 and 5-23.) Copano Bay and the upper Nueces Bay correspond more to Zone III of Fig. 5-44, in which the gradient is low and the entire system salinity responds upward or downward.

Failure to recognize these different regions of interplay between advection and diffusion can make difficult the analysis of field data. For example, Collier and Hedgpeth (1950) examined a weekly time series of salinities in Aransas-Copano Bay from October 1936 through June 1937. This period consisted of a long salinity-intrusion recovery period from the floods of spring 1936, with two superposed minor freshets in November and February. The salinities in Aransas Bay vacillated in response to the minor freshets, while those in Copano Bay increased monotonically throughout the period. Collier and Hedgpeth (1950) concluded that salinity transports by-passed Copano and extended rather from Redfish to Mesquite Bay and on to the mouth of the Guadalupe. While there is little doubt that the inflow from the Guadalupe has an effect on Aransas Bay, the observed response of Copano Bay is completely consistent with its location at the landward end of the salinity gradient.

As a part of the API Project 51, Whitehouse and Williams (1953) carried out several spatially intense surveys in the upper bays of the study area and the adjacent San Antonio system. Measurements of salinity at about 100 stations were performed in the period July-August 1951, at 15 stations in September 1951 after a "drought-breaking" rain (in which the Guadalupe reached flood stage), and in winter of 1952. For the first, reliable isohalines could be constructed only for San Antonio Bay, the values being too homogeneous in the Aransas-Copano area. This was during a period of maximum salinity intrusion, corresponding to the upper profile of Fig. 5-44. Such "flat" salinity gradients are a common feature of the open waters of Corpus Christi Bay, but also occur in Aransas-Copano under extended low-flow conditions. After the September 1951 rainfall event (which unfortunately was smaller than originally hoped for and did not break the drought of the 1950's), the salinities were reduced perhaps a factor of 4/5 in Aransas-Copano (and by about half in San Antonio), and isohalines could be constructed, though the sample density was less than desirable. In the winter 1952 survey, the values were again so homogeneous throughout, even in San Antonio Bay, that isohalines could not be developed.

The detail of a freshwater extrusion event is shown in Fig. 5-45, combining data from a sonde in mid-Nueces Bay with gauged inflow in the Nueces and associated meteorological data. (Robot sondes are especially valuable for this sort of time-intense salinity data.) As the freshwater influx begins to invade Nueces Bay, the salinity gradient is tightened. This steep salinity gradient is then advected past the sonde station by tides, meteorological responses and displacement, resulting in pronounced changes in salinity. The tidal variations, arising from a modest tidal excursion, see Table 4-3, normally do not appear in a sonde record, but with

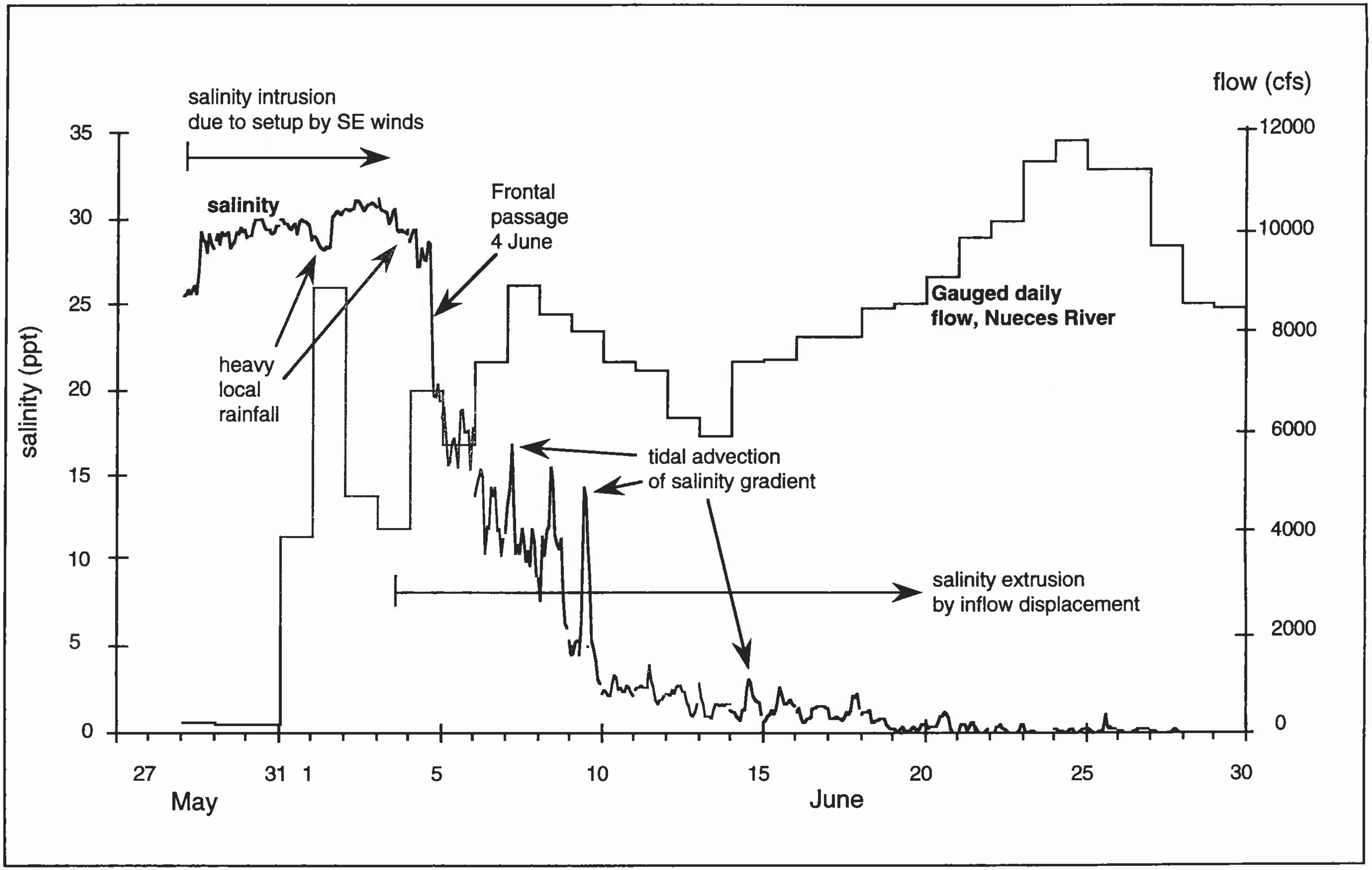


Figure 5-45. Salinity extrusion in Nueces Bay, June 1987

the very steep salinity gradient are clearly revealed. By 10 June, when the salinities have been driven down to about 3 ppt, approximately 100 Mm^3 of freshwater have entered the bay since the beginning of the freshet (assuming a three-day lag from the Mathis gauge to Nueces Bay), which is about equal to the volume of the entire Nueces Bay at this time of year. Since the sonde is located at the midpoint of the bay, this suggests that about half of the inflow has increased the depth in the bay, i.e. overflowing the saline water of the bay. This is consistent with observations that salinity becomes temporarily highly stratified in the early stages of a freshet event.

5.5 Internal transports

The preceding sections have addressed the transports of water created by external forcing of the Coastal Bend Bays, by tides, wind events, and freshwater inflows. Emphasis has been on exchange between the bays and the Gulf, or between separate component bays of the system. Currents can also be generated by processes that are completely internal to the bays, and, while not effecting any substantive exchange of water between component bays, can nonetheless be responsible for the transfer of water, perhaps in significant quantities, within a component bay. The most important rôle of these internal circulations in the present context is in mixing waters in the interior of the bay.

5.5.1 Gyres

Because of the large surface-area morphology of the Texas bays, horizontal circulations, or "gyres," are known to operate in many of these systems, maintained by a combination of bathymetry or wind, and assisted by inflows, barriers or other factors, such as the rotation of the earth. Such gyres represent a quasi-steady circulation pattern that is maintained for the majority of the time. Bathymetry is operative in focusing or concentrating currents driven by other processes (e.g., tides or winds) to create a favored circulation, such as differing trajectories on the flood and ebb current. Wind can create gyres due to the varying fetch for a given direction, producing differentials in the wind-driven currents that form a closed circulation. The existence of such gyres can be determined directly from current measurements over a sustained period or from the trajectories of markers carried by the current such as drogues or drift bottles. They can also be inferred indirectly from the differential transport of waterborne substances. Either data source must be based on observations that are sufficiently resolved in space and time.

In the bays on the upper Texas coast, namely Galveston Bay and Sabine Lake, the salinity gradient is steep enough that salinity measurements over time have been used to deduce directions of salinity intrusion and the sense of large-scale circulations (generally clockwise). No such determinations seem to exist in the literature on Corpus Christi Bay—not surprising given the usual flat salinity gradient—except for the suggestion of a clockwise circulation in lower Aransas Bay proposed by Collier and Hedgpeth (1950).

Surface drifter releases were performed by Texas A&M in the north segment of Corpus Christi Bay (between Ingleside and Indian Point) in 1952 (Hood, 1952). Drift bottles, ballasted to float in the top 10 cm or so of the water column, were released at the Reynolds site. The results can be succinctly summarized: the bottles moved in the direction of prevailing wind, generally to the west. A series of drogue releases were carried out as well, using drogues with vanes set just below the surface. The results were confused. Under a freshening wind most drogues moved with the wind, though a few stubborn drogues traveled upwind. Under a sustained wind (southeasterly), many of the drogues moved upwind into the central bay.

A series of surface drifter experiments were conducted by the Corpus Christi Lab of USGS, reported by Shideler and Stelting (1983). This experiment has to represent the most disproportionate rate of energy investment versus return of any field study in the history of the system. Water sampling, temperature/ salinity measurement and drift-bottle releases were performed from a Coast Guard helicopter at 15 stations distributed from Port Aransas inlet to mid-Nueces Bay, from March 1978 to April 1980. The drift bottles were ballasted to float in the top 10 cm or so of the water column. Water samples were analyzed for total suspended solids. Though the eight sampling runs were described as a "time-sequence," in fact the interval between them averaged four months, so at best they could be described as instantaneous but independent "snapshots." The results of the drifter analyses can be succinctly summarized: the bottles moved in the direction of prevailing wind, usually to the north or northwest, at a distance generally proportional to wind speed. Salinity and TSS were found to be highly variable.

The only program of routine current measurement to have been performed in the system is that of Southwest Research Institute (SWRI) in the early 1970's. Much of the data from this program was recovered and keyboarded by the CCBNEP Water Quality Status & Trends Project (Ward and Armstrong, 1997a). SWRI measured a current velocity profile at each of its 13 routine stations, using an over-the-side directional meter with onboard readout. Measurements were made at the surface and at 5-ft (1.5-m) intervals to the bottom. One profile was obtained at each station during each routine sampling run, without regard for stage of tide, meteorological conditions, or freshwater inflow, usually in the afternoon under a developing seabreeze. Moreover, to obtain a representative current measurement in the presence of natural turbulence and variability, the meter must be held in place to allow averaging over a period of time (at least several minutes) to average out the normal surges and stalls in the current velocity. This was not done by SWRI. For the four-year duration of the data collection period, 1970-73, there are about 50 such current measurements for each station/depth. This is wholly inadequate for characterization of general current patterns in such a variable turbulent system. Compare the problem of characterizing winds at a given location from 50 measurements over a four-year period. Nevertheless, SWRI (1977) gamely presented circulation diagrams based solely on these measurements, for surface and bottom circulations under northeast winds, two levels of southeast winds, and semidiurnal and diurnal tides.

The current profile data from this program have been keyboarded for analysis. To determine whether there is any statistical expression of large-scale gyres, a single level of measurement was addressed. The 1.5-m depth was considered to be the best level for this purpose, since it is deep enough to be indicative of large-scale circulation. The surface measurements have the potential of being corrupted by windwaves or being biased by short-term wind responses. The deeper levels were not measured consistently and were frequently so close to the bottom that the current magnitudes were too small to be measured accurately. The individual current velocities were resolved into east (u) and north (v) components. Table 5-15 presents the componentwise statistical analyses and the vector-mean currents for all of the SWRI data, and Table 5-16 presents the same analyses limited to only the 1972-73 data. (It should be noted that the greatest freshwater inflow event since Beulah occurred in 1971, during the period of the SWRI monitoring program.) In Table 5-15, the componentwise standard deviations range up to 15 times the means. Such a high coefficient of variation means that the accuracy of the mean is very poor. The mean current vectors are displayed diagrammatically in Fig. 5-46 (including Station U, which is technically out of the area of the figure, being located south of the JFK Causeway). Apart from those stations subject to some sort of physiographic confinement, i.e. D, F, L and U, the currents are small and exhibit little spatial coherence, except for a tendency for south-to-north flow in the lower part of the bay. The mean current at Station L is particularly curious, being on the same order, but directed oppositely to the mean current from the power-plant circulation (Table 5-9).

Development of a wind-driven gyre would require quasi-steady winds sustained over a considerable period, perhaps several days or more. This would be much more likely a phenomenon of summer when the prevailing onshore winds from the Gulf are strongest. The SWRI data were subjected to the same analyses as above, but limited to data from summer periods, June, July and August, only. These results are summarized in Table 5-17 for the entire data set, and in Table 5-18 for summer 1973 only. (No data were taken by SWRI in summer 1972.) The mean currents are plotted as vectors in Fig. 5-47. There is the same prominence of currents at Stations D, F and L as in the previous analysis. The currents at Station F are among the highest routinely encountered by SWRI, and over the entire data set are highly variable in direction. For summer, there is about a two-to-one domination by flows to the east, which may imply a continuous outflow from the system, but also given the small number of measurements could be random chance. The flow into Nueces Bay is in fact characteristic more of summer than the other seasons, but the average of the total data set vector (Table 5-15) is dominated by a single measurement of nearly 2 knots to the west on 14 March 1972, see Fig. 5-48.

These measurements are a very sparse offering to base any inference on. There is some indication of a counterclockwise circulation under summer conditions in the lower part of Corpus Christi Bay, i.e. south of the CCSC, and the net flows through Nueces Bay and Lydia Ann Channel are suggestive of the interception of a clockwise flow to the north of CCSC, perhaps following the shoreline. The flow into Nueces Bay cannot continue indefinitely; there must either be a return flow, or the flow must reverse during a portion of each day. The only option for the

Table 5-15
Vector-mean currents at 1.5-m depth from SWRI program 1970-73

Station	*no. of*	*component stats (m/s)*				*mean current*	
	msmts	*u (E)*	*v (N)*	*stdev u*	*stdev v*	*speed m/s*	*dir deg*
A	47	0.03	0.00	0.10	0.14	0.03	86
B	47	0.02	0.00	0.04	0.03	0.02	72
C	50	0.00	0.00	0.10	0.13	0.00	170
D	45	0.03	-0.03	0.11	0.12	0.05	135
E	48	-0.02	0.02	0.15	0.11	0.03	320
F	40	-0.03	0.05	0.40	0.31	0.06	330
G	48	-0.01	0.04	0.10	0.12	0.04	347
H	48	0.02	0.02	0.12	0.12	0.03	46
I	49	-0.01	0.03	0.08	0.11	0.03	331
J	48	0.01	0.02	0.13	0.10	0.02	29
K	49	-0.01	0.00	0.11	0.13	0.01	291
L	51	-0.05	0.04	0.17	0.13	0.06	309
U	34	0.05	0.02	0.16	0.30	0.05	71

Table 5-16
Vector-mean 1.5-m currents from SWRI program, 1972-73 data only

Station	*no. of*	*component stats (m/s)*				*mean current*	
	msmts	*u (E)*	*v (N)*	*stdev u*	*stdev v*	*speed m/s*	*dir deg*
A	20	0.04	0.03	0.06	0.13	0.05	53
B	17	0.02	0.01	0.04	0.04	0.02	70
C	18	0.01	-0.02	0.11	0.11	0.02	147
D	20	0.06	-0.07	0.12	0.10	0.09	139
E	19	0.02	0.02	0.18	0.14	0.03	49
F	19	0.12	0.07	0.26	0.33	0.14	59
G	19	0.00	0.05	0.08	0.12	0.05	356
H	20	0.03	0.03	0.12	0.10	0.05	51
I	20	0.03	0.05	0.09	0.10	0.06	33
J	20	0.03	0.01	0.11	0.10	0.03	72
K	20	-0.01	0.01	30.51	0.10	0.02	318
L	19	-0.05	0.06	0.23	0.08	0.08	323
U	18	0.06	0.06	0.17	0.33	0.09	46

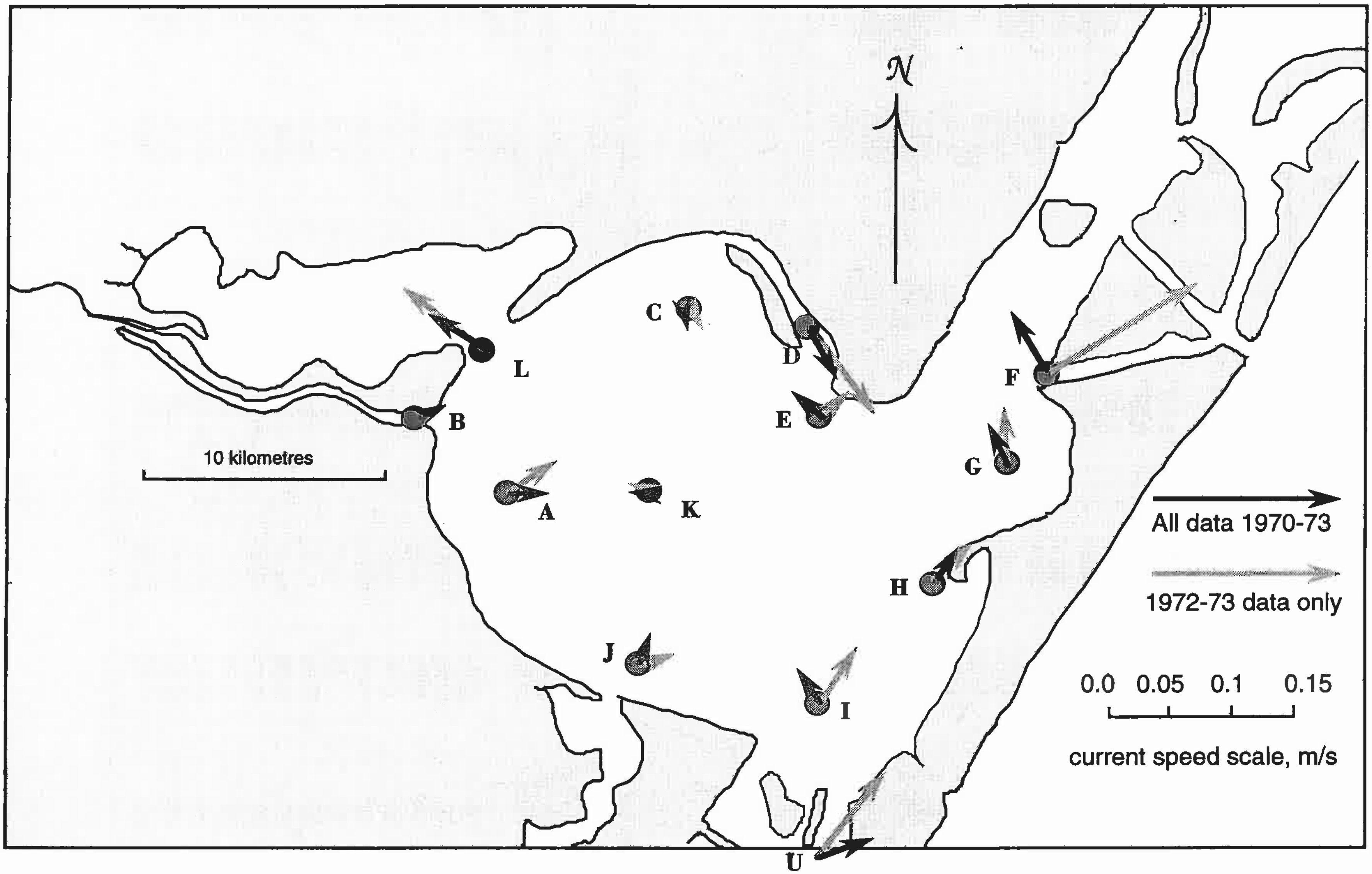


Figure 5-46. Vector-mean currents at 1.5 m, from SWRI program

Table 5-17
Vector-mean 1.5-m currents from SWRI program, summer (JJA) data only

Station	no. of msmts	u (E)	v (N)	stdev u	stdev v	mean speed m/s	current dir deg
		component stats (m/s)					
A	15	0.00	-0.03	0.11	0.12	0.03	171
B	15	0.03	0.01	0.03	0.03	0.03	71
C	18	0.00	0.03	0.11	0.12	0.03	356
D	13	0.08	-0.06	0.14	0.10	0.10	126
E	17	-0.03	0.00	0.17	0.09	0.03	275
F	10	0.16	-0.01	0.31	0.11	0.16	95
G	17	0.03	0.08	0.09	0.11	0.09	19
H	17	0.03	0.03	0.14	0.12	0.04	47
I	17	0.00	0.03	0.11	0.16	0.03	355
J	15	0.02	-0.01	0.11	0.10	0.03	125
K	16	-0.04	-0.02	0.09	0.10	0.04	247
L	18	-0.04	0.11	0.09	0.09	0.12	339
U	12	0.05	0.02	0.16	0.19	0.05	66

Table 5-18
Vector-mean 1.5-m currents from SWRI program, summer 1973 data only

Station	no. of msmts	u (E)	v (N)	stdev u	stdev v	mean speed m/s	current dir deg
		component stats (m/s)					
A	5	0.04	0.02	0.06	0.14	0.04	67
B	4	0.03	0.04	0.04	0.04	0.05	40
C	5	0.05	0.04	0.15	0.14	0.06	49
D	5	0.11	-0.12	0.17	0.11	0.16	137
E	5	0.13	-0.03	0.19	0.11	0.13	101
F	5	0.12	-0.02	0.32	0.15	0.12	98
G	5	0.00	0.05	0.08	0.11	0.05	357
H	5	0.13	-0.03	0.17	0.10	0.14	101
I	5	0.08	0.03	0.09	0.10	0.09	73
J	5	0.06	-0.01	0.08	0.12	0.06	96
K	5	-0.05	-0.02	0.08	0.13	0.05	250
L	5	-0.04	0.06	0.11	0.05	0.07	327
U	5	0.09	0.00	0.22	0.29	0.09	89

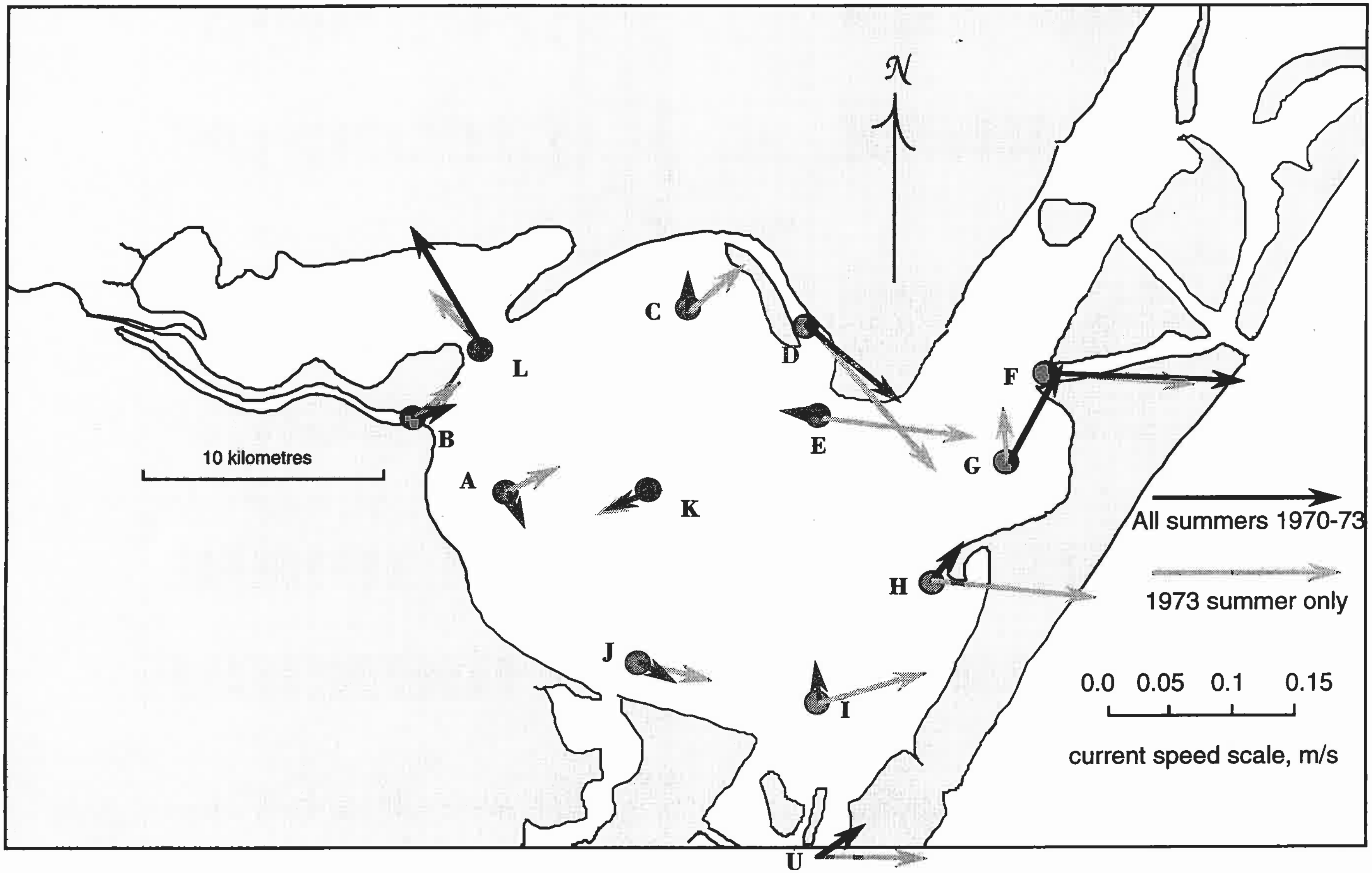


Figure 5-47. Vector-mean currents at 1.5 m, from SWRI program, summer (JJA) data only

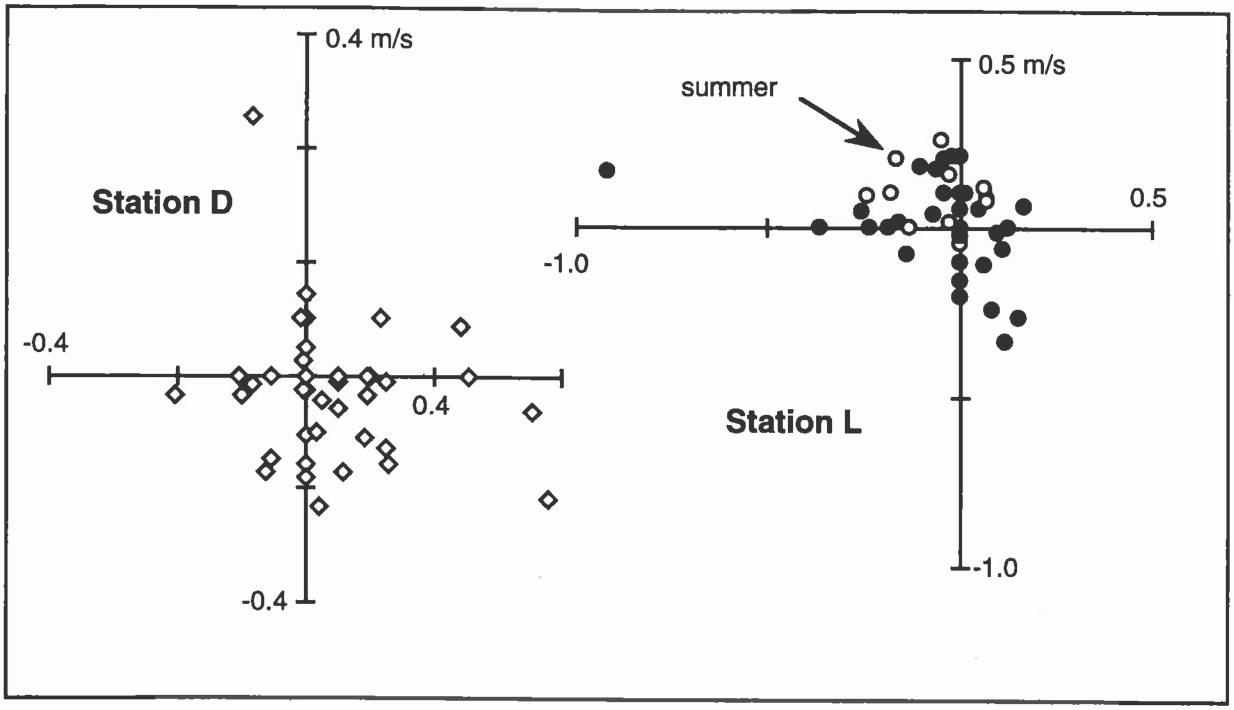


Figure 5-48. Hodographs of SWRI current velocity measurements

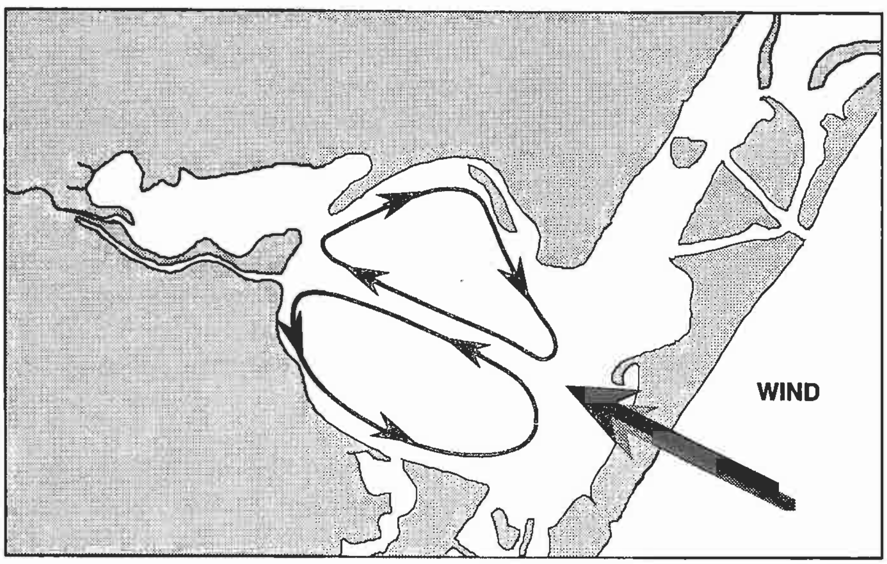


Figure 5-49. Postulated wind-driven gyres in Corpus Christi Bay

return flow is the remaining cross section of Nueces entrance, which seems highly unlikely, so we presume the latter applies. This suggests that the other currents may slacken during the course of the day as well, perhaps in response to the seabreeze cycle. A clockwise circulation in the northern portion of the bay and a counterclockwise flow in the southern part are consistent with the sort of circulations that would be expected from a direct flow driven through the center of the bay by prevailing southeasterly winds. The center of the bay would be the favored location for the direct wind-driven flow, because of the greater fetch and generally deeper water, hence reduced frictional resistance. Along either shoreline would be the favored zone for the return flow, since there is more physiographic sheltering from the direct wind. Such a circulation is sketched in Fig. 5-49. A wind from the south would favor more the northern clockwise gyre, one from the east would favor more the southern counterclockwise gyre, and one from the southeast would develop both gyres. If the SWRI average summer currents in fact indicate the order of magnitude of the currents involved, and assuming that these currents slacken overnight, a mean circulation of several tens m^3/s (or on the order of 10^2 Mm^3/mo) in either gyre would be indicated.

5.5.2 Density currents

The horizontal gradient in salinity in concert with variations in depth produces a component of estuarine circulation referred to as a density current, or "salinity current," one of the prime mechanisms for salinity intrusion into an estuary, and is especially prominent in deepdraft ship channels dredged through shallow estuaries. Density currents are exhibited in two different forms: vertical shear in the horizontal current, and large-scale horizontal circulations. The vertical shearing density current is particularly prominent in deep channels that are laterally confined, such as the Houston Ship Channel above Morgans Point in Galveston Bay. Usually this kind of current is exposed by averaging vertical profiles of current velocity over a tidal cycle. This is the classical estuarine density current observed in these types of systems since the nineteenth century, whose mechanics is that of denser water underflowing and displacing lighter water. The resultant circulation is a tidal-mean influx from the sea into the estuary in the lower layer, and a return flow from the estuary to the sea in the upper layer.

The second kind of density current results from the absence of laterally confining boundaries, so that the return flow is completed in the horizontal plane, rather than in the vertical. This circulation is induced by the presence of a channel of deeper water, in which case the vertical-mean current is directed up (into) the estuary along the axis of the channel, and the return flow to sea takes place in the shallow open bay to either side. In a broad estuary with a natural bathymetry of deeper water near the center and shallower near the side, such as Chesapeake Bay, a combined circulation results with both horizontal and vertical shear, and with secondary circulations in a plane inclined intermediate between the vertical and the horizontal. Because the intensity of the density current increases roughly in proportion to the cube of depth (Ward and Montague, 1996), deepdraft ship channels are especially important in creating density currents.

The above description of density currents did not refer to vertical stratification. Indeed, either kind of density current can take place even when the water-column salinity is homogeneous, because the driving force for density currents is the *horizontal* salinity gradient. The confined density current, especially, will tend to develop salinity stratification, but if the vertical mixing processes are sufficiently intense the salinity can still be maintained nearly homogeneous in the vertical. More information on the mechanics of estuary density currents is given in Ward and Montague (1996) and references cited therein.

Density currents are important modes of transport in most of the Texas bays, providing a sustained influx of water from the sea. Though their current speeds are usually small compared to tidal currents, they are persistent and nonreversing over the tidal cycle, and the tidal-mean transport is nominally an order of magnitude greater than the freshwater throughflow (which maintains the salinity gradient that drives the density current in the first place).

There are two statistical diagnostics for the presence of a density current. First is long-term mean salinities that are higher along the talweg than the adjacent waters. For the Texas bays, the prominent talweg is the deepdraft ship channel, and indeed in the bays on the upper coast such as Galveston there is found a tongue of higher mean salinity aligning with the ship channel. In the case of Corpus Christi Bay, Fig. 5-18, this diagnostic fails, there being no significant difference between the salinities of the ship channel and those to either side.

The second diagnostic is an upstream-directed average current in the ship channel, in which the average is taken over one or more tidal cycles. This requires a data base of current profiles from stations in the channel at a rather intense sampling interval. For Corpus Christi Bay, we have the SWRI profiles at Stations E and F. (Station B is also in the deepdraft channel, but any density current operating there would affect exchange only in the Inner Harbor and would be of little importance to overall circulation in the bay.) If there are enough profiles in the data base to have encountered about every stage of the tide, then indication of a density current may emerge from the averaging. This is not as good as profiles taken over a complete tidal cycle, but can suffice. The period-of-record mean currents at individual depths are tabulated in Table 5-19 for these two stations. These results are equivocal. There is, in fact, a mean current directed into the system at all levels, consistent with the operation of a density current. But there are so few profiles in the data base (less than 50 over four years), under a variety of conditions, and with such high coefficients of variation (at least 700%), that the mean current direction could be an artifact due to the sampling program encountering a few more conditions of Gulf inflow rather than outflow. The fact that the mean current at Station F is directed perpendicular to the axis of the channel makes it even more unlikely that it is a density current. If the mean currents of Table 5-19 are indeed the result of a density current, the associated flow would be on the order of tens of m^3/s, or on the order of 10^2 Mm^3/mo. This is much weaker—about an order of magnitude—than the density currents of the bays on the upper Texas coast.

Table 5-19
Statistics of SWRI vertical current profiles at channel stations

depth (m)	mean (m/s) u	mean (m/s) v	st dev (m/s) u	st dev (m/s) v	speed (m/s)	dir (deg)
			Station E, 46 profiles			
1.5	-0.02	0.02	0.15	0.11	0.03	318
3.0	-0.04	0.01	0.15	0.10	0.04	282
4.5	-0.05	0.00	0.14	0.10	0.05	275
6.0	-0.03	0.00	0.12	0.10	0.03	277
7.5	-0.02	0.00	0.13	0.12	0.02	272
9.0	-0.02	0.01	0.12	0.08	0.02	286
10.5	-0.02	0.00	0.12	0.07	0.02	282
			Station F, 35 profiles			
1.5	-0.03	0.06	0.41	0.27	0.07	332
3.0	-0.06	0.07	0.43	0.21	0.09	319
4.5	-0.05	0.03	0.38	0.24	0.06	305
6.0	-0.05	0.06	0.38	0.20	0.08	319
7.5	-0.05	0.08	0.36	0.19	0.09	330
9.0	-0.04	0.06	0.35	0.18	0.07	324
10.5	-0.03	0.06	0.31	0.17	0.07	333

The fact that a density current would be a much less important factor in Corpus Christi Bay hydrography compared to the bays on the upper coast is not altogether unexpected, due to two key features in which Corpus Christi Bay differs. First, freshets on Corpus Christi Bay are much less frequent and of smaller magnitude (compared to the volume of the bay) than those of the bays on the upper coast. Therefore the conditions of high salinity gradient that produce a density current, caused by freshwater inflow, occur much less frequently. Second, the main salinity gradient in Corpus Christi Bay is most often located in or just outside Nueces Bay, away from the deep ship channel. In the bays on the upper coast, the main gradient lies across the ship channel most of the time, which is where it must be to produce a substantial density current.

5.5.3 Diffusion

An additional transport mechanism operating within the interior of the bay is the collective transport due to small-scale current fluctuations and shear. These include currents due to windwave orbitals, overtopping and breaking waves, small-scale irregularities on the bottom, tidal currents (whose excursion in the open bay is small, see Table 4-3), responses to gusts and downdrafts of wind, prop turbulence, small-scale rotary circulations spun up by shears in the larger scale currents, and so forth. Collectively, these might be categorized as "turbulence" and are particularly important in mixing out locally steep gradients in concentrations of waterborne substances.

These processes are frequently parameterized as a diffusion-type transport, governed by a diffusion coefficient. The diffusion coefficient is best determined by tracing the evolution in time and space of some easily measured waterborne substance. Fluorescent dye is a parameter of choice, since it can be introduced for the express purpose of watermass tracing, its mode of introduction can be optimized for analysis of diffusion coefficients, and it can be quantitatively measured *in situ* in miniscule concentrations using an onboard fluorometer. The ideal experimental procedure for a broad, shallow system such as Corpus Christi Bay is to perform an instantaneous, or "slug," release of dye, then monitor the evolution of the spreading dye patch by executing boat transects across the dye cloud at frequent intervals.

Very few dye releases have apparently been carried out in Corpus Christi Bay. This literature review was able to locate only one experiment by SWRI, this was performed in the Inner Harbor, not in the open bay, and the data were never analyzed (or, at least, their analysis was never reported). Therefore, in order to estimate diffusion, the data compilation of Ward (1985b) of dye-dispersion data from the Texas coast was used. In this study, the diffusion coefficient was decomposed into a "turbulent" or "eddy" component, conceived to behave isotropically, and a "dispersion" component aligning in the direction of the local current (and deriving from the current shear in the bottom boundary layer). The "eddy" component was found to vary directly with local current speed and with the 4/3-power of horizontal scale, and the "dispersion" component was found to vary with local current speed. Using the relations presented in that paper, a value of diffusion coefficient typical for Corpus Christi Bay hydrography and mixing on the 100-m scale would be on the order of 20×10^{-2} m^2/s. Larger-scale processes, say on a 1-km scale, would have a corresponding diffusivity of about 5 m^2/s.

This parameter allows estimation of the time for a gradient in salinity, say, to be mixed out by processes operating on this scale. An example is shown in Fig. 5-50, produced by numerical integration of the time-varying isotropic diffusion equation for a conservative parameter. Integration was begun from a step function in concentration, using a diffusivity of 5 m^2/s. (The actual concentrations are not important: it is only the relative gradient that matters. A quantum jump of 50 ppt in salinity would be mixed out at the same rate as a quantum jump of 5 ppt.) It is evident that mixing processes at this scale are relatively slow, nearly 50 days being required to develop a gradient of 30% per 10 km from an initial step function (infinite gradient) in concentration.

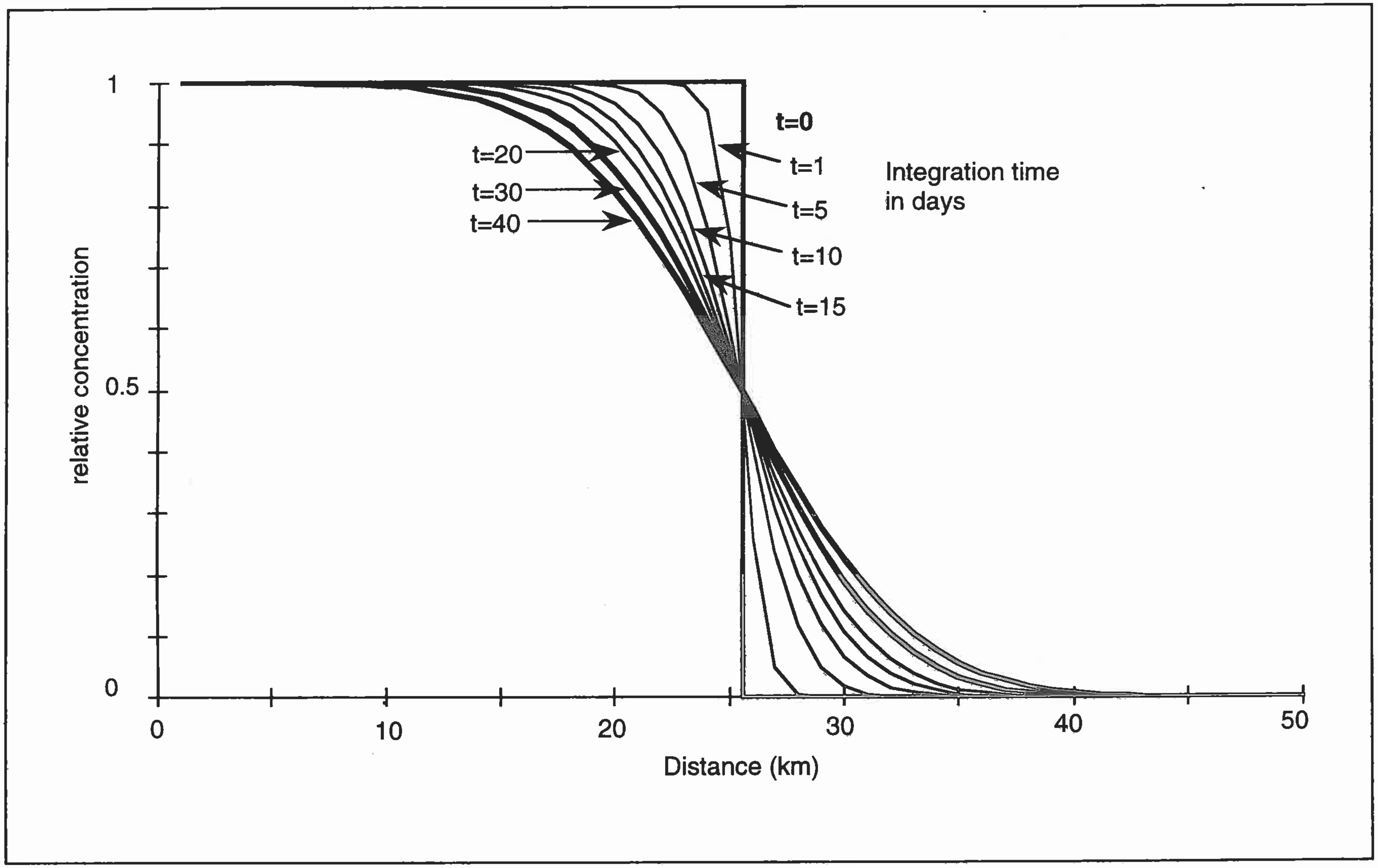


Figure 5-50. Numerical integration of longitudinal mixing along profile, $E = 5\ m^2/s$

6. SYNTHESIS

> I attack the problem in terms of midgets, animals and concrete scientific principles.
>
> — R.L. (Rube) Goldberg, 1944

A highly compressed summary of the mechanics of circulation in Corpus Christi Bay may be formulated as follows:

- The Corpus Christi Bay system is comprised of a series of quasi-autonomous basins connected by highly constricted conduits and driven by several impressed forces.
- An important class of forcings are those that result in transport of water between the basins.
- Most important is the differences in water levels between the basins, which drive flows through the conduits.
- These flows represent exchanges of water between the various basins. The volume of water exchanged depends upon the time variation of the water-level difference.
- The exchanges between the bays and the Gulf of Mexico alternate in direction and there are several important periodicities involved.
- There is an exchange driven by freshwater inflow from the drainageways of the watersheds that is unidirectional, from the upper bays to the Gulf of Mexico, governed by the regional hydroclimatology.
- There is also a surface flux between the bays and the overlying atmosphere whose direction and magnitude are likewise governed by the regional climate.
- The extent to which an exchange acts to dilute or replace water within a basin depends upon its volume relative to that of the basin, and the rate and direction of exchange.
- It also depends upon the intensity with which it is mixed within the basin. This mixing is accomplished by internal circulations.
- Short-period tides, responses to wind stress at the water surface, and local horizontal differences in density are the most important potential sources of internal circulations within Corpus Christi Bay.

In this chapter, the analyses of this study will be summarized by addressing each of these statements. They will be exemplified and quantified based upon information presented in the preceding chapters (Section 6.1). Historical alterations in circulation can then be inferred as resulting from changes in the forcing of exchanges in the system (Section 6.2). Implications for the effects of these changes in the larger context of environmental management will then be presented (Section 6.3).

6.1 Exchange, transport and flushing: a conceptual model

At its largest scale, the CCBNEP study area is comprised of half a dozen interconnected embayments. These embayments may be viewed as shallow basins, in that their surface-area-to-depth ratios are large and their bottom morphology is relatively uniform, except for occasional reefs and shoals in a few of the systems. The connections between these basins are narrow and highly constricted, however. Some connections are ajutages, such as Copano Pass, and Nueces Entrance, while others are longer passages over complexes of reefs and shoals, such as Bulkhead Flats between Corpus Christi Bay and the Laguna Madre. There are also conduits extending out of the study area both to the north (to San Antonio Bay) and to the south (to the Lower Laguna Madre) that carry water exchanges but are beyond the geographic scope of this study.

A conceptual schematic of this overall interbasin exchange is shown in Fig. 6-1, after the style (somewhat) of the inimitable American engineer Rube Goldberg (cf. Kinnaird, 1968). Though the mechanisms depicted are whimsical, the forcing factors and the hydromechanics comprise a realistic model. The major components are depicted as shallow basins of varying volumes and depths. At this scale of depiction, the water surface in each basin is practically level, and it is the difference in levels between the basins that drives flow through their connection. These connections, depicted as hoses of varying diameters and lengths, have much smaller cross sections than the dimensions of the basins they connect and therefore represent highly constricted conduits.

The largest basin is the Gulf of Mexico, and is so large in comparison to the others that the volume of exchange between it and the small basins has no sensible effect on its water level. Instead its water level is governed by astronomical controls and by meteorological conditions. For practical purposes, the only conduit of importance connecting the bay system with the Gulf of Mexico is Aransas Pass inlet. Through this inlet passes water exchanged between the Coastal Bend bays and the adjacent Gulf of Mexico, forced by the difference in water level between the Gulf and the bays. These water-level variations then propagate into the interior basins through each of the connecting conduits, being lagged and attenuated in the process.

There are two primary sources of water-level variation driving this exchange: periodicities primarily of tidal origin and synoptic-scale meteorological disturbances which are nonperiodic except for the annual cycle of climatology. With respect to tidal periodicities, in the Gulf of Mexico the astronomical tide is dominated by three main components: the 12.4-hour semidiurnal and 24.8-hour diurnal tides, and the 13.6-day fortnightly cycle in the magnitude of declination of

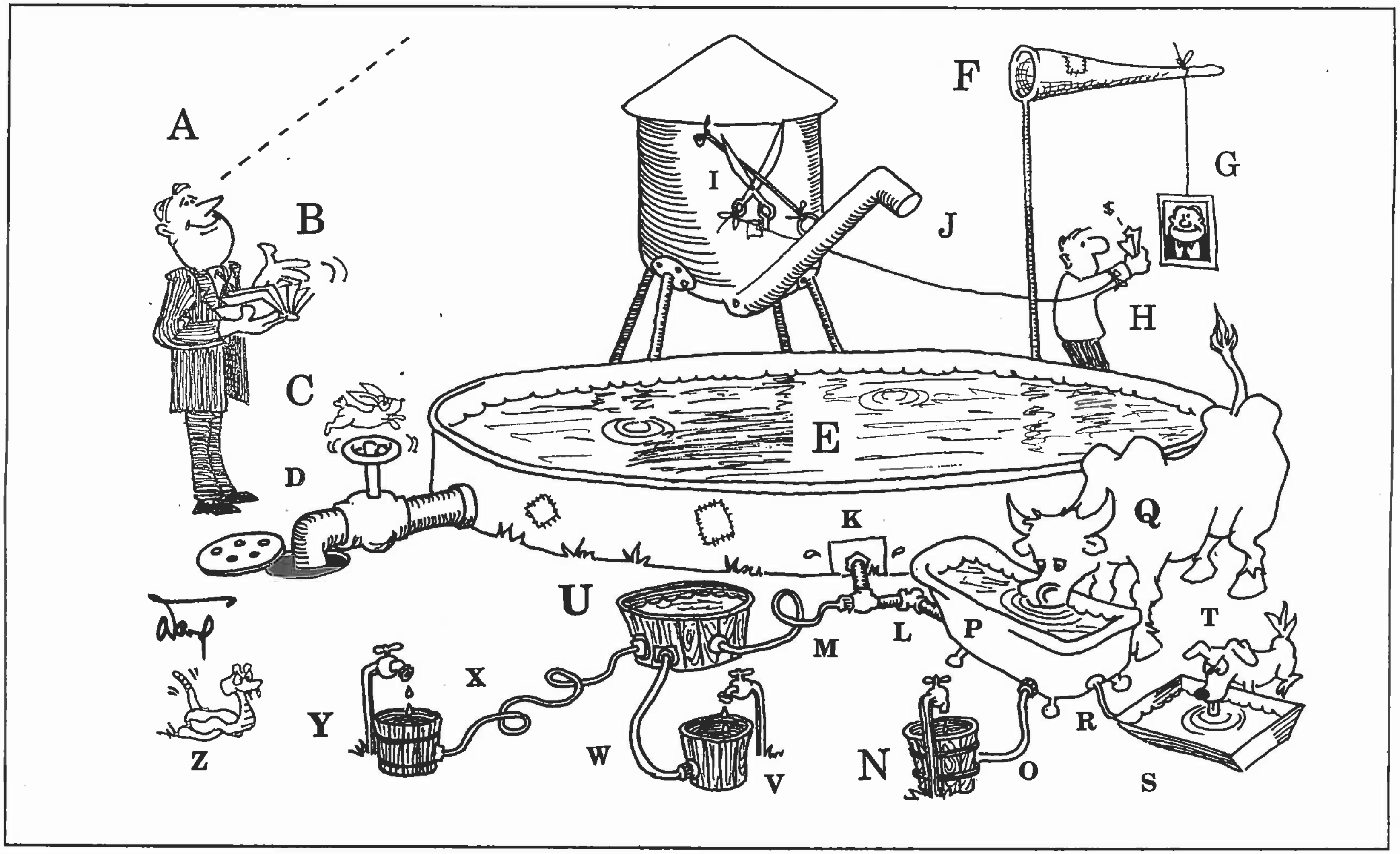


Figure 6-1. Conceptual model of hydraulics of Corpus Christi Bay system (with apologies to Rube Goldberg)

Elevation of moon inspires romantic (A) to wax rhapsodic, flipping pages of Byron's poetry (B). Rabbit (C) mistakes sound for bullets and runs frantically, opening valve (D) releases water into sewer and thereby lowering level of Gulf (E). Strong south wind blows windsock (F), raising into view photograph of Bill Clinton (G), to whom midget (H) tries to pay taxes, pulling scissors (I) to cut cord lowering downspout (J) to release water from tower, thereby raising water in Gulf (E). Water level variations are communicated through Aransas Pass inlet (K) into Corpus Christi Bay (P) through Turtle Cove channel (L) and into Aransas Bay (U) through Lydia Ann Channel (M). Water also enters Corpus Christi Bay (P) from Nueces Bay (N) through Nueces Entrance (O), and is lost to surface flux (Q). Water level variations pass through Bulkhead Flats and Causeway (R) into Upper Laguna (S), which also loses water to surface flux (T). Aransas Bay (U) communicates with Copano Bay (V) through Copano Pass (W) and through Ayres/Carlos Bay (X) with San Antonio Bay (Y), which is beyond scope of present study. Rattlesnake (Z) is also beyond scope of present study.

the moon. (Actually, the declination of the moon varies with a 27.2-day period, but the tidal response is not affected by whether the declination is negative or positive, so only its variation in *magnitude* matters.) Figure 2-14 shows how well using only these three components succeeds in replicating the observed Gulf tide. Phase and proximity (perigee), therefore, have very little importance. The 13.6-day fortnightly variation is manifested in two ways: as a modulator of the range of the 24.8-hr variation and as a 13.6-day rise and fall in average water level.

The relative importance of these three components changes with passage through any one of the inlets in Fig. 6-1. Because of its restricted cross section, the conduit (the hose in Fig. 6-1) will not be able to pass water as quickly as the water rises or falls in the larger basin. In other words, the smaller basins behave like stilling wells, in which the slower, longer-period variations are passed through but the shorter-period variations are significantly filtered out. The most quickly changing tidal component, the 12.4-hr semidiurnal only barely leaks through Aransas Pass, so the interior tide becomes even more dominated by the 24.8-hr signal—which is itself severely attenuated—and the 13.6-day fortnightly signal. After the signal propagates through several such connections to the interior basins of Copano, Nueces and the Upper Laguna, the main tidal variation that survives is the fortnightly, tracking the declination of the moon.

There is also an asymmetry in the passage of water through the inlet. Think of it as arising from the ability of the Gulf to force a flow through the hose when its water level is higher than that of the basin, which then drains out more slowly when the Gulf level falls below that of the basin. (Actually, this asymmetry arises from the differing entrance/exit losses due to the complex geometry, as discussed in Section 4.2 and 4.3.) With this mechanical analogy in mind, it is easy to see that the result will be an average water level in the basin higher than the average in the Gulf, so that there is no long-term *net* flow into the basin.

There is an even slower change in Gulf water levels that is transmitted practically unattenuated into the bays, namely the "secular" semi-annual rise and fall. This is quasi-periodic, with maxima in spring and fall, and minima in winter and summer. However, as shown by the five years plotted in Fig. 2-15, this semi-annual variation exhibits considerable year-to-year differences, both in when exactly the seasonal extremes occur and in what their magnitudes are. The fall maximum is usually the highest level that water normally attains, and the winter minimum the lowest, though the summer minimum is more dependable in its date of occurrence. The causes of this secular variation are not understood; it is probably a result of a combination of both astronomical and climatological forcing, perhaps with some hydrodynamic responses involved as well, see Section 5.1. For the present context, what is important is that it does occur, and must be considered in the water exchange of the study area bays.

Frontal passages produce water-level variations and accompanying transports of water. The primary mechanism is the change in direct wind stress on the water surface, though atmospheric pressure variations can contribute a secondary forcing. As the front approaches the coastline, onshore wind flow is increased, setting up water levels along the coastline. With the frontal passage, winds turn abruptly to the northern quadrant, reversing the direction of stress. The area over which the winds operate and their duration are both important in the magnitude of the response. There is a direct downwind set-up of water levels across a component bay, which is considered below, and there is an indirect water exchange caused by a frontal-induced water-level difference between basins. By far, the most important is the exchange between the study area bays and the adjacent Gulf of Mexico, as suggested by the wind-forcing depicted in Fig. 6-1. The relatively short-lived low-energy frontal passages, referred to in this study as "equinoctial" fronts, may not force a response in the large waterbody of the Gulf. Even if one occurs, the wind reversal and re-establishment of onshore flow take place in a matter of one or two days, too quickly for the bay to respond to the Gulf through the narrow inlet conduit. On the other hand, the large-scale synoptic disturbances that result in outbreaks over the northwestern Gulf of Mexico are most important in inducing an exchange between the Gulf and the interior bays. These "outbreak" fronts (see Section 4.4.3) are most frequently a phenomenon of winter, but can occur from September through May. Their duration is similarly variable, but averages 6-7 days. This is approximately the same duration as the rise of the fortnightly tide. Therefore, a statistical quantification of water-volume exchanges on this time frame, such as given in Table 5-1, will include both tidal and meteorological responses. (These could be separated by determining the tidal and meteorological conditions attending each such event, but this would require a much greater investment of effort than the resources of this project permitted.)

The general magnitudes of these water volume exchanges are summarized in Table 6-1, in terms of the prism, i.e. the volume of water transported into the bay from the larger basin (ultimately the Gulf) from low stage to high stage, and the time period over which this transport occurs. These data are drawn from tabulations presented earlier, as indicated in the notes, and the text discussions should be consulted for details. Several conclusions from this analysis may be drawn:

- Generally, for each time scale the volume of water exchanged diminishes with distance from the Gulf.
- In terms of volume exchanged, the seasonal variation is much larger than the diurnal and fortnightly; however, in terms of the rate of exchange, i.e. volume per unit time, the diurnal is greater
- Generally, the volumes involved are on the order of, or less than, 10% of the volume of the bay.
- The prominent exceptions are the shallow bays of Nueces and the Laguna, for which the volume exchanged is an appreciable fraction of the total (low-tide) volume of the system. For the Laguna in particular, the seasonal exchange of volume is approximately equal to the low-tide volume of the component bay.

Years ago, Collier and Hedgpeth (1950) observed that "the water level variation coincident with the cycle of tropical and equatorial tides is probably the most important so far as the lagoons are concerned. It is these variations which bring about the largest exchange of water between lagoon and Gulf, and which alternately expose and flood the greatest area of tidal flat and marsh." In terms of

Table 6-1
Prisms (10^6 m^3) for water exchanges in Corpus Christi Bay system

Component bay	*bay volume*	*time scale (one-half period or typical rise duration)* 12.4 hrs*	7 days†	3 months††
Copano	429	18	20	55
Aransas	526	21	22	65
Corpus Christi	1566	61	47	130
Nueces	49	15	6	18
Upper Laguna	77	5	8	80
Total	2647	120	103	348

* Table 4-3, volumes vary by factor of 1.5 about these values, minimum at zero lunar declination, maximum at great declination

† Table 5-1, volumes vary by approximately factor of 3.5 about these values, depending primarily upon meteorological conditions

†† Table 5-2, highly variable by factor of 2 about these values from year-to-year and season-to-season

the shorter period astronomical components of the tide, they correctly judged the filtering effect of tidal propagation into the system, which makes the fortnightly component the most important. But the effectiveness of the fortnightly component in flooding the peripheral marshes also depends upon the mean water levels, which are strongly influenced by the secular seasonal variation that Collier and Hedgpeth did not consider.

There is a unidirectional exchange, or throughflow, of water volume as well. This is forced primarily by freshwater inflow and the surface flux of net precipitation less evaporation, which for this area is negative except for brief periods of rainfall (see Sections 2.2.1 and 2.2.3, especially Fig. 2-10), and in two component bays by power-plant cooling water circulations. The freshwater inflow and surface evaporative flux are depicted in Fig. 6-1, but the power-plant returns are not. (This would require bigger animals for one thing.) These throughflow volumes are summarized in Table 6-2, from data collated in Section 5.3.1. These are very long period averages; there is considerable month-to-month variation in these numbers. Indeed, the vacillation from drought to flood is one of the important features of the hydrology of the Coastal Bend Bays, and the ranges about the values given in Table 6-2 are several orders of magnitude.

Several observations follow from inspection of Table 6-2 and the supporting analyses of Section 5.3 above:

Table 6-2
Throughflows (10^6 m^3 mo^{-1}) for Corpus Christi Bay system based upon 1968-90 data, cf. Tables 5-8 and 5-9

Component bay	*bay volume* Mm^3	*watershed inflow* Mm^3/mo	*surface P-E* Mm^3/mo	*Net return - diversion* Mm^3/mo	*power-plant return* Mm^3/mo
Aransas-Copano	955	62.5	-18.0	-	-
Corpus Christi	1566	62.5	-26.8	-4.7	-
Nueces Bay	49	58.1	-3.0	-11.0	48.5
Upper Laguna/ Baffin	511	9.6	-31.2	-	-49.9
Total	3081	134.6*	-68.0	-4.7*	98.4†

* Nueces Bay included in Corpus Christi total
† circulating flow volume: net is zero

- By estuarine standards, over the long term, the average freshwater throughflow is small (a net freshwater replacement time for the system of about 50 months).
- There is a substantial gradient in hydroclimatology across the system, with decreasing inflow and increasing evaporative deficit with distance south. (There is another potential source of inflow not accounted for, from the San Antonio Bay system through Ayres Bay, so the hydroclimatological gradient, if anything, is understated.)
- The inflow history of the system can be succinctly described as widely spaced large influx events, on the order of the volume of the system, superposed on a chronic continuing inflow deficit. (There are points in the record when components of the system lose as much as 20% of their volume per month to evaporation, and there are occurrences when the monthly inflow is great enough to replace the entire volume of the system.)
- On a long-term basis, the diversions for human use are non-negligible but minor compared to the natural inflows and evaporative losses.

However, under the frequent drought scenarios, the relative importance of the diversions becomes much greater.

The power-plant throughflows are geographically restricted and affect only a small portion of the systems in which they are imposed. For Nueces Bay, the power-plant outfall is located in the southeast corner of the bay, relatively near Nueces Entrance. The volume transport is largely confined to this section of the bay and this *portion* of Nueces Bay is replaced at a proportionately greater frequency than the data of Table 6-2, applied to the entire Nueces Bay volume, would indicate. Similarly, the entire Upper Laguna system is not affected by the power-plant withdrawal, but the recirculation can be expected to mainly affect the volume between the Causeway and Pita Island, at a proportionately higher rate.

In summary, there are two separate classes of water-volume transport affecting the Coastal Bend bays, depicted in Fig. 6-1: the bi-directional exchange between the basins of the system, and the unidirectional throughflow forced by influxes and surface losses. These can represent either a displacement or a dilution of water in a basin; which of these depends upon the volume and time-scale of the exchange in comparison to the rate of internal mixing. By "internal mixing" is meant movement and exchange of water masses within a component bay. These can take place on a range of scales:

- small-scale turbulence, due to wind waves, local current shears, and small mechanical disturbances
- movement of water across the bay forced by meteorology, especially frontal passages
- gyres, providing a persistent circulation of waters within larger regions of a bay, spun up primarily by sustained winds

The sudden change in surface wind stress that occurs during a frontal passage produces a direct set-up across the bay. The water movement associated with this set-up is referred to here as cross-bay transport. The measurements of wind and water-level shown in this report (EXHIBIT2 and EXHIBIT3) indicate that this response is virtually immediate, the water surface tracking closely the direction and speed of wind. Several such events are examined in Section 4.4.3 and the response of the bay to fronts is summarized in Section 4.4.4. In particular,

- The frontal response of the Gulf of Mexico is the single most important factor determining the total response of the bay.

- The cross-bay transports are about the same magnitude for both equinoctial and polar-outbreak fronts; however, the prism is much greater for the polar-outbreak fronts since a response to the Gulf is involved.

- The frontal prism is on the same order as the great declination tidal prism, and for the outer bays is generally larger than the great-declination tidal prism.

Table 6-3
Cross-bay transports from direct frontal set-up,
averages of data in Table 4-4

Component bay	*bay volume (Mm^3)*	*cross-bay transport (Mm^3)*
Aransas	526	8
Corpus Christi	1566	16
Nueces	49	1
Upper Laguna	77	6

Because the outbreak fronts induce a water-level response on a time scale of several days, most of their statistical effects on water-volume exchange are included in the data of Table 6-1. The cross-bay transports, see Fig. 4-15, occur much more quickly but entail smaller water-level changes and smaller volumes. The average volumes of cross-bay transport based upon the case studies of Table 4-4 are summarized in Table 6-3. These volumes are generally on the order of 1% of the volume of the bay. The exception is the Upper Laguna, which is an extremely shallow system whose axis aligns with frontal northerly winds, for which the cross bay transport is 10% of the volume and the direction of transport is down the longitudinal axis of the system. (The volume would be even greater were it not for the influx of water through the JFK Causeway forced by set-up in Corpus Christi Bay.) The cross-bay transport, combined with the Gulf set-down response, makes the Laguna particularly responsive to fronts.

The prisms of Table 6-1 and the cross-bay frontal transports of Table 6-3 are examples of advective water exchange accompanied by water-level fluctuations. In interpreting these data, it is important to distinguish between the transport of volume and the movement of individual water parcels. The effect of these prisms is manifested across the entirety of the component bay. However, the movement of individual water parcels is considerably more restricted. A conceptual model of this process is shown in Fig. 6-2. In this model, transport of water volume is modeled by passing boxes of popcorn. There is a net movement of one box of popcorn from the leftmost chair to the rightmost. However, each box moves a distance of only one seat. The tidal excursion for example (see Table 4-3) more properly measures the movement of individual water parcels and is the upper bound on the distance over which any kind of mixing would take place. Such cross-bay transports enhance the rate of mixing by increasing water velocities which in turn increases turbulence production and shear dispersion. However,

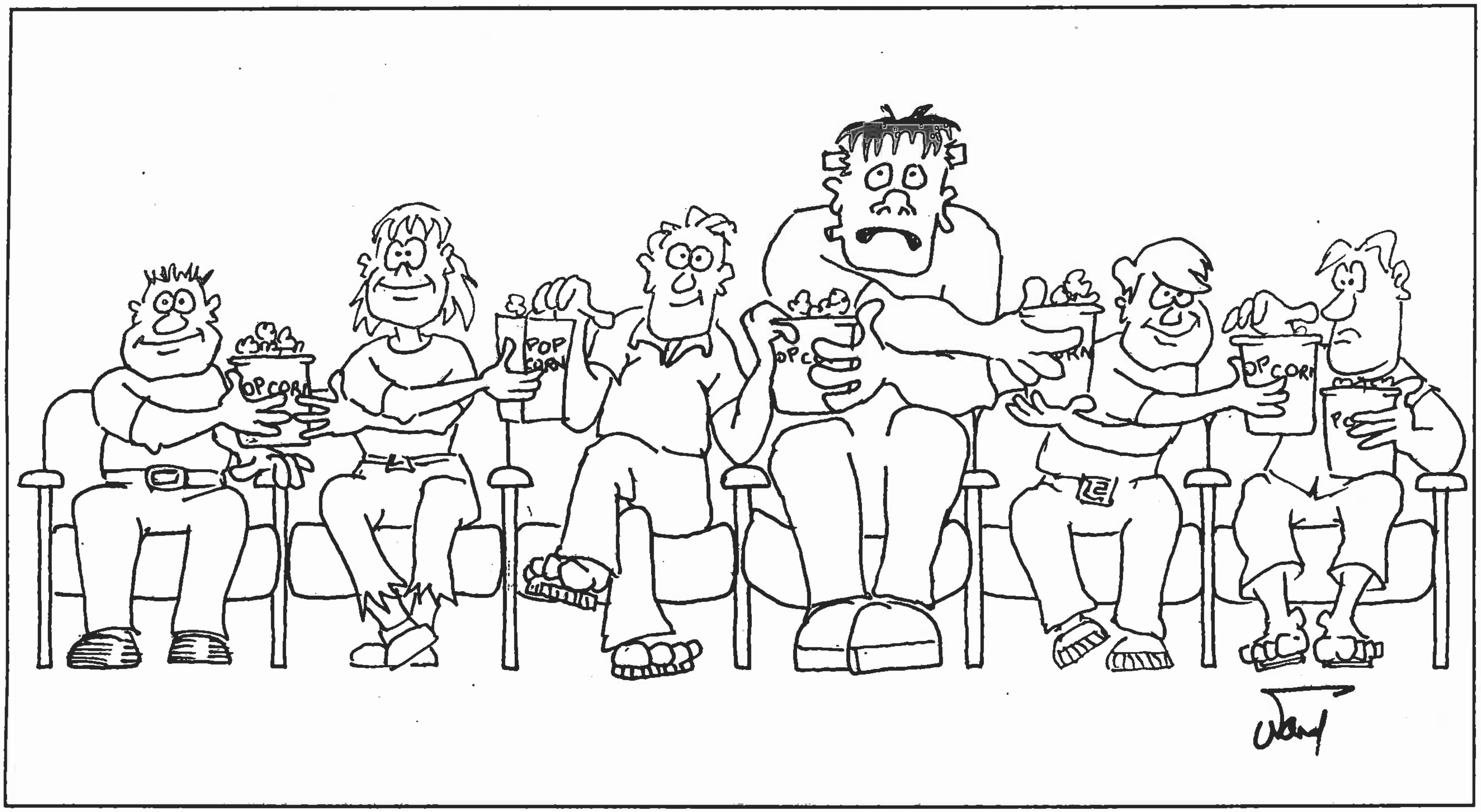


Figure 6-2. Conceptual model of cross-bay volume transport, as passing popcorn during matinee (see text)

the effectiveness of mixing is limited by the time scale of these processes. For diffusivities typical of Corpus Christi Bay, Fig. 5-50 shows that tens of days are necessary to begin to mix down a gradient in properties.

Internal circulation such as density currents and gyres are more effective in promoting mixing because, unlike the tidal and frontal prisms which are bulk movements of water, they accomplish differential movement of water and thereby bring waters of dissimilar properties into proximity so as to increase the rate of mixing for a given level of turbulence. Unfortunately, good current data in the interior of the study are bays are too sparse to allow delineation of internal circulations. There is no indication in the salinity structure or in the few current profiles extant from the Corpus Christi Ship Channel that a salinity-driven density current operates in Corpus Christi Bay. In Fig. 5-49, suggested wind-driven gyres under prevailing winds from the southeasterly quadrant were sketched, based on the statistical tendencies indicated in the SWRI current meter data. In 1976, the DMRP briefly operated two Endeco current meters nearly dead center in Corpus Christi Bay, just south of the CCSC at Beacon 56 (Schubel et al., 1978). One current meter failed, but the one moored at 1.1-m depth yielded a 25-hour record of currents, shown in the upper panel of Fig. 6-3 as a vector hodograph. Wind conditions were steady southeasterly winds averaging 3 m/s at Corpus Christi airport, with a superposed seabreeze circulation. One isolated tidal cycle of current measurement proves little, but this one was taken in the most ideal season, 24-25 August, when the system is dominated by steady summer conditions, and is seen to be composed of a westerly net current at approximately 0.02 m/s and a 25-hr oscillating component along a NW-SE axis of amplitude 0.07 m/s, as shown in the lower panel of Fig. 6-3. The net component is consistent in speed and direction with the postulated gyre of Fig. 5-49, and the 25-hr oscillation is consistent with a superposed tidal variation (see Table 4-3) and seabreeze-driven component. The volume of flow postulated for the wind-driven gyre is on the order of 10^2 Mm^3/mo.

A summary of the exchanges and throughflows as a proportion of each of the component bays is given in Table 6-4. The diurnal tide and frontal cross-bay transports have too short a time scale to allow appreciable mixing, so these represent more of an oscillation of the water within a bay rather than a dilution. An example is Fig. 5-45, during the replacement of Nueces Bay waters by a freshet influx. Note that the salinity gradient is preserved during this process, as evidenced by the sharpness of the salinity peaks of 6-10 June, as this gradient is advected back and forth by the salinity monitor. Though the rate of water movement is less for the semifortnightly and seasonal prisms, the duration of time over which this new water is in the component bay would allow more mixing with other waters. Thus these exchanges are viewed as representing more true dilution capability, in contrast to the shorter term diurnal tide and frontal set-ups which effect water-mass displacement. The shallow systems of Nueces Bay and the Upper Laguna, in particular, would be effectively diluted by the seasonal secular variation. For throughflow, whether the mechanism results in a displacement and mixing, therefore a dilution of water in the component bay, or a complete replacement of water, depends upon the volume of flow. Freshets are

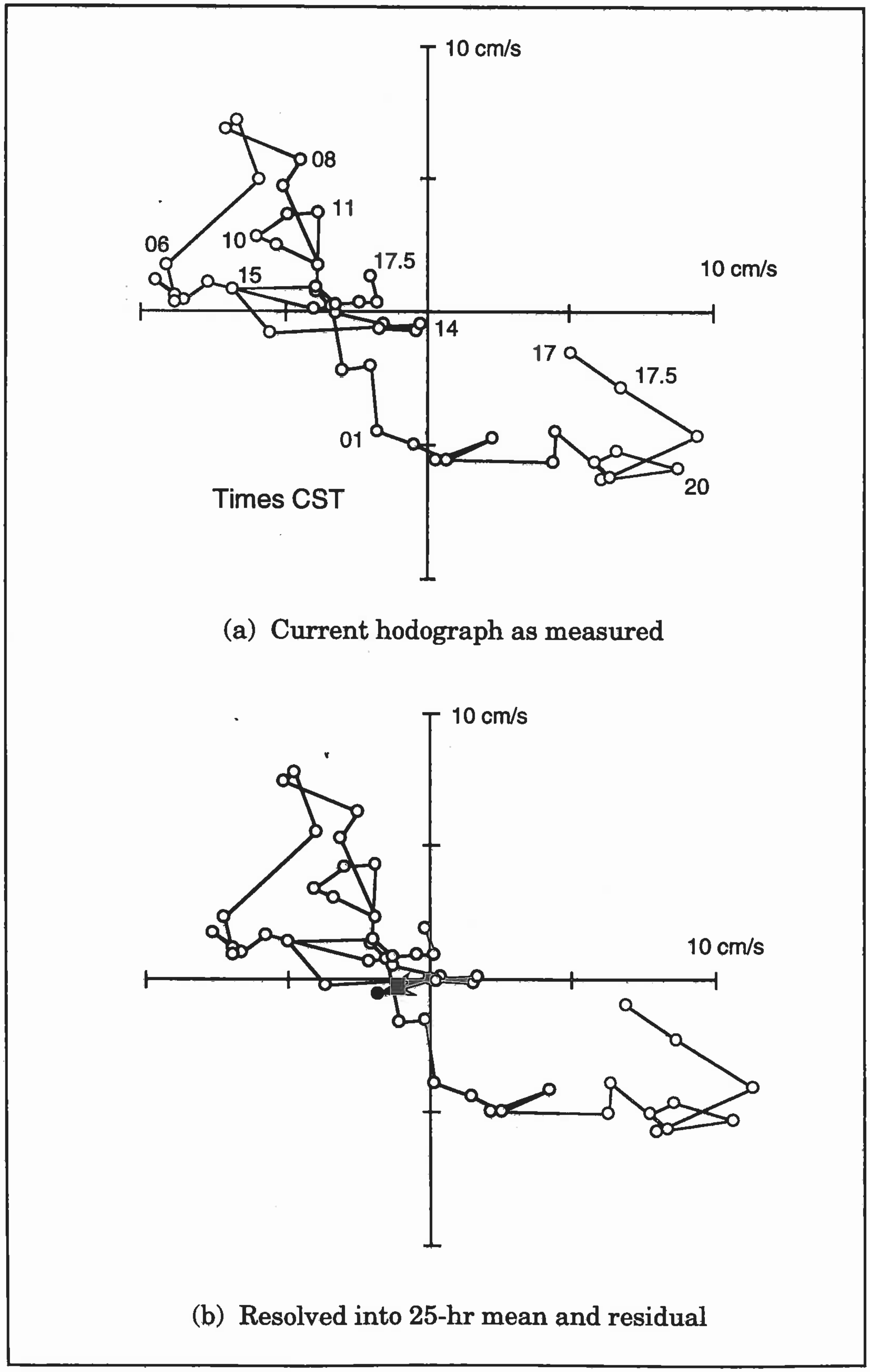


Figure 6-3. Measured current at 1.1-m depth over tidal cycle 24-25 August 1976 in mid-Corpus Christi Bay, from Schubel et al. (1978)

Table 6-4
Transports as proportion of (low-tide) bay volume

Bay:	*Copano*	*Aransas*	*Corpus Christi*	*Nueces*	*Upper Laguna*	*Baffin*
			exchanges (per cent)			
diurnal tide	4.2	4.0	3.9	30.6	6.5	-
frontal cross-bay	~1.5?	1.5	1.0	2.0	7.8	-
semifortnightly	4.7	4.2	3.0	12.2	10.4	-
seasonal	12.8	12.4	8.3	36.7	103.9	-
			throughflows (per cent per month)			
inflow	~11.7	11.9*	4.0†	118.6	12.5††	2.2
P-E	-2.0	-1.8	-1.7	-6.1	-20.9	-3.5
Net returns	0	0	-0.3	-22.4	0	0
power-plant return	0	0	0	99.0	-64.8	0

* includes Copano † includes Nueces †† inflow from Baffin

large enough that they can effectively replace the volume of Nueces and Copano Bays. Usually they act to dilute the volume of the larger Corpus Christi system (but this, again, depends upon their magnitude). On average, the system that is most effectively replaced is Nueces Bay. The net freshwater inflow is the sum of net returns (negative because these are withdrawals from Calallen) and inflow (which counts the releases from storage of the LCC/CC system). The component bays that are least effectively replaced/diluted are Corpus and Baffin.

Frequently, the proportion of estuary volume replaced by inflow is used as a measure of flushing of the system. This is often expressed as a time (e.g., the reciprocal of the entries in Table 6-4 times 100 gives times in months), the so-called flushing time of the system. Ward and Montague (1996) criticize this parameter because there are other sources of dilution/replacement water operating in an estuary not taken into account. This is clearly illustrated for Corpus Christi Bay by the data in Table 6-4 in which it is apparent that, except for the outer systems, the other transports are on average just as important, or even more so, than freshwater inflow.

Finally, it is instructive to consider how throughflow and exchange interact in establishing a gradient of concentration of some waterborne constituent. As an example, we examine the longitudinal distribution of salinity in an estuary without surface flux (evaporation). This gradient is established by a balance between throughflow, which is essentially an advective process, and up-gradient mixing, which is essentially a diffusive process (see Section 5.4.4). A conceptual model of this process is diagrammed in Fig. 6-4, again in the style (somewhat) of Rube Goldberg, in which the concentration of salinity is modeled as the depth of paper in front of the individual desks.

Throughflow, freshwater inflow in this example, is manifested as the rate of movement of the conveyor, carrying the paper from left to right. This is advective transport. The paper encounters the wall at the right, piles up and tumbles back up the conveyor. The steeper the slope of the paper pile, the greater the rate at which the paper tumbles back up the conveyor. The slope attempts to adjust itself to a zero level: this is diffusive transport. For a steady rate of conveyor movement, the transport of paper to the right exactly compensates the gravitational cascade to the left, so the amount of paper (though not the individual reports) in front of each desk becomes steady. The rôle of the work assigner to the right is important: he maintains a fixed level of paper at the wall. This is analogous to the fixed concentration of salinity in the ocean. An abrupt increase in the rate of conveyor movement creates a temporary disequilibrium, the pile at the wall increasing (and spilling over), and the slope of the pile steepening, i.e. salinity extrusion. A decrease in the conveyor rate results in the pile tumbling and cascading further up the conveyor (supplemented by more paper heaved over the wall to keep the level there fixed), i.e. salinity intrusion.

6.2 A hydrographic timeline of Corpus Christi Bay

Since approximately the latter quarter of the last century, major physical modifications have been underway to the Corpus Christi Bay system, as recounted in Chapter 3. A chronological listing of these modifications is given in Table 6-5. In light of the analyses of transport and hydrodynamics presented in Chapters 4 and 5, we can now infer the probable effects of these physical modifications on circulation in the system.

As noted in Section 3.1.1, the stabilization, jettying and dredging of the inlet channel has probably resulted in an increase in diurnal tidal prism at least on the order of 10%, due to the increased cross section and reduced friction. On the other hand, it is unlikely that there has been a similar effect on the longer period components, such as the fortnightly or seasonal prisms, because the time scale of these is sufficiently long that they would be transmitted into the system through the inlet in its natural state.

There have been frequent statements in the literature that the chronic closure of Corpus Christi Pass early in this century has resulted from tidal-prism capture by the enlarged Aransas Pass inlet (e.g., USCE, 1962). Tidal-prism capture occurs when an inlet located in a hydraulically favorable position on a barrier island is created or enlarged so that it becomes the dominant tidal passage. Any pre-existing inlet sees a reduction in flow, and often increased shoaling. The classical example on the Texas coast is the capture of the tidal prism of Pass

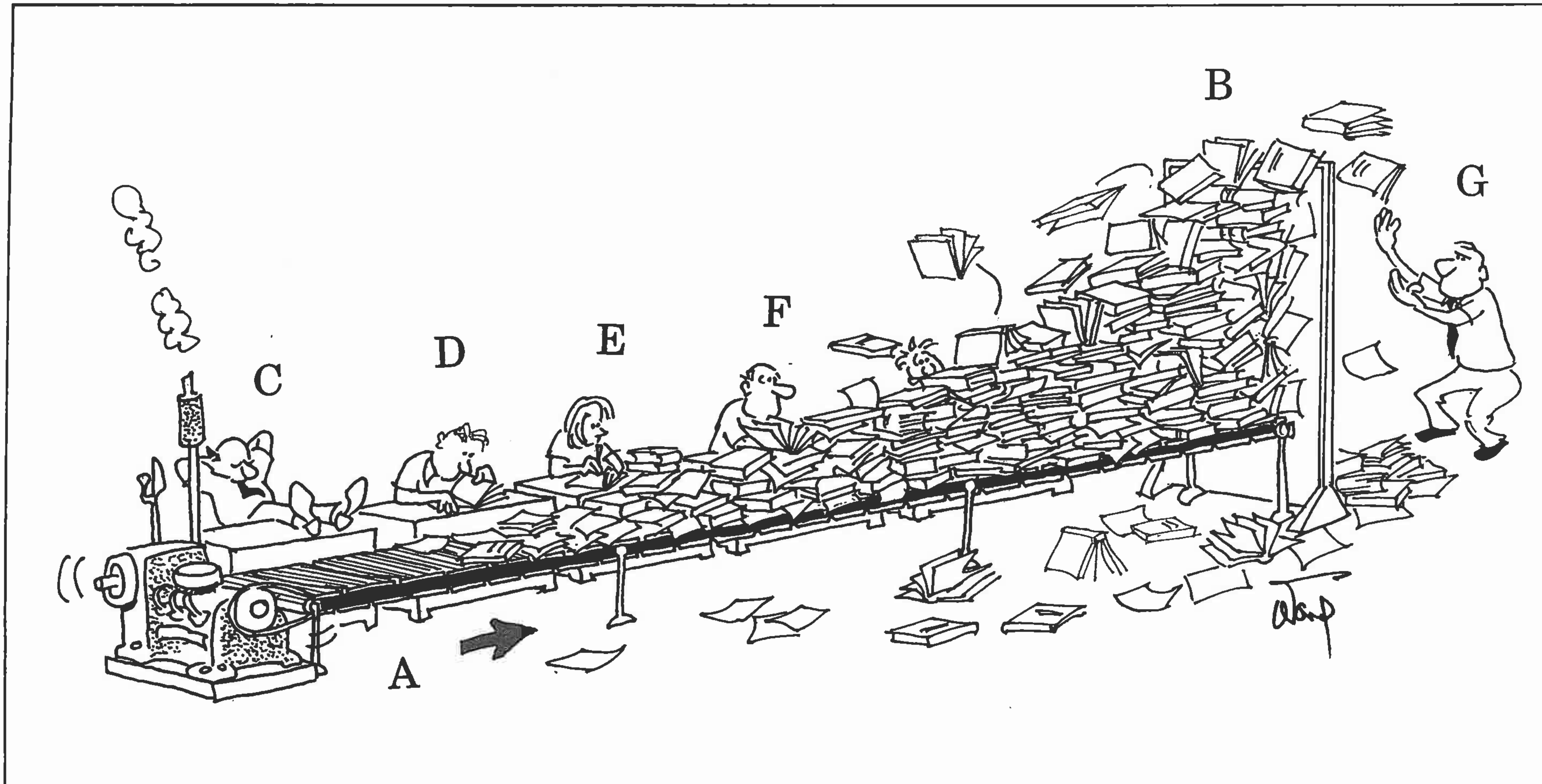


Figure 6-4. Conceptual model of salinity intrusion in estuary, as paper flow in state agency.

Conveyor belt (A) transports reports, contracts, and permit applications to right, until barrier (B) is encountered. Paper piles up and tumbles back up conveyor. Equilibrium is established between movement of conveyor and slope of paper pile. Supervisor (C) controls conveyor rate (freshwater inflow) and work assigner (G) maintains constant level of paper at barrier (ocean salinity). Amount of paper in front of each work station (D, E, F, proceeding down organization chart) is analogous to concentration of salinity in estuary.

Table 6-5
Chronology of major physical modifications
to Corpus Christi Bay system through 1990

1881-1919	Stabilization and jettying of Aransas Pass inlet
1898	Calallen "Dam" (saltbarrier) constructed on Nueces
1900 circa	Closure (natural) of Corpus Christi Pass
1915	Nueces Bay causeway complete, Nueces Entrance 75% constricted
1925-26	25 x 200 ft channel dredged through Turtle Cove & across bay
1926	Nueces Bay "dike" created as part of Turning Basin project
1930-40 circa	Major removal of oyster reefs in Mesquite/Aransas Bay
1934	La Fruta Dam on Nueces closed, capacity ca. 50,000 ac-ft.
1930-80	Increase in CCSC channel dimensions to 45 ft
1930-80	Side-casting of dredged material in areas N and S of CCSC
1934	Inner Harbor channel extended to Avery Point within Nueces Bay "dike"
1941	30 x 200 ft channel dredged across Corpus Christi Bay from Ingleside to Flour Bluff (not maintained)
1941	Nueces Bay SES at 30 MW
1945	12 x 125 ft channel dredged through Aransas Bay to Aransas Pass
1949	12 x 125 ft channel opened through Mudflats of Laguna Madre, dredged material placed in area E and W of channel, forming barrier along axis
1949	Nueces Bay SES circulating 120 cfs
1949	Landfill sections of JFK Causeway completed across Bulkhead Flats in Upper Laguna
1950	Nueces Bay "dike" extended to Tule Lake Turning Basin
1950-58	Nueces Bay "dike" built up as disposal area for channel dredging
1950-68	Major removal of "mudshell" from Nueces Bay
1954-80	Deepdraft La Quinta channel dredged to Reynolds, dredged material placed to west of channel to create dike
1958	Seale Dam closed, forming Lake Corpus Christi, 300,000 ac-ft capacity
1959	Dredging of Cedar Bayou
1965-73	Nueces Bay SES flow increased to 650 cfs
1972	Opening of New Corpus Christi Fish Pass
1974-76	Barney Davis online, flow increased from 335 cfs to 670 cfs
1979	Deliberate closure of Cedar Bayou (emergency bulldozing)
1982	Choke Canyon Dam closed, capacity 270,000 ac-ft
1983 circa	Closure (natural) of New Corpus Christi Pass
1988	Dredging of Cedar Bayou

Cavallo by the artificial Matagorda Entrance Channel (Ward, 1982b). A study of the history of Corpus Christi Pass (Section 3.1.2) indicates that this inlet was only marginally stable in the Nineteenth Century, long before modifications were made in Aransas Pass. Its small cross section together with the limited tidal range of Corpus Christi Bay would imply a miniscule tidal prism, on the order of that measured at the new inlet after it was opened in 1972, only 5% of the modern prism of the bay (Defehr and Sorensen, 1973). Moreover, from the historical perspective, Corpus Christi Pass seems to have already become chronically closed by 1908 prior to the completion of the jetty and inlet channel work. A more balanced judgement would be that the pass has closed due to a natural overload of littoral sands.

Considering that Corpus Christi Pass is advantageously located at the southeastern extreme of a large bay, where it can be scoured by currents driven by frontal passages, much like Bolivar inlet in the Galveston system and Pass Cavallo in the Matagorda system, the bigger mystery is why Corpus Christi Pass was not a larger, more stable inlet in its natural state. The diminishment in the ratios of inlet cross sections to bay areas with distance down the Texas coast is suggestive that the southward convergence of littoral drift is the reason. This would also explain the eventual demise of New Corpus Christi Pass, despite its engineering design to be stable, and the total failure of Yarborough Pass (née Murdock Pass) to remain open, even while it was being dredged.

The small tidal prism implies that the opening and closure of Corpus Christi Pass would have had little effect upon circulation in the larger Corpus Christi Bay system. This raises the question of whether the artificial inlets of New Corpus Christi Pass or Yarborough Pass would accomplish the water exchange with the sea which was one of the prime objectives for their construction (e.g., Carothers et al., 1959). The answer would appear to be negative. As noted in Section 3.1.2, Collier and Hedgpeth (1950) reported that Gunter conducted salinity measurements in the Laguna while Yarborough was open and determined that its effect of reducing salinities by dilution with seawater was limited to about a quarter mile. No specific studies were found addressing the effect of Corpus Christi Exchange Pass, but a qualitative examination of the historical salinities from Ward and Armstrong (1997a) from nearby segments, Fig. 6-5, evidences no influence of the pass. Although their remark addressed specifically Murdock's Pass, Collier and Hedgpeth (1950) were dead on in their comment, "The amount of water which could be exchanged is infinitesimal, as compared with the total volumes of highly saline water [in the bay]." Of course, even if the benefits of these artificial passes for water exchange are exaggerated, they may still serve an important ecological function as migratory accesses, but this lies beyond the domain of circulation processes.

Probably the single most significant physical modification to the Corpus Christi system was not the stabilization and jettying of the inlet, but rather the opening of the Turtle Cove mud flats to deepdraft dimensions in 1925-26. The evidence of deep scouring in Lydia Ann Channel, and the navigational superiority of the Aransas-Copano system (versus Corpus Christi Bay) in the Nineteenth Century

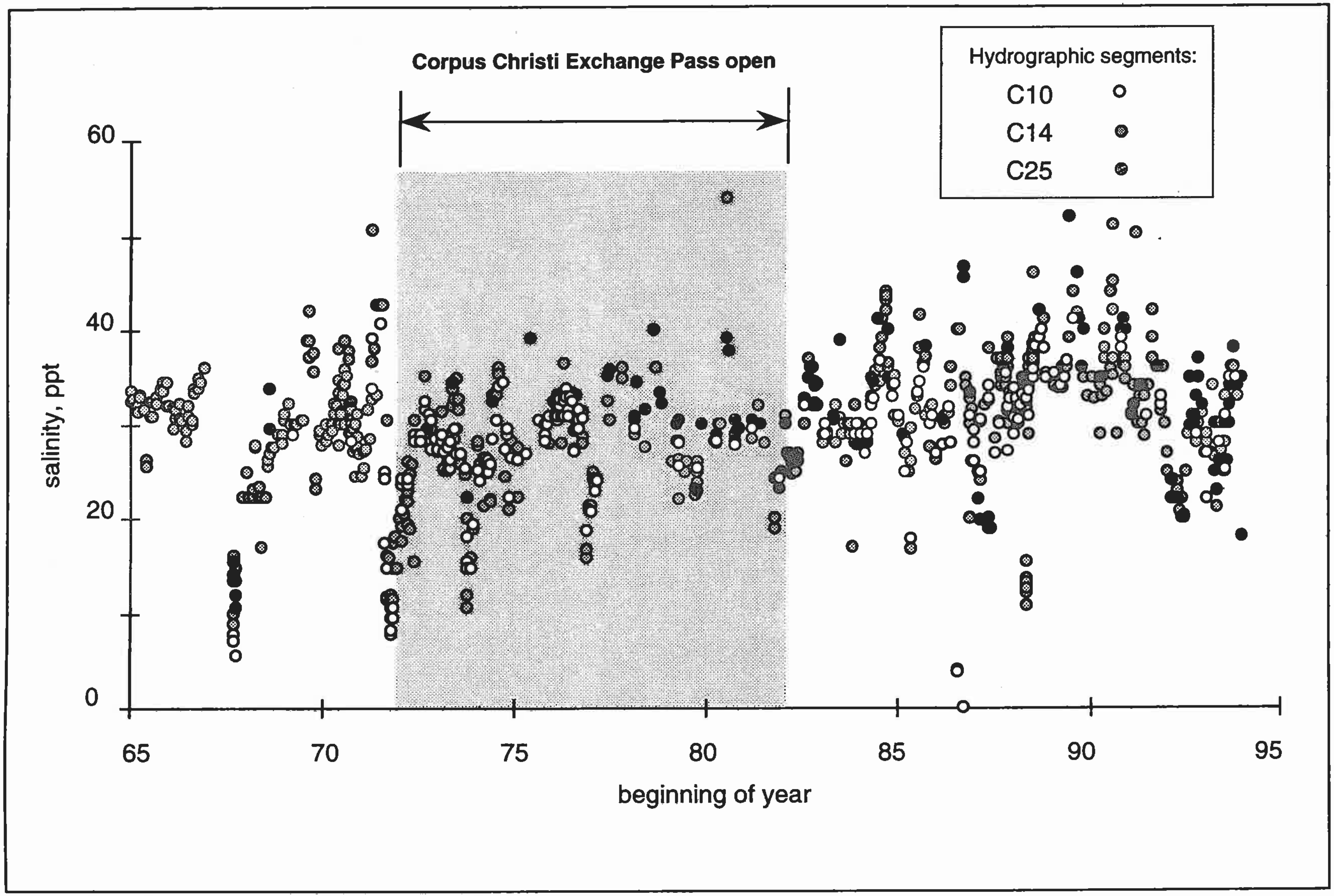


Figure 6-5. Salinities in upper 1 m in segments near Corpus Christi Pass, see Fig. 5-16

clearly demonstrate that the main tidal exchange through Aransas Pass was with the upper system. Very little diurnal tide would have been capable of passing the Turtle Cove/Redfish Bay flats into Corpus Christi Bay (though certainly the seasonal and probably the fortnightly variations would have been transmitted). Once this passage was opened, the tidal behavior would have become more like the modern system, in which Corpus Christi Bay is the primary co-oscillating basin, and tidal propagation into Aransas and Copano is attenuated and lagged (see Section 4.3.2). It is noteworthy that the currents are now sufficiently swift in the Turtle Cove channel that bank erosion has been stimulated. This passage has therefore been forced across the threshold from shoaling (as evidenced by its propensity to shoal prior to 1926) to scouring.

In all of the Texas bays, the most obvious anthropogenic physical modification is the creation of deepdraft channels. For Corpus Christi Bay, through 1980 approximately 105 Mm^3 have been excavated from the main ship channel, plus another 20 Mm^3 in the service channels (mainly the La Quinta Channel). The rate of channelization is remarkably linear with time, see Fig. 3-11(a). This represents a re-configuration of about 10% of the volume of Corpus Christi Bay *per se*. The term "re-configuration" is used because the dredged material is not removed from the system but disposed primarily in unconfined areas adjacent to the channels. In Corpus Christi Bay, these disposal areas along the main CCSC have created shoal areas, see Figs. 3-8(b) and 2-1. It is noteworthy that there is a considerably higher maintenance rate in the middle reach of the CCSC from La Quinta junction (Ingleside) to Beacon 82 compared to the reaches to the west or east, see Fig. 3-11(b). The postulated clockwise gyre in the northern segment of the bay, Fig. 5-49, would indicate a mean current across the disposal area, Fig. 3-8(b), over the channel, suggesting a tendency to re-deposit the excavated material back into the dredged channel.

With the construction of the La Quinta Channel in the late 1950's, the dredged material has been used to build up a dike to the west of the channel in the northern segment of Corpus Christi Bay, Fig. 2-2. To the present, this fill has displaced 420 ha of what was previously bay bottom. The current measurements of SWRI suggest that this dike and the LaQuinta Channel intercept a portion of the hypothesized clockwise circulation (cf. Fig. 5-49 and Fig. 5-47).

In the bays on the upper Texas coast, creation of deepdraft channels has led to greatly increased density currents (which increase roughly as the cube of depth) and an associated accelerated salinity intrusion. In the Corpus Christi system, this does not seem to be as important. Density currents no doubt occur, but are limited to those freshet events that are large enough to force the main salinity gradient into the open bay system, which are rare. Most of the time, the salinity gradient is in the Nueces Bay system, or in the Aransas-Copano system, and does not lie along the deepdraft ship channel. The lack of systematically elevated salinities along the channel and of tidal-mean upstream flow in the few current profiles that have been taken in the ship channel is evidence that density-current-driven salt intrusion is of little statistical importance to the bay's salinity structure.

Little attention has been given the Inner Harbor in this report. Very little inflow and runoff occur into the Inner Harbor channel; it is, for practical purposes, a dead-end channel subject only to tidal flushing. While its internal circulation is important to dispersal of wasteloads, it is considered to have little influence on the overall circulation of Corpus Christi Bay. As a historical footnote, in the 1960's a proposal was made to divert the Nueces River into the head of the ship channel in order to flush this system. At that time, matters relating to pollution of the nation's watercourses were handled by the Water Supply and Pollution Control Division of the U.S. Department of Health, Education and Welfare (this Division later becoming the Federal Water Pollution Control Administration). The Regional Program Director fortunately recognized a bad idea when he saw it, and commented that the discharge of municipal and industrial waste into the waterway was not causing a nuisance or a pronounced pollution problem, at least sufficient to warrant a river diversion (see USCE, 1968).

While the Inner Harbor is of at most secondary interest with respect to the circulation processes of the larger system, its creation has had a significant physiographic effect on the Nueces Bay system, because this has entailed reclamation of a major segment of the bay. Approximately 15% of the bay along the southern shoreline (Fig. 3-9) has been converted to fast land by hydraulic fill.

The other major channel project in the Coastal Bend bays, the GIWW, represents a total excavation of about 3 Mm^3 in the Aransas reach and about 8 Mm^3 in the Upper Laguna, as a quantum event in the late 1940's, a re-configuration of, respectively, less than 1% and about 10% of the volumes of these systems. The effect on circulation in the Aransas system is probably minor. In the Upper Laguna, these disposal areas have created an axial barrier running virtually the length of the Laguna. One widely asserted additional effect is an enhanced exchange with the Lower Laguna via the "landcut" through the Mudflats. This is considered in 6.3 below.

In addition to channel dredging, the dredging of "mudshell" has been a significant activity in the study area until about 1970. In the 1930's, large volumes of shell were removed from the reef systems between Aransas Bay and Carlos/Mesquite Bay. No volumes or specific dates could be established, but it seems certain that this removal has enhanced the exchange and freshwater throughflow between the San Antonio system and the Aransas system. Most of the shell dredging in the study area, however, has been in Nueces Bay. A total of about 20 Mm^3 have been removed from Nueces Bay in shell dredging since 1934, most of it over the period 1950-68. This is not as great as the volumes mined from the bays on the upper coast, but for a system as small as Nueces Bay, it is substantial. This represents about a 50% increase in the volume of the bay. The extensive shell deposits of the old reef in Nueces Entrance were greatly reduced in this process (again, no specific date or volume data could be found), probably facilitating the exchange between Nueces Bay and Corpus Christi Bay.

Construction of the earthfill JFK Causeway in 1950 has engendered much concern since before it was built (e.g. Collier and Hedgpeth, 1950) to the present, mainly with reduction of exchange between Corpus Christi Bay and the Upper

Laguna. From a historical perspective, this general area of Bulkhead Flats (Fig. 3-6) was an extremely constricted conduit even before physical modifications began (see, e.g., Collins, 1878, TGFOC, 1930). Most of it consisted of bars and flats that were emergent much of the time. The most significant scoured channel was found on the western margin between Demit Island and Flour Bluff Point, where natural depths on the order of 1 m occurred (according to a 1931-32 survey of the Corps of Engineers, on file at Galveston District). In 1878, this same channel was shown to have depths of about 4 m adjacent to Flour Bluff Point (where a packery was located) then shoaling to about 1 m further south in Bulkhead Flats (Collins, 1878).

The two inlets in the JFK Causeway, see Fig. 3-13, have in fact scoured substantially since 1949. The deeper channel of the GIWW obviously plays an important part in ducting tidal flows through the Causeway inlet. The reasons for scour and enlargement of the Humble Channel, which began as a small service canal for access to well pads in the area, is not so readily apparent. We speculate that the scour of the original Demit Island pass and the present Humble Channel are due to the same phenomenon, the accumulation of water in the northwest area of Upper Laguna Madre in response to the normal prevailing southeasterly winds. Since this region is adjacent to Corpus Christi Bay, which would be set down by the same wind regime, a gradient in water level would result capable of driving a substantial local flow. With the JFK Causeway in place, the same accumulation of water set up on the south by the southeasterly winds and set down on the north in the open waters of Corpus Christi Bay would result in a head gradient across the western section of the embankment, but in this case driving flow through Humble Channel. (Brown et al., 1995, argue the same mechanism for flow through Humble Channel, and demonstrated, by operation of a two-dimensional hydrodynamic model and comparison to velocity measurements, the sensitivity of currents in the Humble Channel to wind conditions.)

The water-level data examined in Chapter 4 (EXHIBIT2 and EXHIBIT3) indicate the magnitude of exchange presently operating in this area, and how it is controlled by water-level variations and frontal passages. While there is no doubt that the Causeway is a significant constriction of exchange, as evidenced by the almost total filtering of diurnal tides, the natural, pre-Causeway cross section of extremely shallow depths and high frictional resistance was unlikely to have allowed any greater exchange, and perhaps less. This was exactly the same conclusion reached by Carothers et al. (1959) based upon hydraulic computations of flow. Unfortunately, the modeling study of Brown et al. (1995) did not include a pre-Causeway scenario.

Two major reservoir projects have been implemented in the study area, both on the Nueces. In 1958, Lake Corpus Christi was closed, with capacity 370 Mm^3 and in 1982 Choke Canyon was closed, with capacity 333 Mm^3. These reservoirs can be expected to have two impacts on flow in the Nueces: reduction in inflow and alteration of the time signal of inflow. The first impact, a reduction in net flow to Corpus Christi Bay, is a consequence of their purpose of water supply, in that they will allow a net consumption of freshwater, mainly due to diversions for human water use, but also due to evaporation and infiltration losses. The net diversion (gross diversion less return flows) to Corpus Christi Bay has averaged about 5 Mm^3/mo since 1968, see Table 6-2. If we assume the evaporation and infiltration losses to be on the same order, probably an overestimate, then this would imply a total net reduction of about 10 Mm^3/mo, or about a 15% reduction in inflow to Corpus Christi Bay.

Note that this estimate addresses actual past impacts of water use. Future use is a different matter. The combined yield from these reservoirs is estimated to be about 300 Mm^3/yr, some of which will still find its way to the bay as return flows. If the method of Henley and Rauschuber (1981) is followed, Section 5.2.2, the net reduction in freshwater inflow at full development, counting return flows, is 115% of the yield, or 29 Mm^3/mo. This seems too high. But even if a value of half this magnitude is used, it is clear that a net reduction of 25% of average total inflow would result from full-yield commitment of the reservoir. Of course, it is not that simple. The operating permit for Choke Canyon requires a quasi-guaranteed inflow of 185 Mm^3/yr (subject to a monthly release pattern, drought-contingency plans, and pass-through criteria implemented in subsequent operating orders, which will not be discussed in this report). There is no direct relation among this number, the reduction in inflow to the system, or constraints on the yield of LCC/CC. Complete watershed/reservoir simulations would be required to quantify these impacts.

The second impact of the LCC/CC reservoirs is to produce a greatly smoothed time signal of freshwater inflow, with decreased peaks, and increased hydrograph time bases. Because the reservoirs are drawn down below conservation level most of the time (a consequence of the drought-prone hydrology of the basin), they will detain freshets, and they will create an integrated time signal of flows even when flood releases occur. The combined capacity of reservoirs on the Nueces is approximately equal to its long-term-average annual flow, which gives some indication of the capacity of the LCC/CC system to absorb and smooth freshets. Peaked impulses of inflow are important to Corpus Christi Bay hydrography in two ways. First, they promote overbanking and flooding of the Nueces delta. As described in Section 5.2.2, under LCC operation, events that were large enough to result in significant inundation of the delta occurred only about once every two years. With Choke Canyon on line, this return frequency is estimated to increase to once every three years. Second, impulse freshets are more effective in salinity extrusion, because the bay water is replaced rather than diluted, cf. Fig. 5-44 and the conceptual model of Fig. 6-4. Smoothed freshets would not *per se* result in a change in average salinity, but would decrease the variance of salinity.

The traditional indicator of the effects of freshwater inflow on an estuary is the salinity regime. Quantification of the impact of these reservoirs from salinity observations in the system is difficult, however, because there are other factors which exert strong influences on salinity, including evaporation (and everything it depends upon), exchange of water between the estuary and the Gulf (and everything it depends upon, including meteorology), and alterations in the supply of freshwater that have nothing to do with reservoir operation, particularly the highly variable hydroclimate of the watershed. As summarized in Section 5.4, there are trends in salinity that emerge from the long-period data compilation of Ward and Armstrong (1997a). In both Nueces Bay and Corpus Christi Bay, the general trend is for increasing salinities, in the former at an average rate of 0.25 ppt/yr and in the latter at 0.05 ppt/yr. There is also a declining trend in Nueces inflow, see Section 5.4.3, on the order of 29 cfs per year. At least part, if not most, of this trend is considered to be hydroclimatological in origin. It is notable that increasing trends in salinity were also determined in Copano Bay, where there is as well a declining trend in inflow of 5.1 cfs/yr; of course in this watershed, there are no major reservoir operations.

6.3 Circulation and the bay environment

Circulation is rarely viewed as a management endpoint, but rather is an intermediate or transitional feature affecting other management endpoints, mainly the distribution of waterborne parameters. Two such concerns with the Corpus Christi system have brought circulation into recent public attention: the circulation of the Upper Laguna, and the effect of freshwater inflow on salinity.

Circulation *per se* has been an issue with the Upper Laguna Madre since the last century. In 1879, for example, there was a suggestion to close Corpus Christi Pass with a dam to force more circulation into the Upper Laguna (Howell, 1879). Blocked by Bulkhead Flats on the north and the Mudflats on the south, this region exchanged with the adjacent systems only under the right conditions of meteorology and seasonal high water, except for minor tidal exchange with Corpus Christi Bay through the Demit Island Channel. Most of the concern about the Upper Laguna derives from the widespread view that the fishery of the Laguna is limited by its poor circulation. Fish kills in the shallow hypersaline pools of the Laguna have been endemic throughout its history. One of the most notorious fishkill areas is a basin just north of the Mudflats and west of Padre Island, known as The Hole or, more graphically, the Fish Graveyard (lying just off the mapped area of Fig. 2-4). While the specific causative agent has been asserted to be the high salinity itself, depleted oxygen, low temperatures, high temperatures, algae oxygen crashes, algal toxicity, excessive turbidity, or freshwater salinity crashes, the common perceived solution is better circulation. This has led to the strategy of cutting fish passes through Padre Island, see Section 3.1.2. As long ago as 1926 the U.S. Bureau of Fisheries studied the problem of the Laguna and the feasibility of an exchange pass. The 1930 yearbook of Texas Game Fish & Oyster Commission (TGFOC, 1930) stated, "Commercial fishermen, and sportsmen as well, have contended for years that Padre Island should have an artificial pass to admit the waters of the Gulf."

With this history, it could be expected that any physical modifications to the area would be judged by their potential effect on circulation. The JFK Causeway has been criticized for diminishing exchange with Corpus Christi Bay, as discussed above. It is frequently stated that the GIWW cut through the Laguna Madre has had a beneficial effect by promoting exchange (e.g., Simmons, 1957, Quammen and Onuf, 1993) especially with the Lower Laguna Madre. The evidence cited for this is moderation of the formerly high salinities. As a part of this study, the basis for the asserted improvement in circulation was examined.

Inference of the effects of any of these changes based upon the response of measured salinities is made problematic by two factors: (1) the salinity data base is deficient, and (2) the system is subjected to too many external complicating factors. With respect to (1), most of the older salinity measurements, particularly those of the TGFOC, U.S. Bureau of Fisheries, Marine Science Institute and Humble Oil & Refining, have not been preserved. What remain are a few isolated measurements, falling in the rubric of anecdotal information, or highly reduced space-time averages (e.g. Collier and Hedgpeth, 1950, Simmons, 1957). A careful examination of the salinity data presented in both of the example papers cited above (Simmons, 1957, Quammen and Onuf, 1993) reveals that the data do not really support the arguments of improved circulation.*

The second factor (2) derives from the multiplicity of events. Both the Causeway (allegedly restricting circulation) and the GIWW (allegedly improving circulation) were imposed in the same year, 1949. The next eight years were dominated by the great drought of the 1950's, with blowing sand, mobilization of dunes, and encroachment of the Mudflats. Superposed on all of these are the vacillations of the climate, the seasonal rises and falls in water level which even without the GIWW would have led to exchange between the Upper and Lower Laguna (see below), and the infrequent runoff events, such as Alice in 1954, Beulah in 1967 and Fern in 1971. Even if measured salinities indicate a change after 1950—which may be impossible to validate statistically in view of the high variance in the data—the cause is difficult to isolate.

From a purely hydraulic viewpoint, the opening of the GIWW created an improved exchange through Bulkhead Flats, which was unaffected by the Causeway, that is especially important for shorter period responses. The extent of exchange now admitted in the diurnal and semifortnightly prisms approaches 18% of the MLT volume of Laguna Madre, from Table 6-4. Although no calculations have been made, from a hydraulic viewpoint the natural Bulkhead Flats must have passed a much smaller volume of flow at these periods. Because internal circulations in the Laguna are weak due to its shallow depths, impediments to flow, and sheltered physiography, the mixing of this prism is considered to be limited and is primarily advective, cf. Fig. 6-2. On the south, exchange between the Lower Laguna and the Upper Laguna requires hydraulic continuity over the Mudflats, which occurs primarily in association with the seasonal secular rises in water level (spring and fall) and is facilitated by frontal passages. With respect to the response to frontal events, HOR used aerial

* The reported extreme measurements (in the 100's, the highest being 380 ppt reported by Fisk, 1959) have in fact diminished in frequency since approximately 1950. But it is not clear whether this is may be due simply to sounder sampling strategy in the modern data. This region is still subject to high evaporation, and in isolated nearshore areas, where saturation is approached and salts are beginning to precipitate (the conditions under which Fisk measured 380 ppt), one can easily obtain a value in the 100's.

surveillance to map the water boundary on the Mudflats every few days in 1948-49; the Texas General Land Office performed a similar aerial mapping daily from April through October in 1995. Comparison of the two—albeit qualitative—indicates that the mechanisms of frontal encroachment and hydraulic continuity establishment occur in the present system much as they did before creation of the GIWW. This is not unexpected, given the limited hydraulic capacity of the GIWW for transmitting short-time-response events (see Sections 4.2 and 4.4.4).

The most important effect of the GIWW is upon admitting the longer-period components, especially the fortnightly exchanges and the secular seasonal variation. The GIWW transmits the seasonal rise through both the Bulkhead Flats and the Mudflats barriers of the Upper Laguna with little attenuation, and appears to be almost as effective in transmitting the fortnightly prism, associated with lunar declination and outbreak fronts. From Table 6-4, these represent over 100% of the MLT volume of this shallow watercourse, and their time frame is long enough that substantial mixing with resident water should be accomplished by internal processes. In this context, the forced circulation of the Barney Davis plant represents a monthly exchange of 65% of the Upper Laguna volume, Table 6-4, though in fact confined to the northernmost section of the lagoon. This is replaced by influx from Corpus Christi Bay through the Causeway. We speculate that the circulation from the Laguna through Oso Bay into Bulkhead Flats and through the Causeway induced by this power plant may be the reason for the statistically probable increasing trend in salinity detected in the hydrographic segments just north of the Causeway, see Fig. 5-36.

Because of the critical importance of freshwater inflow to the Corpus Christi system, salinity has become the central hydrographic and habitat variable of Corpus Christi Bay. Of all of the conventional water-quality indicators, salinity has probably been more in the public view in the Corpus Christi Bay system than in any of the other estuaries of Texas, due to this perceived link to freshwater inflow and the intense local concern with the supply of inflow to the bay.

In an estuary, we expect the long-term average salinities to exhibit a landward decline toward the sources of inflow. What is striking about the distributions in the CCBNEP study area, Figs. 5-17 through 5-21, is that the overall gradient in salinity runs from north to south across the study area, from lowest salinities in the Aransas-Copano system to highest salinities in Baffin Bay, but without clear association with points of major inflow. The north-south gradient is undoubtedly the result of the diminishing freshwater inflow from Copano in the north to Baffin in the south, reinforced by increasing *net* evaporation, due primarily to the southward decrease in rainfall. The effect of evaporation on the salt budget is amplified by the limited exchange of the entire system with the ocean, especially for the lower bays of Baffin and the Upper Laguna, which do not exchange well even with the larger body of Corpus Christi Bay.

As remarkable as this north-to-south salinity gradient is, equally remarkable is the lack of a prominent gradient in salinity in those regions most affected by freshwater inflow. In Copano Bay, Fig. 5-17, which receives the greatest quantity of inflow, the average gradient is only about 4 ppt from the causeway to the mouths of the rivers. In Nueces Bay, even more surprisingly, the gradient from the mouth of the bay to the delta is flat, only a couple of ppt, Fig. 5-18. This is clear evidence that the effect of freshets in depressing salinity is relatively infrequent and short-lived (no surprise from the hydrology of the Nueces River, see Sections 2.2.1 and 5.2). Indeed, the usual locations of the freshet-induced salinity gradients are better delineated by the standard deviations rather than the mean salinities, see Figs. 5-22 through 5-25.

The popular view of salinity as a management indicator (even among some environmental agencies) is based upon two premises, which for Corpus Christi Bay are fallacious: (1) salinity is a measure of the relative concentration of seawater in a water sample, and (2) salinity is inversely proportional to the level of inflow. The former is rendered invalid because of the significant rôle of evaporation in the water budget, as exemplified by Tables 6-2 and 6-4. Just as soon as salinities begin to re-intrude after a freshet, their concentrations are accelerated by surface evaporation. This becomes especially important during a prolonged drought, when a freshet may not even dilute salinities into the brackish range.

The fallacy of the latter is to conclude that there is a *direct* association between a given level of inflow and the salinity at a point in the bay. Many attempts have been made by past researchers to extract a salinity-inflow relationship by statistical-regression analysis (e.g. TDWR, 1981, Longley, 1994), none of which has been satisfactory. Salinity in the bay responds more as an integrator of freshwater inflow, i.e. with a longer time scale of variation than that of the inflow itself. Moreover, the response of salinity is affected by the operative physical processes, e.g. tidal excursions, antecedent salinity gradients, meteorological forcing, semi-permanent circulation patterns, and evaporation. Salinity extrusion, especially in Nueces Bay and Copano Bay, is basically a mechanism of displacement by freshwater, and occurs rather rapidly when forced by freshets. Salinity intrusion, on the other hand, takes place by mixing and advection by tidal currents, internal circulations, dispersion, and density currents, and intrusion into the inland or more isolated segments of the system (e.g. Baffin Bay and the Upper Laguna) generally requires a comparatively longer time, cf. Figs. 5-44 and 6-4. The salinity at any point in the bay is in a state of dynamic response to the integrated resultant of present and earlier hydrological and hydrographic factors. The complete analysis of this behavior cannot be by statistical association alone but rather must take explicit account of the time-response character of the variates.

From the standpoint of management of the Corpus Christi Bay environment, the primary importance of circulation is in the transport of waterborne parameters. Circulation can be beneficial, in effecting a dilution and a removal of waterborne constituents that are detrimental to aquatic life. The dilution of pollutants immediately comes to mind in this category, but this can also apply to moderation of excessive salinities and temperatures. Circulation can be detrimental as well, in concentrating parameters to undesirable levels by confluence of flow, or transporting constituents into a region where their concentrations are deleterious. For example, the forced circulation from the Inner Harbor into

Nueces Bay due to the Nueces Bay SES (Fig. 3-10, Table 6-2) may be one reason for the high concentrations of sediment and water-phase metals in Nueces Bay described by Ward and Armstrong (1997a). When management actions devolve to achieving a desirable concentration range of some waterborne parameter, almost always the governing circulation processes must first be identified and quantified.

At the largest scale, one important aspect of Corpus Christi Bay circulation is that, in comparison to the bays on the upper Texas coast, it is not as well flushed and therefore has a greater tendency to concentrate waterborne substances. For example, the tidal prism of Galveston Bay is about 220 Mm^3, or 0.17 m mean tidal range (i.e., 0.17 cu m prism per sq m surface area), while the comparable prism for Corpus Christi Bay is 120 Mm^3, or 0.10 m mean tidal range. In terms of volume, the Galveston prism is 8% of its volume, while the Corpus Christi fraction is 4%. (The prism varies more than a factor of two about this mean value, depending upon lunar declination.) The outer bays of the Corpus Christi system in particular are more poorly flushed than are the secondary bays of the much more open systems of the upper coast. Compare Tres Palacios in Matagorda, or East Bay in Galveston with Copano or the Upper Laguna, for example. The frontal response of the upper Texas systems is much greater than that of Corpus Christi, also.

The freshwater throughflow is likewise smaller for Corpus Christi Bay, 23 months replacement time (Table 6-2, freshwater inflow alone) compared to 7 months for the Galveston system. The high rate of evaporation in Corpus Christi Bay not only increases the freshwater replacement time to 50 months, Table 6-2, but also is a mechanism for concentrating waterborne substances in solution that are not lost to the atmosphere, including most contaminants. One important transport mechanism operating in the upper bays on the Texas coast is the estuarine density current, greatly enhanced by the deepdraft channels. While this density current is responsible for increased salinity intrusion, it also represents a net influx of water into the estuary from the sea, about an order of magnitude *greater* than the freshwater inflow, which provides additional dilution and mixing in these systems. In the Corpus Christi system, in contrast, the density current is at most of only secondary importance.

While the present level of loadings to the Corpus Christi system is much less than those to Sabine Lake or Galveston Bay, these flushing considerations suggest that a wasteload will have a magnified effect in the Corpus system because it is relatively poorly flushed. It should be emphasized that these are comparative statements only, indicating the need for greater care in determining the assimilative capacity of the Corpus system. The overall health of both the Galveston and Corpus systems is good throughout the deeper, open waters of both systems (Ward and Armstrong, 1992; Ward and Armstrong, 1997a). At present there is no indication that the assimilative capacity of either has been pressed. Since Corpus Christi Bay is potentially more sensitive to wasteloads, however, prudence and vigilance in its management are necessary.

6.4 Recommendations

In the course of this study, several avenues for work or research became evident that lay beyond the scope of the present project, but would profit our understanding and management of the Corpus Christi system. These are summarized here in the form of recommendations for further work. Generally, these are outside the purview of the National Estuary Program, but could be implemented by the participating regional and state agencies.

(1) A major source of information about the hydraulics of the present system is the TCOON network and data base, operated by the Conrad Blucher Institute of Texas A&M University–Corpus Christi. The importance of this data-collection enterprise to the state of Texas in general, and the Corpus Christi area in particular, cannot be overestimated! The analytical potentials afforded by this rich source of data have barely been scratched. (In order to keep its scope bounded, the present study treated only twelve stations. Yet the displays of EXHIBIT2 and EXHIBIT3 demonstrate the quality and content of this data base.) This program needs to be continued and maintained as a perpetual observing network. The next seven recommendations are specific to processing and application of TCOON data.

(2) In the processing of the twelve data stations used in the present study, a number of anomalies and apparent data errors were detected, as summarized in Appendix B. The fact that these errors have survived without detection is indicative of the limited use that has been made of much of the TCOON data. The entire set of data files needs to be subjected to intensive data scrubbing. Also, there was evidence that valid data had been rejected by some of the CBI data-screening routines, which are designed to serve the application of statistical water-level analysis. This data rejection occurred when dynamic hydrodynamic forcing produced sudden marked changes in water surface elevations. It would be desirable to devise separate data-screening routines more appropriate for hydrodynamic evaluations. One additional data base needing more intensive data scrubbing is the TCOON anemometer data. Some of the anemometers appear to have anomalous direction responses (compare, e.g., Port Aransas and the Naval Air Station in 1996).

(3) Several new TCOON stations are recommended for the Corpus Christi Bay area, which would facilitate hydraulic analyses of component bays. One is needed in the eastern segment of Nueces Bay. Together with the White Point station, this would allow much more accurate water-surface slope determinations. (Also, the problem of the White Point gauge pegging at low water needs to be rectified.) A second station in Baffin Bay inside the entrance would be extremely desirable, see (5) below. A station in the vicinity of the GIWW just south of the JFK Causeway would be useful in better determining the behavior of the Upper Laguna.

(4) The method of empirical levelling devised for this study offers great potential for the rigorous quantitative analysis of hydraulic behavior of the Coastal Bend bays. The present scope did not permit its thorough application (see Appendix C). In particular, the levelling of the Upper Laguna requires additional work, with a

wider range of levelling events and more attention given to the actual response times of the system. The systematic northward slope of the water surface may in fact be a residual levelling error (though it does not affect the estimates of tidal and frontal prisms or cross-bay exchanges, because these are all based upon changes in water elevation). Similarly, there may be some residual errors in the Nueces Bay levelling, since there was only one station to work with in this system. We recommend extending the procedure to the other gauges in the system, and identifying many more levelling events in the period of record.

(5) No water-level analyses were carried for Baffin Bay, because the limited availability of data and the remoteness of the system did not justify the investment of project resources in this activity. We recommend that the same sorts of analyses be carried out for the Baffin system as applied to the remainder of the study area. In particular, the hypothesized rôle of the seabreeze in driving the water levels of Baffin needs to be further explored.

(6) The importance of meteorological forcing, particularly frontal passages, is central to the hydrodynamic behavior of the Coastal Bend bays. In the present study, the exchanges and responses were quantified for only six such meteorological events (Table 4-4). A comprehensive data analysis of the detailed behavior of these bays under meteorological forcing needs to be undertaken, analyzing the entire period of record, additional gauges (once they are empirically levelled), and detailed study of the synoptic systems producing the observed effects. Additional separation of the inverse-barometer contribution needs to be made as well.

(7) High water stands are a frequent occurrence on the Texas coast. Many of these occur in association with the seasonal elevations in water level, see (8) following, but some occur at other seasons, though perhaps for only 2-3 days. Their potential economic importance was demonstrated by the damage and disruption accompanying the October 1996 high water, but they probably have equally important, but less dramatic, effects on water exchange in the system. These are poorly understood. The October 1996 event was briefly discussed in Section 5.2, in which it was noted that there was a similar event in fall 1995 which missed the same media attention by only 10 cm. Further, Tropical Storm Josephine had nothing to do with this event, despite widespread belief to the contrary. It is recommended that a comprehensive study of such events be carried out, utilizing not only the TCOON data sets, but also historical tide records on file at NOS, USCE, USGS and other agencies.

(8) A related but separate phenomenon is the secular "seasonal" variation in water level, with highs in spring and fall, and lows in winter and summer, see Section 2.3.2 and 5.2. This variation is responsible for a major volume of water exchange in the Corpus Christi system. Yet, the exact mechanisms causing this variation are unknown. Specific research into the underlying physical processes is recommended.

(9) Both the Texas Water Development Board and Conrad Blucher Institute have operated robot "sondes" in the study area for the purpose of logging hydrographic

and water-quality data, especially conductivity (which is a proxy for salinity) and dissolved oxygen. For salinity especially, this is a potentially valuable source of data since it samples a time scale of variation that is practically unsampled by other conventional strategies. An example of how this information can be interpreted and the insight it provides into transport processes is given in Fig. 5-45. Yet none of this data could be used in the present study, because the data is either uncorrected or unreliable. Conductivity sensors degrade with time in the saline environment. The operation of sondes must be carried out with this in mind, including frequent field servicing, pre-deployment and post-deployment bench comparisons to standards, and *in situ* measurement of conductivity with a field meter at deployment and retrieval. Each record must be inspected upon retrieval for anomalies, such as quantum shifts, poor temporal response and drift. Neither agency has followed the necessary procedures, and much of the data appears anomalous. It is recommended that more rigorous procedures be implemented, and that the necessary investment in time and effort be made to reconcile and correct—of necessity, on a *post facto* basis—the data records on hand.

(10) Freshwater inflow is one of the more important controls on the Corpus Christi Bay system. Yet very little rigorous detailed work has been carried out on the watersheds of the study area, especially the Nueces basin, which has engendered so much public attention. The analyses presented here, and in the companion CCBNEP study on freshwater inflow status & trends (Mosier et al., 1995) are only a beginning. More extensive precipitation data exist (in hard-copy format in the NCDC archives) and need to be incorporated into a watershed-wide analysis. Variations of climate, including droughts and storms, need to be quantified, morphology of storm hydrographs require parameterization and analysis as discrete events (along the lines of Section 5.2.2), and the operation of the reservoirs–both past and projected–needs careful evaluation. Comprehensive watershed models based upon deterministic formulations of runoff processes, such as the HSPF applications made by USGS (Mosier et al., 1995), are especially valuable in such an analysis. The issue of how the Corpus system behaved in pre-development hydrology is not just a theoretical question, but lies at the basis of the "pass-through" approach to inflow management. Determination of the "naturalized flow" by modeling and data analysis would be useful in formulating management strategies. Similarly, the rôle of inflow developed from the peripheral watershed, in comparison to that supplied by the Nueces River, needs much better delineation.

(11) A related deficiency of present hydrological understanding of the Coastal Bend bays is the precise effect of San Antonio bay inflows on the rest of the system. Because San Antonio Bay lies outside the study area, it was not given specific study in this project nor in the companion freshwater inflow project of USGS (Mosier et al., 1995), yet it is probable that a portion of the inflow from the San Antonio and Guadalupe Rivers is transported through Ayres/Carlos Bays into the study area. Specific studies of this mechanism are recommended.

(12) Ward and Armstrong (1997a) recommended quantitative salt-budget analyses to establish cause-and-effect relations of salinity behavior in the study area. We

echo this recommendation from the standpoint of circulation. The salinity responses of Nueces Bay are of particular practical importance, because of their use in determining effects of releases from the LCC/CC system. The rôle of evaporation throughout the CCBNEP study is particularly important, and improved estimates—in both analysis and measurement—are needed.

(13) The importance of internal mixing processes was emphasized in Section 5.5 especially Section 5.5.3, as these basically control the time necessary for exchanged water to accomplish dilution. This is of great practical importance in the management of the estuary both from the standpoint of transports (e.g., freshwater inflows) and water quality (e.g., assimilative capacity determinations and wasteload permitting). Yet there is practically no quantitative data from the Corpus Christi Bay system. We recommend an experimental program of carefully executed tracer studies, including fluorescent dye tracing, to better quantify this aspect of bay circulation.

(14) The two main components of internal circulation in a Gulf estuary, wind gyres and density currents, have very little observational basis in Corpus Christi Bay. Diagnostic studies suggest that density currents are of little importance in the bay, despite the presence of a deepdraft channel (Section 5.5.2). We hypothesize a double-vortex wind-spun gyre circulation in the main body of Corpus Christi Bay, Fig. 5-49. While this is consistent with the small amount of current-meter data available, and is consistent with the physics of stress under prevailing southeasterly winds, this aspect of bay circulation needs much more study. Practically no information is extant concerning internal circulations of the secondary bays. A combination of long-term Lagrangian tracer studies, and Eulerian current profiling is recommended to quantify this aspect of bay circulation.

(15) As noted at the outset, modeling as a source of information was deliberately avoided in this study. Modeling, properly prosecuted, has the potential of yielding considerable insight into the physics of circulation, as well as providing the basis for quantification of circulation-based responses, such as transport and distribution of key water-quality indicators. It is particularly attractive to the management enterprise for its ability to perform "what-if" exercises. We note, also, that there are many fallacies that modelers can be drawn into, such as using calibration to compensate for model deficiencies, or failing to recognize boundary- or initial-condition dominated problems. Even a properly formulated and operated model does not substitute for analysis. Stommel's (1987) remark about ocean models is equally applicable to estuaries: "These models generate such masses of tabular data that they are as much a challenge to understand as the ocean itself. Consequently, the numerical results seldom get the detailed study, interpretation, and explanation they deserve. In the hands of some they are a wasteful, idle exercise." Stommel was characteristically kind; he should have said, "In the hands of many... ." Continued model development and application, in its proper rôle as a codicil, are recommended.

(16) The Bureau of Reclamation has constructed a diversion works below Calallen to facilitate inundation of the delta by overbanking events. Proper evaluation of

this experiment requires careful hydrologic and hydrodynamic observations in the river and delta, as well as chemical and biological observations. This offers the potential of another degree of freedom in the management of inflow to Nueces Bay whose effects need to be quantitatively evaluated. A comprehensive program of salinity and current measurement in the distributaries of the delta, and in the adjacent Nueces Bay, is recommended to provide a management basis for a strategy of diversion. We note that this would also require the detailed hydrological evaluations of Recommendation (10) above.

(17) Finally, the preservation of older circulation data from the study area is critical for cause-and-effect evaluation of variations in the physical system taking place on decadal time scales. Yet the loss rate of this older, irreplaceable data is appalling. This problem was addressed in detail in the companion CCBNEP study on water and sediment quality (Ward and Armstrong, 1997a). In the present context, we recommend a concerted effort to recover and digitize the older salinity and temperature determinations, particularly those of the Texas Game, Fish & Oyster Commission, which may still exist in the archives and warehouses of Texas Parks and Wildlife Department. An inventory of the older holdings and the Rockport Lab and at the TPWD storage facility in Weslaco should receive top priority, and any older data that can be recovered should be keyboarded for preservation in a digital format.

REFERENCES

Allhands, J.L., 1931: *Gringo builders*. Privately printed.

Almonte, J.N., 1835: Statistical report on Texas. C.E. Castañeda (trs.), 1925. The *Southwestern Historical Quarterly 28* (3), pp. 177-222.

Alperin, L.M., 1977: *Custodians of the coast*. Galveston: U.S. Army Corps of Engineers.

Anderson, Arvid A., 1960: Marine resources of the Corpus Christi area. Research Monograph No. 21, Bureau of Business Research, University of Texas, Austin, TX.

Attwood, W., and A. Johnson, 1924: *Marine structures, their deterioration and preservation*. Report of the Committee on Marine Piling Investigations. Washington, D.C.: National Research Council.

Baines, W.D., 1958: Tidal currents in constricted inlets. In: *Proceedings, Sixth Conf. Coastal Engr.* (J. Johnson, ed.), pp. 545-561. Council on Wave Research, The Engineering Foundation.

Beer, Tom, 1983: *Environmental oceanography*. Oxford: Pergamon Press.

Behrens, E. and R. Watson, 1977: Corpus Christi water exchange pass 1972-1976. *Coastal Sediments '77*, pp. 790-796. Charleston, SC: Am. Soc. Civil Engrs.

Behrens, E., R. Watson, and C. Mason, 1977: Hydraulics and dynamics of New Corpus Christi Pass, Texas: a case history, 1972-73. Rep. No. 8, General Investigation of Tidal Inlets, Coastal Engineering Research Center, U.S. Corps of Engineers.

Benefield, R.L., 1976: Shell dredging sedimentations [*sic*] in Galveston and San Antonio Bays 1964-69. Tech. Ser. No. 19, Texas Parks and Wildlife Department, Austin.

Blaha, J., and W. Sturges, 1981: Evidence for wind-forced circulation in the Gulf of Mexico. *J. Mar. Res. 39* (4), pp. 711-734.

Blum, M., R. Morton, and J. Durbin, 1995: "Deweyville" terraces and deposits of the Texas Gulf coastal plain. *Trans., Gulf Coast Assoc. Geol. Soc., 45*, pp. 53-60.

Blunt, E.M., 1837: *The American coast pilot, 13th ed., improved*. New York: Edmund and George W. Blunt.

Bober, W. and R. Kenyon, 1980: *Fluid mechanics*. New York: John Wiley & Sons.

Bomar, G. W., 1983: *Texas weather*. Austin: University of Texas Press.

Bowden, K.F., 1983: *Physical oceanography of coastal waters*. New York: John Wiley & Sons.

Broecker, W. S., 1975: Climatic change: are we on the brink of a pronounced global warming? *Science 189*, pp. 460-463.

Brown, C., V. Jones, and R. Rogers, 1948: Report on sedimentation in Lake Corpus Christi and the water supply of Corpus Christi, Texas. Report SCS-TP-74, Soil Conservation Service, USDA, Ft. Worth, Texas.

Brown, C., A. Militello, and N. Kraus, 1995: Hydrodynamic assessment for elevation of the J.F.K. Causeway, Corpus Christi, Texas. Rep. No. TAMU-CC-CBI-95-07, Conrad Blucher Institute, Texas A&M University—Corpus Christi.

Brown, E.I., 1928: Inlets on sandy coasts. *Proceedings ASCE 54* (2), pp. 505-553.

Brown, J., A. Colling, D. Park, J. Phillips, D. Rothery, and J. Wright (Open University Course Team), 1989: *Waves, tides and shallow-water processes*. Oxford: Pergamon Press.

Brown, L., J. Brewton, J. McGowen, T. Evans, W. Fisher and C. Groat, 1976: Environmental geologic atlas of the Texas coastal zone—Corpus Christi area. Bureau of Economic Geology, University of Texas at Austin.

Burg, T.M., 1974: Surveillance of mudshell dredging in San Antonio and Matagorda Bays, Texas, 1964-1974. Coastal Fisheries Project Reports, Texas Parks and Wildlife Dept., Austin.

Caller-Times, 1952: *Centennial history of Corpus Christi*. Corpus Christi: the Caller-Times.

Cameron, Brewster, 1898: Discussion on origin of the Gulf Stream. *Trans. ASCE 40*, pp. 110-112.

Carothers, H.P. et al., 1959: Development report on fish passes and water interchange of the Upper Laguna Madre and Corpus Christi Bay, coastal Texas. Lockwood, Andrews and Newnam, Inc., Corpus Christi.

Chew, F., 1964: Sea-level changes along the northern coast of the Gulf of Mexico. *Trans., Am. Geophys. Union 45* (1), pp. 272-280.

Clements, G.L., 1975: Shell management annual report, September 1974 - August 1975. Coastal Fisheries Project Reports, Texas Parks and Wildlife Dept., Austin.

Cline, I.M., 1926: *Tropical cyclones*. New York: The Macmillan Company.

Cline, J.L., 1946: *When the heavens frowned.* Dallas: Mathis, Van Nort & Co.

Collier, A. and J. Hedgpeth, 1950: An introduction to the hydrography of tidal waters in Texas. *Publ. Inst. Mar. Sci. 1* (2), pp. 125-194.

Collins, H.C., 1878: Report on survey of Aransas and Corpus Christi Passes and Bays. Attached to Howell (1879).

Corthell, E.L., 1884: The South Pass jetties.—Ten years' practical teachings in river and harbor hydraulics. *Trans. ASCE 13*, pp. 313-330.

Corthell, E.L., 1899: Discussion on reaction breakwater. *Trans. ASCE 42*, pp. 501-512.

Crowley, T. and G. North, 1991: *Paleoclimatology*. New York: Oxford University Press.

Cummins, A.B., 1953: The physical and cultural geography of parts of San Patricio and Aransas Counties. M.A. Thesis, University of Texas, Austin.

Defant, A., 1961: *Physical oceanography* (2 vols.). London: Pergamon Press.

Defehr, K. and R. Sorensen, 1973: A field investigation of the hydraulics and stability of Corpus Christi water exchange pass, Texas. C.O.E. Report No. 170, Coastal, Hydraulic and Ocean Engineering Group, Civil Engineering Department, Texas A&M University, College Station.

Denton, G. and T. Hughes (eds.), 1981: *The last great ice sheets.* New York: John Wiley and Sons.

Donague, L., 1996: Bob Hall Pier open today. *Corpus Christi Caller-Times*, 12 October 1996.

Doran, E., 1965: Shell roads in Texas. *Geogr. Rev. 55*(2), pp 223-240.

Dowell, C. and S. Breeding, 1967: Dams and reservoirs in Texas. Rep. 48, Texas Water Development Board, Austin.

Dunn, J.B., 1932: *Perilous trails of Texas*. Dallas: Southwest Press.

Dutton, J.A., 1986: *The ceaseless wind.* (Rev. enlarged ed.) New York: Dover Publ., Inc.

Dyer, K. R., 1973: *Estuaries: a physical introduction*. London: John Wiley & Sons.

Eigsti, S. L., 1978: The coastal diurnal wind cycle at Port Aransas, Texas. Rep. No. 48, Atmospheric Science Group, College of Engineering, University of Texas at Austin.

Elliott, A.B., 1958: Recent sediments of Corpus Christi and Nueces Bays, Nueces County, Texas. M.A. Thesis, University of Texas, Austin.

Engineering News-Record, 1930a: Building new dam for Corpus Christi water supply. *ENR 105* (14), 2 October 1930, pp. 520-523.

Engineering News-Record, 1930b: Corpus Christi Dam fails with loss of north abutment wall. *ENR 105* (22), 27 November 1930, p. 861.

Engineering News-Record, 1930c: Cause of Corpus Christi Dam failure still undetermined. *ENR 105* (23), 4 December 1930, p. 897.

Engineering News-Record, 1930d: Corpus Christi Dam failure. *ENR 105* (25), 18 December 1930, pp. 974-978.

Evans, C.A., ed., 1899: *Confederate military history, 11.* Atlanta: Confederate Publ. Co.

Escoffier, F.F., 1977: Hydraulics and stability of tidal inlets. Report 13, General Investigation of Tidal Inlets, Coastal Engineering Research Center, U.S. Corps of Engineers.

Espey, Huston & Associates, Inc., 1981: Nueces marsh enhancement: a feasibility study of the introduction of river flows. Doc. No. 81328R, Report to Galveston District Corps of Engineers, Espey, Huston & Assoc., Austin, Texas.

Fairbanks, R.G., 1989: A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on Younger Dryas event and deep-ocean circulation. *Nature 342*, pp.637-642.

Fisk, H.N., 1949: Geological investigation of the Laguna Madre flats. Unpubl. rep., Geologic Research Section, Humble Oil & Refining Company, Houston, Texas.

Fisk, H.N., 1959: Padre Island and the Laguna Madre flats, coastal south Texas. *Second Coastal Geogr. Conf.*, Louisiana State University, Baton Rouge.

Frazier, R.D., 1921: Early records of tropical hurricanes on the Texas coast in the vicinity of Galveston. *Mo. Wea. Rev. 49*(8), pp 454-457.

Fulton, G.W., 1880: Letter to Maj. S.M. Mansfield. Reproduced in USCE (1880), Appendix N, pp. 1253-4.

Galtsoff, P.S., 1931: Survey of oyster bottoms in Texas. Inv. Rep. No. 6, Bureau of Fisheries, USGPO, Washington, D.C.

Geiser, S.W., 1944: Racer's storm (1837), with notes on other Texas hurricanes in the period 1818-1886. *Field and Laboratory 12* (2), pp. 59-67.

Gilardi, A.J., 1942: *Report on Galveston Bay, Texas for the reduction of maintenance dredging.* 3 vols. Corps of Engineers, Galveston. [Bibliographic note: Gilardi's name does not appear on the published report, but his authorship is established by the Memo from A.B. Gillette to Col. L.H. Hewitt, D.E., 1942, re: "Comments on report prepared by Mr. A.J. Gilardi, Engineer, on Galveston Bay, Texas," in Galveston District files.]

Gillette, C.E., 1904a: Seacoast harbors in the United States. *Trans. ASCE 54*, Pt. A, pp. 297-324.

Gillette, C.E., 1904b: Discussion on harbors. *Trans. ASCE 54*, Pt. A, pp. 385-451.

Goldberg, R.L., 1944: *The Rube Goldberg plan for the post-war world.* New York: Franklin Watts, Inc.

Gough, Buddy, 1989: Cedar Bayou is back. *Texas Parks & Wildlife 47* (7), pp. 18-23.

Grant, M.L., 1996: Storm gave island residents a taste of hurricane's fury. *Corpus Christi Caller-Times*, 13 October 1996.

Grave, C., 1905: Investigations for the promotion of the oyster industry of North Carolina. Rep. 1903, U.S. Fish Comm., Washington, D.C., pp. 247-341.

Hall, G., A. Bouma and G. Huebner, 1976: Overall circulation and tides in San Antonio Bay. In: *Shell dredging and its influence on Gulf Coast environments* (A. Bouma, Ed.), pp. 71-78. Houston: Gulf Publishing Co.

Haltiner, G., and F. Martin, 1957: *Dynamical and physical meteorology.* New York: McGraw-Hill Book Co.

Harland Bartholomew and Assoc., 1968: Preliminary report upon water and sewer facilities, Coastal Bend Region. Report to Coastal Bend Regional Planning Commission, HBA, St. Louis, Missouri.

Harris, D.L., and B.R. Bodine, 1977: Comparison of numerical and physical hydraulic models, Masonboro Inlet, North Carolina. Report 6, General Investigation of Tidal Inlets, Coastal Engineering Research Center, U.S. Corps of Engineers.

Harris, D.L., and C.V. Lindsay, 1957: An index of tide gages and tide gage records for the Atlantic and Gulf coasts of the United States. Rep. No. 7, National Hurricane Research Project, U.S. Weather Bureau, Washington, D.C.

Harris, R.A., 1900: *Manual of tides, Part IV A.* Appendix No. 7, Annual Report of the Superintendent, U.S. Coast and Geodetic Survey, Washington, D.C.

[Note: the Committee on Tidal Hydraulics has reprinted sections of the *Manual* as its Tech. Bull. No. 11, Waterways Experiment Station, U.S. Corps of Engineers, 1966.]

Harts, W.W., 1901a: Description of Coos Bay, Oregon, and the improvement of its entrance by the government. *Trans. ASCE 46*, pp. 482-506 *et seq*.

Harts, W.W., 1901b: Discussion on Coos Bay harbor improvement. *Trans. ASCE 46*, pp. 547-550.

Hauck, L. and G. Ward, 1980: Hydrodynamic mass-transfer model of deltaic systems. *Estuarine and wetland processes* (P. Hamilton and K. McDonald, eds.), pp. 247-265. New York: Plenum Publ. Corp.

Haupt, L.M., 1888: The physical phenomena of harbor entrances. *Proceedings, Amer. Phil. Soc. 25* (127), pp. 19-41.

Haupt, L.M., 1889: Discussion on the dynamic action of the ocean in building bars. *Proceedings, Amer. Phil. Soc. 26* , pp. 146-171.

Haupt, L.M., 1891: The Galveston Harbor problem. *J. Franklin Inst. 132* (4), pp. 275-287.

Haupt, L.M., 1896: Correspondence on single jetty harbor improvements. *Trans. ASCE 36*, pp. 133-134.

Haupt, L.M., 1898: Discussion on origin of the Gulf Stream. *Trans. ASCE 40*, pp. 99-106.

Haupt, L.M., 1899: The reaction breakwater as applied to the improvement of ocean bars. *Trans. ASCE 42*, pp. 485-500.

Haupt, L.M., 1900: Discussion on reaction breakwater. *Trans. ASCE 43*, pp. 104-106.

Haupt, L.M., 1901a: Discussion on Coos Bay harbor improvement. *Trans. ASCE 46*, pp. 507-526.

Haupt, L.M., 1901b: Methods of improving ocean bars. *Proc. Amer. Phil. Soc. 40*, pp. 62-85.

Haupt, L.M., 1904: Discussion on harbors. *Trans. ASCE 54*, Pt. A, pp. 341-352.

Haupt, L.M., 1910: Discussion on bar harbors. *Trans. ASCE*, pp. 360-362.

Haupt, L.M., 1927: Tides and their engineering aspects, discussion. *Proc. ASCE 53* (8), pp. 2053-2055.

Haupt, L. and H. Ripley, 1895: Joint letter of 12 June 1895 to Aransas Pass Harbor Company. Reproduced in Gillette (1904b).

Haurwitz, B., 1947: Comments on the sea-breeze circulation. *J. Met. 4* (1), pp. 1-8.

Hays, J., J. Imbrie, and N. Shackleton, 1976: Variations in the earth's orbit: pacemaker of the ice ages. *Science 194*, pp. 1121-1132.

Head, P.C. (ed.), 1985: *Practical estuarine chemistry, a handbook.* Cambridge, UK: Cambridge University Press.

Hedgpeth, J.W., 1967: Ecological aspects of the Laguna Madre, a hypersaline estuary. In: *Estuaries* (G. Lauff, ed.), pp. 408-419. Washington, D.C., American Association for the Advancement of Science.

Henley, D. and D. Rauschuber, 1981: Freshwater needs of fish and wildlife resources in the Nueces-Corpus Christi Bay area, Texas: a literature synthesis. Report FWS/OBS-80/10, U.S. Fish & Wildlife Service, Albuquerque, New Mexico.

Henningson, Durham & Richardson, Inc., 1980: Phase IV report, studies of freshwater needs of fish and wildlife resources in Nueces-Corpus Christi Bay area, Texas. U.S. Fish & Wildlife Service, Albuquerque, New Mexico.

Henry, W., D. Driscoll and J. McCormack, 1982: Hurricanes on the Texas coast (rev.). Rep. No. TAMU-SG-75-504, Center for Applied Geosciences, Texas A&M University, College Station.

Hess, S., 1959: *Theoretical meteorology.* New York: Holt, Rinehart & Winston.

Hiller, Ilo, 1974: Young naturalist: tides. *Texas Parks & Wildlife 32* (11), pp. 29-31.

Hollon, W.E., ed., 1956: *William Bollaert's Texas.* Norman: University of Oklahoma Press.

Hood, D.W., 1952: A hydrographic and chemical survey of Corpus Christi Bay and connecting water bodies: Progress report for quarter ending July 31, 1952. Project 40, Department of Oceanography, Texas A&M College, College Station.

Hopkins, S. and L. McKinney, 1976: A review of the literature pertaining to the effects of dredging on oyster reefs and their associated faunas. In: *Shell dredging and its influence on Gulf Coast environments* (A. Bouma, Ed.), pp. 3-12. Houston: Gulf Publishing Co.

Howell, C.W., 1879: Survey of Aransas Pass and Bay up to Rockport and Corpus Christi, Texas and Corpus Christi Pass and Channel. Appendix K, Annual Report, Chief of Engineers. U.S. House of Representatives, 46th Congress, 2nd Session, pp. 928-950.

Huson, Hobart, 1955: *Refugio*. (Two vols.) Woodsboro, Texas: Rooke Foundation.

Kana, T., P. Reinhart, and S. Dinnel, 1980: Oceanographic surveys of Brazos-Santiago Pass, Aransas Pass, and Pass Cavallo, Texas for contingency planning January-February 1980. Progress Report to MESA Program Office/NOAA, Research Planning Institute, Inc., Columbia, SC.

Kastl, A.E., 1898: Discussion on origin of the Gulf Stream. *Trans. ASCE 40*, pp. 115-116.

Kennedy, William, 1841: *Texas: the rise, progress, and prospects of the Republic of Texas*. Reprinted 1925 from the 2nd London ed. Fort Worth, Texas: The Molyneaux Craftsmen.

Kerr, A., ca. 1970: *The Texas reef shell industry*. Texas Industry Series No. 11, Bureau of Business Research, The University of Texas at Austin.

Keulegan, G.H., 1967: Tidal flow in entrances, water-level fluctuations of basins in communication with seas. Tech. Bull. No. 14, Committee on Tidal Hydraulics, Waterways Experiment Station, Vicksburg.

Kieslich, J.M., 1981: Tidal inlet response to jetty construction. Rep. No. 19, General Investigation of Tidal Inlets, Coastal Engineering Research Center, U.S. Corps of Engineers.

Kinnaird, C. (ed.), 1968: *Rube Goldberg vs. the Machine Age*. New York: Hastings House.

Kutzbach, J.E., 1987: Model simulations of the climatic patterns during the deglaciation of North America. In: *North American and adjacent oceans during the last deglaciation* (W. Ruddiman and H. Wright, eds.), pp. 425-446. Vol. K-3, Geology of North America, Geological Society of America.

Kutzbach, J. and H. Wright, 1985: Simulation of the climate of 18,000 yr BP; results for the North American/North Atlantic/European sector. *Quart. Sci. Rev., 4*, pp. 147-187.

Le Baron, J.F., 1900: Discussion on reaction breakwater. *Trans. ASCE 43*, pp. 95-101.

Linn, J.J., 1883: *Reminiscences of fifty years in Texas*. New York: D. & J. Sadlier & Co.

Longley, W.L. (ed.), 1994: Freshwater inflows into Texas bays and estuaries: ecological relationships and methods for determination of needs. Texas Water Development Board, Austin, Texas.

Mandelbrot, B.B., 1983: *The fractal geometry of nature.* New York: W.H. Freeman.

Martin, G.C., ca. 1930: Preliminary archaeological survey of a portion of the Texas coast. Part 1 (St. Charles Bay and Copano Creek) and Part 2 (Live Oak Peninsula). Privately printed.

McCampbell, Coleman, ca. 1934: *Saga of a frontier seaport.* Dallas: Southwest Press.

McCampbell, Coleman, 1952: *Texas seaport: the story of the growth of Corpus Christi and the Coastal Bend area.* New York: Exposition Press.

McEachron, L., G. Saul, J. Cox, C. Bryan, and G. Matlock, 1984: Fish kill; cold weather takes big toll on marine life. *Texas Parks & Wildlife 42* (4), pp. 10-13.

McGowen, J., C. Groat, L. Brown, W. Fisher and A. Scott, 1970: Effects of Hurricane Celia—a focus on environmental geologic problems of the Texas coastal zone. Geol. Circ. 70-3, Bureau of Economic Geology, The University of Texas at Austin.

McGowen, J., L. Garner and B. Wilkinson, 1977: The Gulf shoreline of Texas: processes, characteristics, and factors in use. Geol. Circ. 77-3, Bureau of Economic Geology, The University of Texas at Austin.

McGraw-Hill, 1960: *Directory of electric utilities.* New York: McGraw-Hill Publ. Co.

McKinstry, C.H., 1901: Discussion on Coos Bay harbor improvement. *Trans. ASCE 46*, pp. 532-547.

Mercer, E.T., 1880: Letter to Col. Thomas Sedgwick, Assistant Engineer. Reproduced in USCE (1880), Appendix N, pp. 1250-2.

Merrill, W.E., 1886: Discussion on the South Pass jetties. *Trans. ASCE 16*, pp. 223ff.

Miertschin, J., 1992: Effect of Nueces Bay Power Station on salinity in Nueces Bay. James Miertschin & Assoc., Austin, Texas.

Mitchell, Glenn A., 1959: The geography of Nueces County, Texas. M.A. Thesis, University of Texas, Austin, Texas.

Morton, R. and W. Price, 1987: Late Quaternary sea-level fluctuations and sedimentary phases of the Texas coastal plain and shelf. In: *Sea-level fluctuation and coastal evolution* (D. Nummedal, O. Pilkey and J. Howard, eds.), pp. 181-198. Sp. Publ. 41, Society of Economic Paleontologists and Mineralogists.

Morton, R. and J. Suter, 1996: Sequence stratigraphy and composition of late Quaternary shelf-margin deltas, northern Gulf of Mexico. *Bulletin, AAPG, 80* (4), pp. 505-530.

Mosier, J., W. Asquith, and M. Jennings, 1995: Current status and historical trends in freshwater inflows to the Corpus Christi Bay national estuary Program Study Area. Report submitted to CCBNEP, Water Resources Division, U.S. Geological Survey, Austin, Texas.

Mourhess, Charles A., 1913: Triangulation on the coast of Texas, from Sabine Pass to Corpus Christi Bay. Sp. Publ. 17, U.S. Coast & Geodetic Survey, Government Printing Office, Washington, D.C.

National Hurricane Center, 1996: Tropical Depression Ten, Intergovernmental discussions and advisories (unpubl.). National Weather Service, NOAA, Miami.

Neumann, C. G. Cry, E. Caso, and B. Jarvinen, 1978: Tropical cyclones of the North Atlantic Ocean, 1871-1977. Asheville, N.C.: National Climatic Center.

Neumann, G. and W. Pierson, 1966: *Principles of Physical Oceanography*. New York: Prentice-Hall.

Olmsted, F.L., 1857: *A journey through Texas*. New York: Dix, Edwards. (Reprinted 1978, University of Texas Press.)

Orlando, P., L. Rozas, G. Ward, and C. Klein, 1991: Analysis of salinity structure and stability for Texas estuaries. Strategic Assessment Branch, National Ocean Service, Silver Spring, Maryland.

Orlando, P., L. Rozas, G. Ward, and C. Klein, 1993: Salinity characteristics of Gulf of Mexico estuaries. National Estuary Inventory Series, Strategic Assessment Branch, National Ocean Service, Silver Spring, Maryland.

Orlando, P., F. Shirzad, J. Schuerholz, P. Mathieux, and S. Strassner, 1988: Shoreline modification, dredged channels, and dredged material disposal areas in the nation's estuaries. Draft report, Strategic Assessment Branch, National Ocean Service, NOAA, Rockville, Maryland.

Palmén, E., and C. Newton, 1969: *Atmospheric circulation systems*. New York: Academic Press.

Parker, C.A., 1968: The effect of a cold-air outbreak on the continental shelf water of the northwestern Gulf of Mexico. Ref. 68-3T, A&M Proj. 286-2, Dept. of Oceanography, Texas A&M University, College Station.

Pitts, T.D., 1899: Discussion on reaction breakwater. *Trans. ASCE 42*, pp. 526-530.

Prewitt, E., S. Lisk and M. Howard, 1987: National Register assessments of the Swan Lake site, 41AS16, on Copano Bay, Aransas County, Texas. Rep. Inv. No. 56, Prewitt & Assoc., Austin, Tex

Price, W.A., 1954: Oyster reefs of the Gulf of Mexico. In: *Gulf of Mexico, its origin, waters and marine life* (P. Galtsoff, ed.), p. 491. Fish. Bull. 89, Fish & Wildlife Service, Washington, D.C.

Pritchard, D.W., 1952: Estuarine hydrography. *Adv. Geophys., 1*, pp. 243-280.

Pugh, D.T., 1987: *Tides, surges and mean sea-level*. Chichester: John Wiley & Sons.

Quammen, M., and C. Onuf, 1993: Laguna Madre: seagrass changes continue decades after salinity reduction. *Estuaries 16* (2), pp. 302-310.

Riley, Mary C., 1951: *History of the development of the port of Corpus Christi*. M.A. Thesis, The University of Texas at Austin.

Ripley, H.C., 1898: Correspondence on origin of the Gulf Stream. *Trans ASCE 40*, pp. 117-122.

Ripley, H.C., 1899: Discussion on reaction breakwater. *Trans. ASCE 42*, pp. 520-526.

Ripley, H.C., 1901: Discussion on Coos Bay harbor improvement. *Trans. ASCE 46*, pp. 530-532.

Ripley, H.C., 1924: The economic location of jetties. *Trans. ASCE 87*, pp. 979-986.

Roberts, O.M., 1881: *A description of Texas, its advantages and resources, with some account of their development, past, present and future*. St. Louis: Gilbert Book Co.

Ruddiman, W.F., 1987: Synthesis; the ocean ice/sheet record. In: *North American and adjacent oceans during the last deglaciation* (W. Ruddiman and H. Wright, eds.), pp. 463-478. Vol. K-3, Geology of North America, Geological Society of America.

Schmidt, F.H., 1947: An elementary theory of the land- and sea-breeze circulation. *J. Met. 4* (1), pp. 9-15.

Schubel, J., H. Carter, R. Wilson, W. Wise, M. Heaton, and M. Gross, 1978: Field investigations of the nature[,] degree, and extent of turbidity generated by open-water pipeline disposal operations. Tech. Rep. D-78-30, Dredged

Material Research Program, Waterways Experiment Station, Vicksburg, Mississippi.

Schweitzer, N.B., 1898: Origin of the Gulf Stream and circulation of waters in the Gulf of Mexico, with special reference to the effect on jetty construction. *Trans. ASCE 40*, pp. 86-98.

Shackleton, N.J., 1988: Oxygen isotopes, ice volume, and sea level. *Quartenary Sci. Rev. 6*, pp. 183-190.

Shideler, G. and Stelting, 1983: Maps showing time-sequence surface patterns of estuarine hydrography and suspended sediments in Corpus Christi Bay, Texas Gulf coast. Map MF-1530, U.S. Geological Survey, Arlington, Virginia.

Sidner, B and A. Bouma, 1976: Shell dredging regulations and revenues in Texas. In: *Shell dredging and its influence on Gulf Coast environments* (A. Bouma, Ed.), pp. 422-432. Houston: Gulf Publishing Co.

Simmons, E.G., 1957: An ecological survey of the Upper Laguna Madre of Texas. *Publ. Inst. Mar. Sci. 4* (2), pp. 156-200.

Simpson, J.E., 1994: *Sea breeze and local winds*. Cambridge: The University Press.

Singh, V.P., 1989: *Hydrologic Systems, Vol. II: Watershed modeling*. Englewood Cliffs, NJ: Prentice-Hall.

Smith, N.P., 1979: Meteorological forcing of coastal waters by the inverse barometer effect. *Est. Coast. Mar. Sci. 8* (2), pp. 149-156.

Southwest Research Institute, 1977: Effects assessment of candidate navigation plans for Corpus Christi Bay area; Part K: Historical and baseline conditions for waters of bay system and nearshore Gulf. Final Report, Contr. DACW-75-C-0075, Ocean Science Lab, SWRI, Corpus Christi.

Stephens, A. R., 1964: *The Taft Ranch, a Texas principality*. Austin: University of Texas Press.

Stommel, H., 1987: *A view of the sea*. Princeton, New Jersey: Princeton University Press.

Sturges, W. and J. Blaha, 1976: A western boundary current in the Gulf of Mexico. *Science 192*, pp. 367-369.

Suarez, D. and G. Ward, 1978: Climatology of Texas hurricanes and their effects on the siltation of channels and harbors. Doc. No. 78137, Espey, Huston & Assoc., Austin, Texas.

Symons, T.W., 1896: Improving the entrance to a bar harbor by a single jetty. *Trans. ASCE 36*, pp. 109-124.

Symons, T.W., 1899: Discussion on reaction breakwater. *Trans. ASCE 42*, pp. 516-520.

Texas Department of Water Resources, 1981: Nueces and Mission-Aransas estuaries: A study of the influence of freshwater inflows. Report LP-108, TDWR, Austin, TX.

Texas Game, Fish & Oyster Commission, 1927: Annual report, Fiscal Year 1927. TGFOC, Austin, Texas.

Texas Game, Fish & Oyster Commission, 1928: Annual report, Fiscal Year 1928. TGFOC, Austin, Texas.

Texas Game, Fish & Oyster Commission, 1930: Coast fisheries. In: *Yearbook on Texas conservation of wildlife*, pp. 49-58. Annual report, Fiscal Year 1930. TGFOC, Austin, Texas.

Texas Game, Fish & Oyster Commission, 1936: Annual report, Fiscal Year 1936. TGFOC, Austin, Texas.

U.S. Coast & Geodetic Survey, 1916: *United States coast pilot, Section E, Gulf Coast from Key West to the Rio Grande*. Ser. No. 45, USC&GS, Dept. of Commerce. Washington, D.C.: U.S. Government Printing Office.

U.S. Coast & Geodetic Survey, 1936: *United States coast pilot, Gulf Coast (Key West to the Rio Grande)*. Ser. No. 590, USC&GS, Dept. of Commerce. Washington, D.C.: U.S. Government Printing Office.

U.S. Coast & Geodetic Survey, 1949: *United States coast pilot, Gulf Coast (Key West to Rio Grande)*. Ser. No. 725, USC&GS, Dept. of Commerce. Washington, D.C.: U.S. Government Printing Office.

U.S. Corps of Engineers, 1880: *Annual Report, Appendix N (Part II)*. Washington, D.C.: Government Printing Office.

U.S. Corps of Engineers, 1912: *Annual Report*. Washington, D.C.: Government Printing Office.

U.S. Corps of Engineers, 1944: Report on survey of Nueces River and tributaries, Texas, for flood control and allied purposes. (4 vols.) Galveston: War Department.

U.S. Corps of Engineers, 1949: History of the Gulf Intracoastal Waterway. Galveston: U.S. Army Engineer.

U.S. Corps of Engineers, 1962: Port Aransas - Corpus Christi Waterway, rehabilitation of north and south jetties. Galveston: U.S. Army Engineer.

U.S. Corps of Engineers, 1963: Port Aransas - Corpus Christi Waterway, Texas (40 ft project). Design Memo. No. 4, General Design Memorandum. Galveston: U.S. Army Engineer.

U.S. Corps of Engineers, 1968: Review of reports on Port Aransas - Corpus Christi, Texas (45-ft Project). Galveston: U.S. Corps of Engineers.

U.S. House of Representatives, 1922: Rivers and Harbors Act. House Doc. 321, (Ser. No. 8006), 67th Congr., 2nd Sess. Washington, D.C.: Government Printing Office.

U.S. Naval Observatory, 1994: *The astronomical almanac for the year 1995*. Washington, D.C.: Government Printing Office. (Published jointly with the Royal Greenwich Observatory, Her Majesty's Stationery Office, London.)

Van Dorn, W.G., 1974: *Oceanography and seamanship*. New York: Dodd, Mead & Co.

Wallace, J., and P. Hobbs, 1977: *Atmospheric science: an introductory survey*. New York: Academic Press.

Walraven, Bill, 1990: *El Rincon: a history of Corpus Christi Beach*. Corpus Christi: Texas State Aquarium.

Ward, G.H., 1980a: Accuracy of Harbeck Diagram for forced evaporation. *J. Energy Div., ASCE, 106* (EY1), pp. 23-31.

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

Ward, G.H., 1981: Intensive inflow study, Laguna Madre of Texas, 1980. Doc. No. 81013, Espey, Huston & Assoc., Austin, Texas.

Ward, G.H., 1982a: Thermal plume area calculation. *J. Energy Div., ASCE, 108* (EY2), pp. 104-115.

Ward, G.H., 1982b: Pass Cavallo, Texas: case study of tidal-prism capture. *J. Waterway, Port, Coastal & Ocean Div., ASCE, 108* (WW4), pp. 513-525.

Ward, G.H., 1985a: Marsh enhancement by freshwater diversion. *J. Water Res. Planning & Mgmt., ASCE, 111* (1), pp. 1-23.

Ward, G.H., 1985b: Dye diffusion experience in the Texas bays: low-wave conditions. *J. Geophys. Res. 90* (C3), pp. 4959-4968.

Ward, G.H., 1991: Modeling options for Galveston Bay. In: *Proceedings, Galveston Bay characterization workshop* (F. Shipley and R. Kiesling, eds.). Report GBNEP-6, Galveston Bay National Estuary Program, Webster, Texas.

Ward, G.H., 1993: Dredge-and-fill activities in Galveston Bay. Report GBNEP-28, Galveston Bay National Estuary Program, Webster, Texas.

Ward, G., and N. Armstrong, 1992: Ambient water and sediment quality of Galveston Bay: present status and historical trends. Report GBNEP-22, Galveston Bay National Estuary Program, Webster, Texas.

Ward, G., and N. Armstrong, 1997a: Ambient water, sediment and tissue quality of Corpus Christi Bay: present status and historical trends. Publ. CCBNEP-13, Corpus Christi Bay National Estuary Program, Corpus Christi, Texas.

Ward, G., and N. Armstrong, 1997b: Data bases for Corpus Christi Bay. Draft report, submitted to Corpus Christi Bay National Estuary Program, Corpus Christi, Texas.

Ward, G. and C. Montague. 1996: Estuaries. Chapter 12 in *Water Resources Handbook,* L. Mays (ed.). New York: McGraw-Hill Book Company

Ward, G., and P. Proesmans, 1996: *Hydrological predictands for climate-change modeling*. Technical Report, Global Climate Change Response Program, U.S. Bureau of Reclamation, Denver, Colorado.

Watson, R. and E. Behrens, 1976: Hydraulics and dynamics of New Corpus Christi Pass, Texas: a case history, 1973-75. Rep. No. 9, General Investigation of Tidal Inlets, Coastal Engineering Research Center, U.S. Corps of Engineers.

Wells, G.L., 1983: Late-glacial circulation over central North America revealed by aeolian features. In: *Variations in the global water budget* (A. Street-Perrott, M. Beran, and R, Ratcliff, eds.), pp. 317-330. Dordrecht, The Netherlands: D. Reidel.

White, W., T. Calnan, R. Morton, R. Kimble, T. Littleton, J. McGowen, H. Nance, and K. Schmedes, 1983: Submerged lands of Texas, Corpus Christi area: sediments, geochemistry, benthic macroinvertebrates, and associated wetlands. Bureau of Economic Geology, University of Texas, Austin.

White, W., T. Calnan, R. Morton, R. Kimble, T. Littleton, J. McGowen, and H. Nance, 1989: Submerged lands of Texas, Port Lavaca area: sediments, geochemistry, benthic macroinvertebrates, and associated wetlands. Bureau of Economic Geology, University of Texas, Austin.

Whitehouse, U. and W. Williams, 1953: Descriptive physical oceanography of San Antonio Bay, Mesquite Bay, and Aransas Bay, Texas and adjacent waters. Res. Rep. No. 1, Proj. 34B, Dept. Oceanography, Texas A&M College, College Station.

Winker, C.D., 1979: *Late Pleistocene fluvial-deltaic deposition, Texas coastal plain and shelf.* M.A. Thesis, University of Texas at Austin.

Wisner, G.Y., 1899: Discussion on reaction breakwater. *Trans. ASCE 42*, pp. 512-516.

Work Projects Administration, Writers' Program, 1942: *Corpus Christi, a history and guide*. Corpus Christi Caller-Times.

APPENDICES

APPENDIX A

INSTALLATION OF EXHIBITS

The diskettes in the endpocket of this report contain compressed files for the Exhibits. These are designed for operation on a PC-compatible machine with at least a 286 processor. You will need about 7 megabytes available on your hard drive. Installation is carried out from DOS. If WINDOWS is operating, this will require an exit from WINDOWS to the DOS prompt.

It is recommended that the Exhibits be installed in a separate directory on the hard drive. The first step is to create such a directory. At the DOS prompt, enter:

md circuln

where "circuln" is the name chosen for the directory. (You may, of course, choose any name you wish, subject to the DOS limitations on length and characters.) Verify that the new directory has in fact been created by entering

dir /p

(The "/p" freezes the screen when it is filled. The display is continued by pressing any key.) For convenience, change to this directory, by entering

cd circuln

Insert the first diskette in the 3.5-in drive. Assume that this drive is **a:** and the hard drive on which you have created the directory "circuln" is **c:**. Enter the command:

a:exhibit c:\circuln

(If these drives have other designations, e.g. if the 3.5-in drive is **b:**, and/or the hard drive is **d:**, then the appropriate substitution is necessary in the above command. The user familiar with DOS operations and de-compression software will recognize that the above command can be shortened.) This is a self-extracting file. The following files will be unpacked and written to directory "circuln":

INLETHR.DAT	ARANSHR.DAT
CCBAYHR.DAT	EXHIBIT1.EXE

Now insert the second diskette and enter (again) the above command. The following additional files will be unpacked and written to directory "circuln":

NUECESHR.DAT	LAGUNAHR.DAT
EXHIBIT2.EXE	EXHIBIT3.EXE

Specific instructions for executing the Exhibits are given in Sections 4.2, 4.3.1 and 4.4.1 of the main text. All of these are executed from the DOS prompt, so, as above, you will first need to exit from WINDOWS. It is also necessary to change to the directory "circuln" before executing the exhibit (assuming that you are not in that directory). This is done, as above, by entering:

cd circuln

Any exhibit is executed by entering

EXHIBIT*n*

at the DOS prompt, where ***n*** designates 1, 2 or 3, depending upon which Exhibit is being operated. The execution may be terminated at any point by pressing "Q" or by pressing the CTRL and BREAK keys together.

Error exits and probable diagnostics are included in the codes, so if something goes wrong, you will get information on the screen. The code has been written to be as robust and platform-independent as possible. But with the present roach-like proliferation of processors, machines and operating systems, one never knows. Execution has been tested on every platform available to the author. On some network operations that are finicky about where executables are housed, there may be a problem with the program being able to access the data files (which are supposed to be in the same directory as the executable). Your network manager should be able to help with that. On one platform operating under WINDOWS 95, the screen display (e.g. Fig. 4-6) was distorted, so that the hodograph panel was elliptical rather than circular. The cause for this could not be determined, but probably has to do with a peculiar hardware glitch of that manufacturer aggravated by the operating system. (If you encounter this problem, you might try de-activating WINDOWS entirely and re-booting from DOS, assuming that DOS is available on your machine. Or perhaps you might call Bill Gates.)

The date in EXHIBIT2 and EXHIBIT3 is coded by a five-digit number, the last three of which are the day number, counted from 1 January. For reference, Table A-1 tabulates the day numbers for the last day of every month.

Table A-1
Day numbers for ***last*** day of each month

January	31	May	151	September	273
February	59	June	181	October	304
March	90	July	212	November	334
April	120	August	243	December	365

Note: For leap years, add 1 to all months except January

APPENDIX B

CORRECTIONS TO BLUCHER WATER-LEVEL DATA

The digital principal water level records of the CBI gauges proved to contain anomalies that had to be removed or otherwise corrected before the data could be applied in hydrodynamic analyses. This proved to be a labor-intensive process, requiring the detailed visual inspection of the entire record for each gauge used in the analysis, noting any odd shifts in values, data gaps, phasing versus other continuous gauge records. Each of the gauge records contains many such events. As many natural events operating in the Corpus Christi Bay system will produce sudden changes in water level or will alter the relative phase of two gauges, most of these manifestations in the gauge data prove to be real. However, there is a residual of anomalies, arising evidently from gauge malfunctions, settling, or processing errors, that had to be removed. These are described in this Appendix. All gauge records utilized in this study were corrected as described below before being used in quantitative analysis. For the animation files (EXHIBIT2 and EXHIBIT3) the records were similarly corrected. For base comparison purposes, the raw data files did not embody such corrections.

B.1 Port Aransas

For practical purposes, the record at this gauge begins in early 1993, though there are a few cycles recorded from early 1991. The February-March 1993 record is very suspicious, with numerous gaps, and odd phasing relations between Bob Hall Pier and Port Aransas. To avoid this period, only data after 93100 were employed in quantitative analyses.

B.2 Ingleside

The record for this gauge begins 92119, but is "gappy" throughout 1992, some of the data gaps being of 1-2 day duration. This did not affect calculations in this study because the period of record for such calculations begin 93269. Quantum shifts in the record were identified beginning on 93095, 93194, and phase problems may be indicated beginning on 93126 and 93175. Because all of these antedate the period for quantitative application of the data, no action was taken to correct the records.

On 95005, the gauge record undergoes a quantum increase of 77 mm, see Fig. B-1, which stays with the data for the remainder of the record. As all relative leveling analyses were performed for periods prior to this shift, it had to be removed from the record. This was done by subtracting a constant 77 mm from the time of the initial shift onwards.

B.3 Naval Air Station

From the beginning of the record through 93060, this record contains numerous lengthy gaps. The period of application in the present study was taken to begin 93061, to avoid these numerous record gaps. On 95307, the record undergoes a

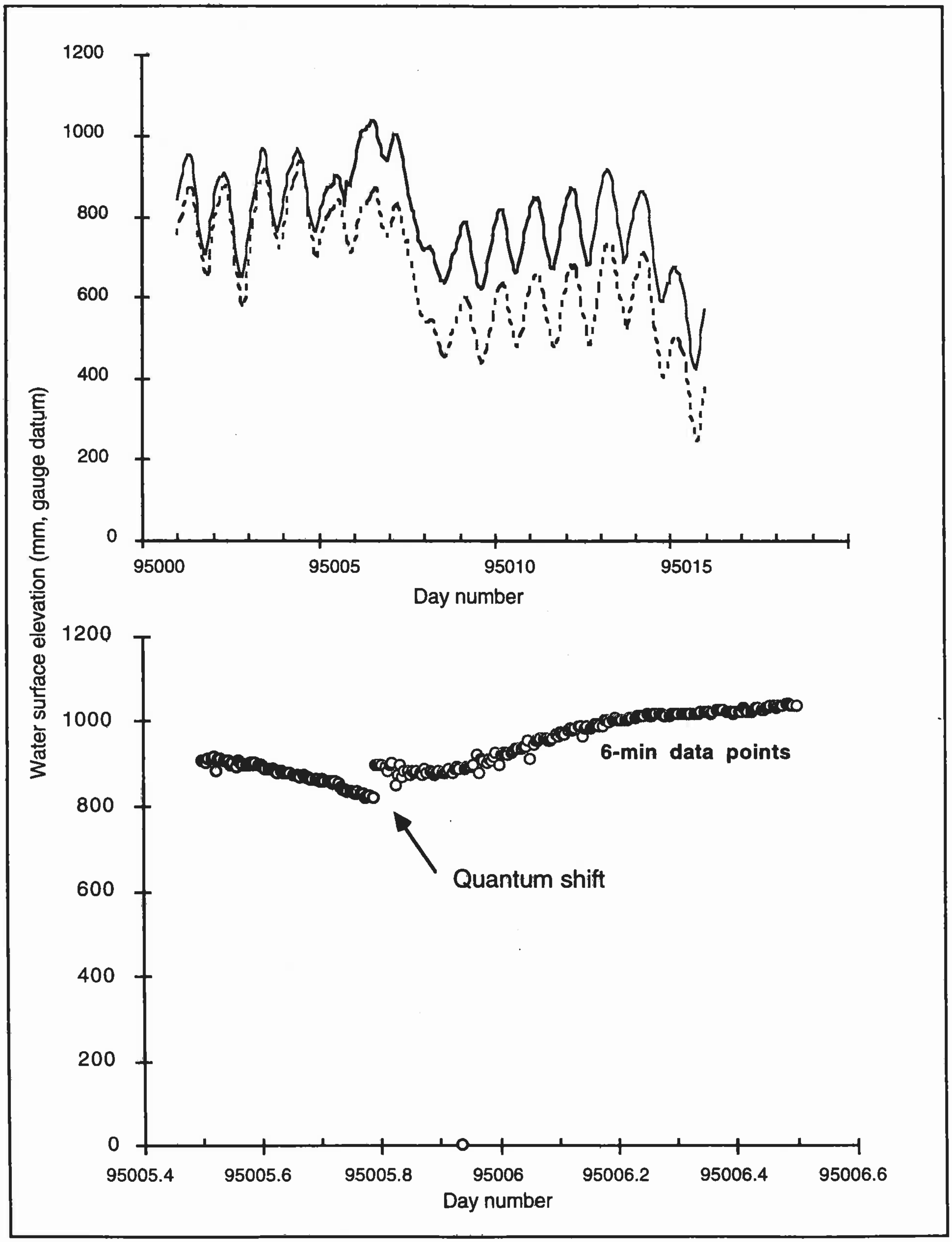


Figure B-1. Anomalous shift in Ingleside record quantum increase of about 237 mm, and remains displaced by this amount for a week, until 95314 when another quantum shift returns to its original level, Fig. B-2. Though it probably would have been easier to simply delete this week of anomalous data, the correction was applied.

B.4 State Aquarium

Generally the record for this gauge from its start on 93269 has good continuity, with just a few gap periods. No quantum shifts were encountered that indicate data malfunction, so no changes were made to the record. A curious shift occurs at 93364 00Z, followed by an apparent change in phase lag relative to NAS by 2-3 hours. However, over the next 14 days the record gradually re-acquires its phase with NAS. This was judged to be a natural event, and data modifications were not warranted.

B.5 White Point

This is the only gauge in Nueces Bay, so it is frustrating that the gauge appears to be bottoming. Any values less than 0.25 m (gauge datum) are missing. The resulting frequent data gaps also frustrate detection of level shifts. None could be unequivocally detected, so no corrections were implemented.

B.6 Shamrock Island

Early data from 1992 is corrupted by pegging, flatlines, gaps, etc. When gauge record resumed on 93209 it was much better behaved, with only occasional missing data. Because this gauge operation was discontinued after January 1995, it was only used in the present study to verify other gauge operations in Corpus Christi Bay, and therefore was not subjected to close inspection and/or correction.

B.7 Rockport

Co-operated by National Ocean Service, the available record for this gauge is longer than most of the CBI gauges. No shifts or phase aberrances were detected. An 8-hour period on day 95244 was flatlined and was deleted from the record.

B.8 Copano Bay Causeway

The record for this CBI station begins 92342, but the first few months are a mess, with numerous data gaps, elevation shifts, and apparent timing errors. For example, after a gap on 93005 the record returns about 12 hours out of phase relative to Rockport, i.e. 180° out. On 93020 there is a quantum shift, returning the phase relation to normal, but then on 93024, after another quantum jump in elevation, this gauge *leads* Rockport by two hours. After a break on 93030, the record re-attains normal phase, but now has a tidal amplitude that is greater than Rockport. And so it goes. The record prior to 93085 is full of such corruptions. The easiest course in the present study was to disregard all data before 93085 and use only the data recorded afterward. No corrections were necessary for this truncated record.

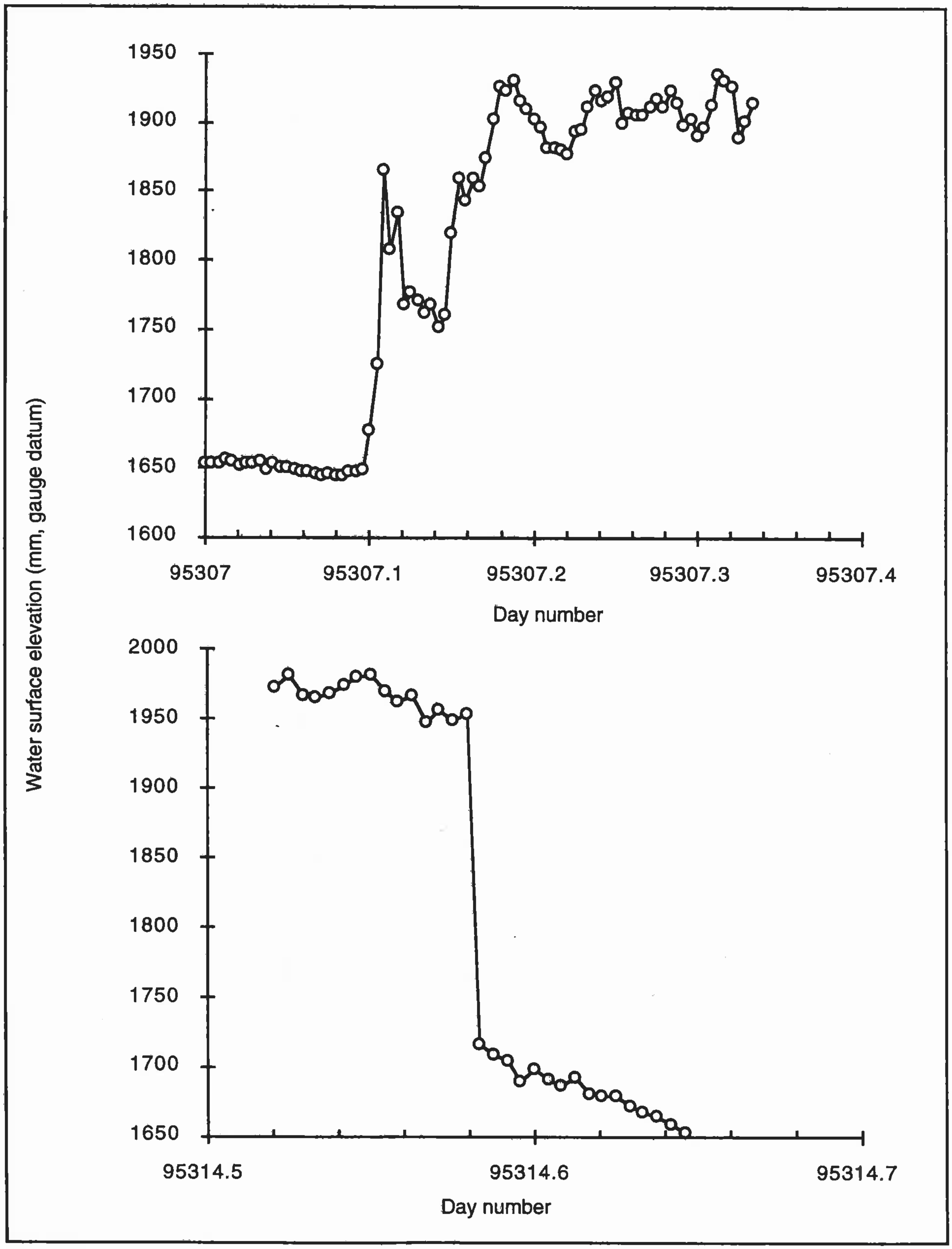


Figure B-2. Anomalous shifts in record at Naval Air Station

B.9 Bayside

The record for this gauge runs from 91148 until 95329, after which its operation was discontinued. There are numerous gaps in the record prior to February 1993. Over a period of about a week, from 3 January 1995 to 11 January 1995, the gauge record evidences multiple corruptions, both quantum shifts and flatline periods. This is evident in Fig. B-3, the lower panel showing 6-min data for a brief isolated section of this period, in which both flatlining and an upward shift are evident. Based on a comparison to the Copano record for the same period, we judge a net upward quantum shift in the Bayside data of 12.5 mm, which was subtracted from the record after 11 January. This is, at best, approximate. The ideal approach would have been to re-level the gauge using level-surface periods after the date of the corruption, but this could not be undertaken within the resources of the project.

B.10 Packery Channel

Also one of the longer extant CBI gauges, the record for Packery (which is in fact located off the GIWW north of the JFK Causeway) begins 90233, but the early record (1991 and 1992) contain numerous gaps. In the present study, only data after 93092 were used. No anomalies *per se* could be identified in the record, but there is a drift in the relation between Packery Channel and Naval Air Station in spring of 1995 that may be real, but warrants additional examination.

B.11 South Bird Island

The record for this gauge begins 93092 and is relatively gap-free. One pair of vertical shifts occur in the record. On 94157 there is a downward quantum shift of 241 mm, and on 94172 a quantum shift upward of the same amount, compensating for the earlier shift, see Fig. B-4. The exact amount was determined by examining the 6-min mean data points, in which the shift is quite obvious. Therefore, 241 mm was added to the recorded data from 941257 20Z through 94173 18Z. Because of the small, practically nonexistent tidal variation at this gauge, it is very difficult to discriminate flatline periods at the relatively cursory level of inspection performed by this study. No obvious such periods were detected, but the record needs closer evaluation.

B.12 Yarborough Pass

This station is located just off the GIWW south of the old Yarborough Pass Channel. The record begins 90233, but for this study only the data record after 93091 was used. The period from 94019 through 94090 is significantly corrupted, with data gaps, vertical shifts, and flatlines. Moreover, this gauge, at the lower extreme of Upper Laguna Madre is not highly correlated with other gauges, primarily because of the effects of wind, so it is difficult to separate data anomalies from real water-level variations. A quantum shift upward occurs on 94024 after a three-day gap, as shown in Fig. B-5, in which the Packery Channel Station record is plotted for comparison (shifted by an arbitrary constant to bring the two traces onto the same graph). Note the flatline period. Over two months later on 94090 the record shifts downward, shown by the hourly data plotted in Fig. B-5 (lower panel). Although this gauge warrants further study, this could not be undertaken within the resources of this project. After inspection of the records before and after this aberrant period, we assume (1) the upward net shift on 94024 is compensated by the downward shift on 94090, (2) the magnitude of the upward/downward shift is 150 mm. A correction of this amount was applied for this period. Also, the flatline period 94022-24 was deleted.

Some justification for (1) is afforded by the level-period analyses of Appendix C. Period 1 for leveling this station (and the other gauges) was from 1993, before the aberrant shifts, while the remaining leveling periods occurred after the shifts. A comparison of these periods in Table C-1 shows that the differences between South Bird Island and Yarborough Pass are generally consistent before and after the aberrant period.

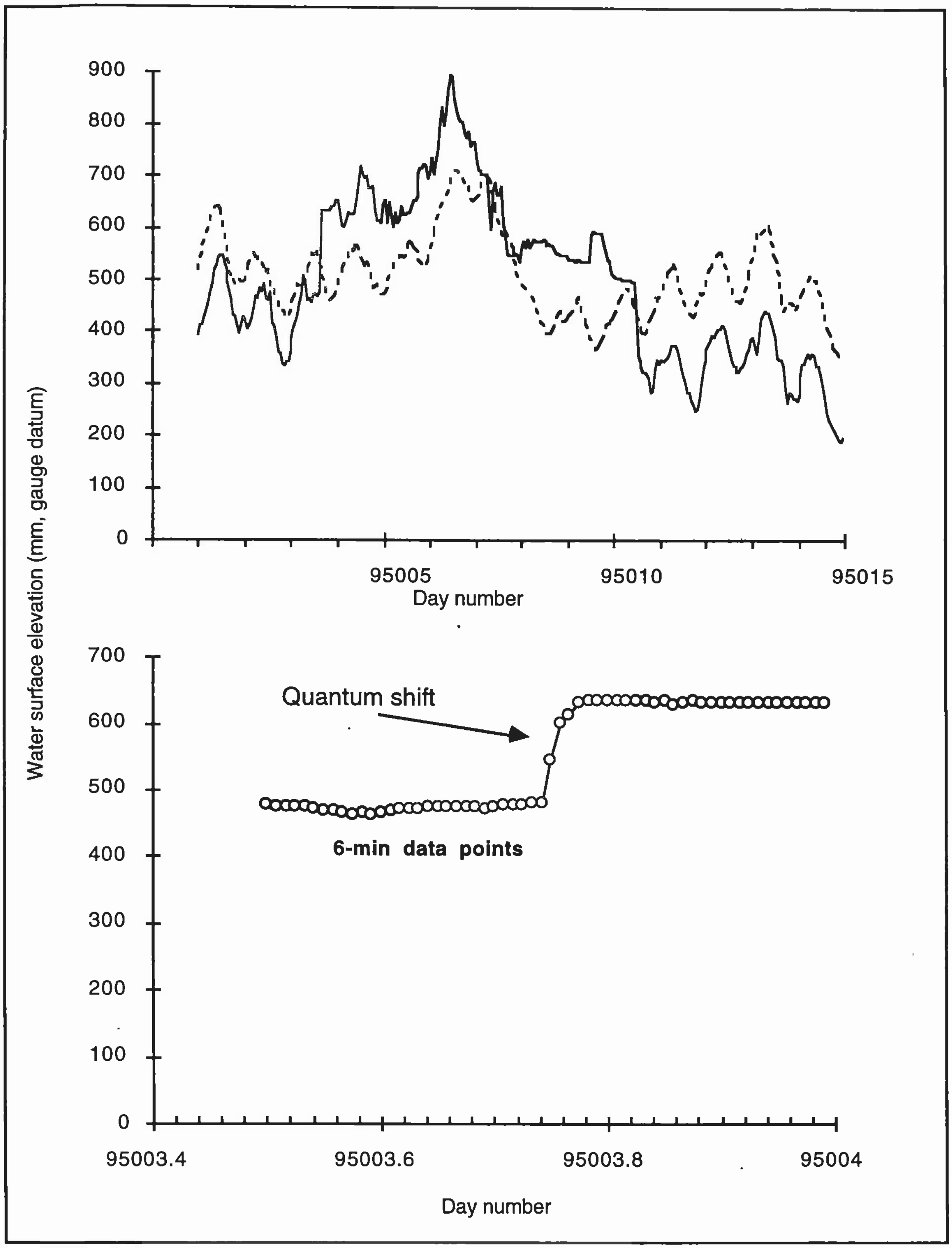


Figure B-3. Anomalous shift in Bayside record

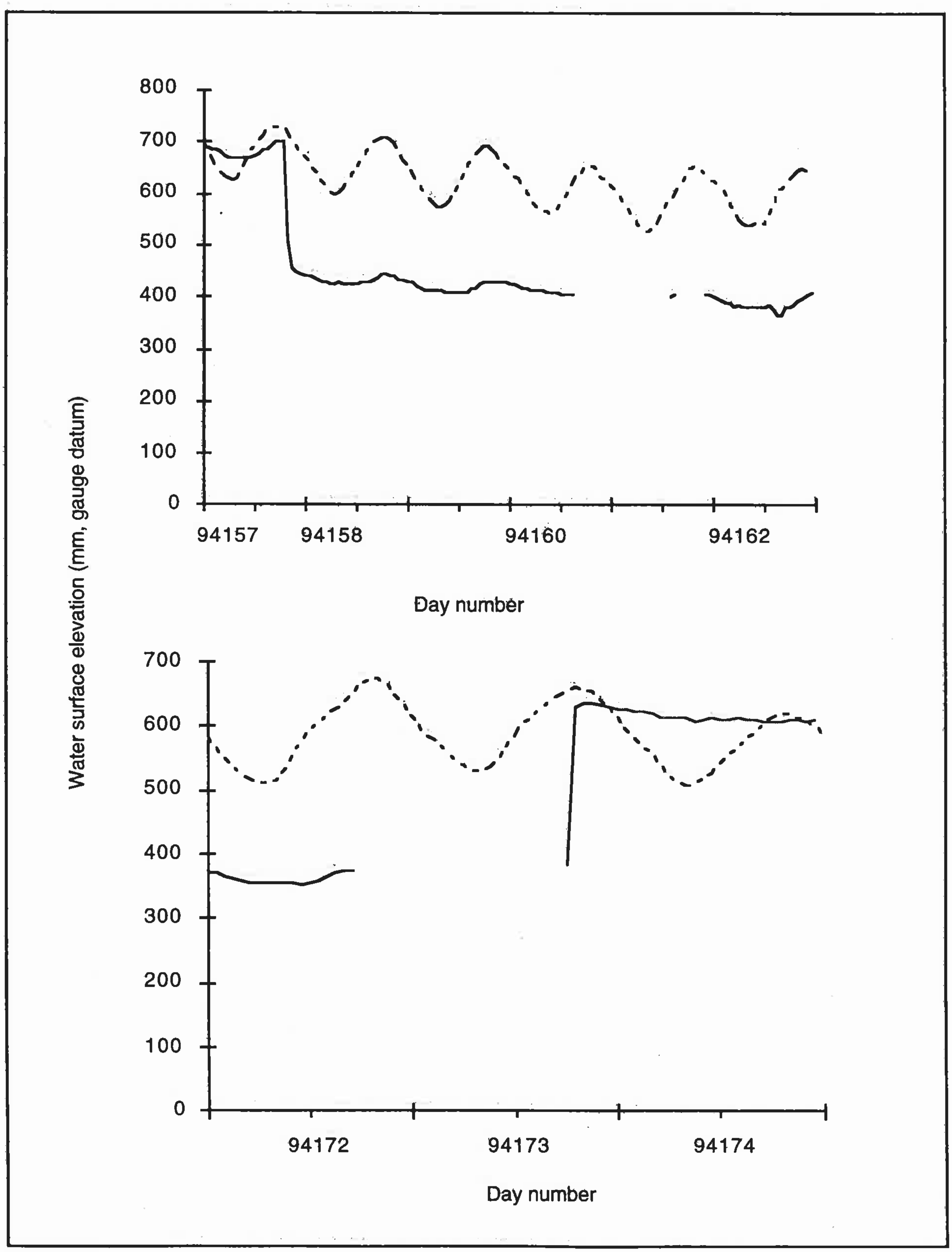


Figure B-4. Anomalous shifts in South Bird Island record

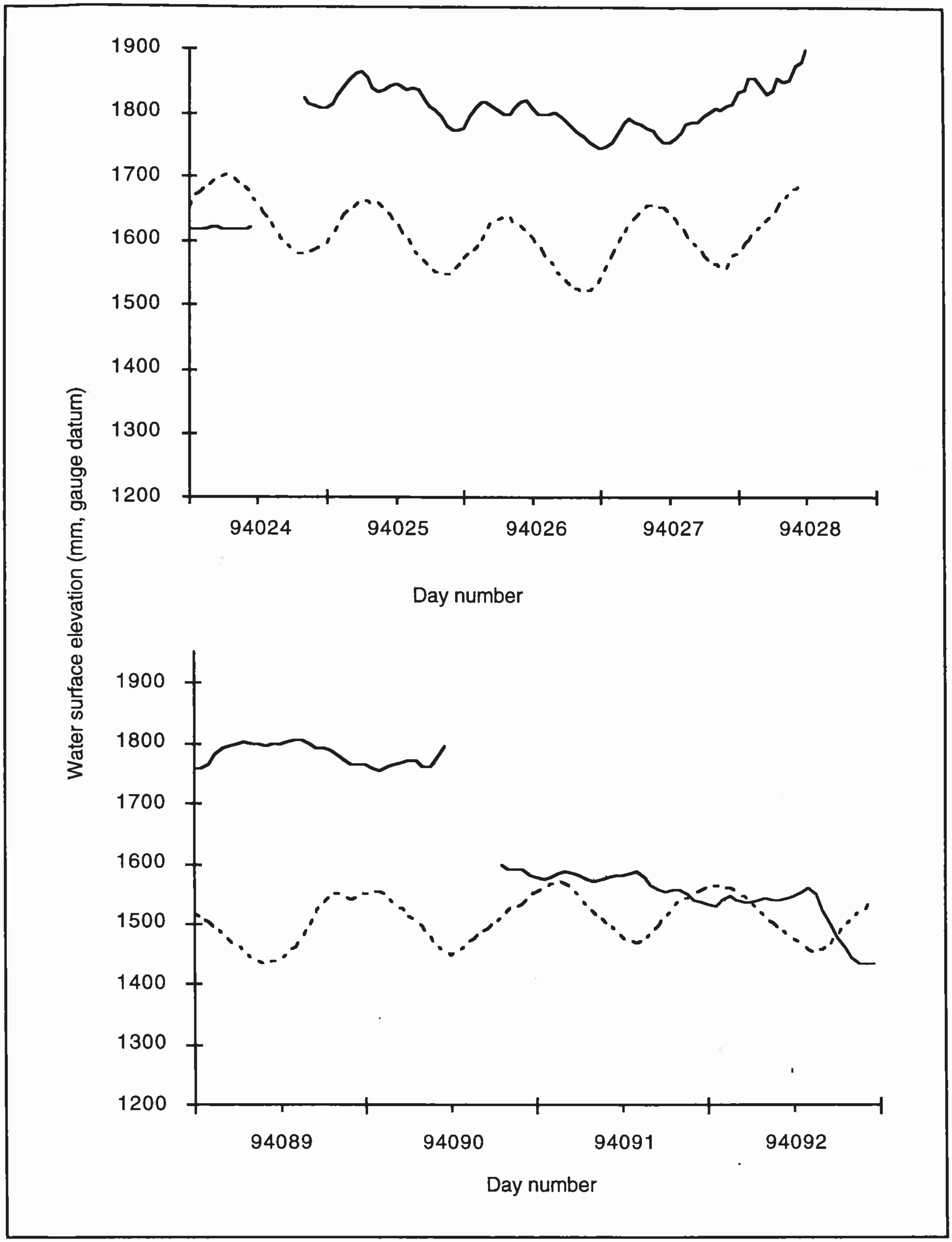


Figure B-5. Anomalous shifts in Yarborough Pass record

APPENDIX C

LEVELING OF BLUCHER TIDE GAUGES

In order to perform hydrodynamic analyses based upon the CBI water-level gauges, it is necessary to reference the CBI gauges to a common datum. This had to be done empirically. In principle, if the water level throughout the system is horizontal and stable, the level reading at each gauge can then be used as a datum reference d, i.e. the measured water level at any time h(t) can be referenced to this level,

$$H(t) = h(t) - d$$

thereby rendering equivalent the zero of H(t) for all of the gauges. The problem of course is identifying a true horizontal surface. The gauge readings themselves cannot be used for such an identification, because they implicitly contain bias due to their arbitrary reference levels.

In this study, this identification was based upon hydrodynamic principles: that the water surface would be approximately horizontal if the normal forcing functions are of negligible magnitude for a sufficient time for the water level to equilibrate. For this, we required the following combination of conditions:

- near-zero lunar declination, thereby ensuring a minimal tidal range
- sustained high-pressure following a frontal passage of sufficient energy to have advanced a considerable distance over the Gulf of Mexico
- sustained near-calm winds

The data record starting 93121 (1 May 1993, when most of the CBI tide and wind data records were usable, see Appendix B) was scrutinized for the occurrence of this combination of events. We required that these be maintained for at least a 12 hour period, both to provide a sufficient number of independent data points to compute a reliable average, and to ensure that whatever residual tidal variation might remain could be averaged out.

Such a combination of conditions is rare. Cold-air outbreaks intruding over the Gulf of Mexico are primarily a wintertime phenomenon. Moreover, at the latitudes of the study area, the prevailing onshore winds turn around quite soon after the initial frontal passage, so that periods of sustained calm after a frontal setdown are even more rare. Only two small-declination periods occur each month, approximately, and these rarely fall in the proper sequence after a cold-air outbreak. Finally, the response of the system, especially the outer bays, requires several days for water levels to equilibrate, by which time, usually, wind setup is underway again.

Eight candidate leveling periods were identified in the record, the data downloaded for each and evaluated carefully for applicability. Even with the requirement of small declination, there was usually a residual tidal variation during the candidate period, especially at Bob Hall Pier and in Aransas Inlet. The mean water levels were examined carefully for evidence of systematic variation (indicative that the water levels had not yet equilibrated to the meteorological and tidal conditions), and each candidate period was ranked by suitability. The four most suitable such periods proved to be:

1 - 12-23 Z 93325 (21 Nov)
2 - 11 Z 94262 - 11 Z 94263 (19-20 Sep)
3 - 04-15 Z 94125 (5 May)
4 - 09-12 Z 94113 (23 Apr)

The hourly water level variations for the upper, lower and central bays are shown in Figs. C-1 through C-12, on which are marked these leveling periods. Average levels for these four periods for each of the CBI gauges are summarized in Table C-1. For convenience, these averages were expressed relative to Ingleside, which was set to 900 mm, so that the resulting water levels would range around zero, thus facilitating plotting.

Inspection of Figs. C-1 through C-12 discloses that each period above is not equally suitable for all sections of the Corpus Christi Bay system. For example, during Period 1, the gauges in the upper bays (Aransas, Copano, Nueces) were increasing, indicating that this part of the system was still in considerable disequilibrium. In Table C-1 these less suitable periods for the upper, central, or lower bays are marked with an asterisk. The recomputed averages (omitting the period or periods marked) are given in the last column of Table C-1. These were employed as estimated datums for the hydrodynamic analyses of this study.

It should be emphasized that these approximate the *relative* datums among the gauges, i.e., the result of referring all of the gauges to a common zero surface. These datums therefore provide a means of determining relative water elevations in the system. Nothing is implied about the relation of these datums to any absolute vertical datum, such as a reference spheroid, or NGVD.

Table C-1

Empirical datums for CBI gauges (mm)
relative to Ingleside

CBI gauge	*Period:* *1*	*2*	*3*	*4*	*mean†*	*mean omitting* *
	*					
Ingleside	835.3	893.8	898.0	871.4	900	900
Bob Hall Pier	6676.8	6742.7	6750.6	6715.8	6747	6749
Port Aransas	1630.6	1688.2	1698.4	1671.8	1698	1698
Aquarium	1503.1	1545.5	1569.9	1532.0	1563	1561
NAS	1560.1	1582.8	1598.8	1563.0	1602	1594
Shamrock	280.8	329.2	339.7	320.1	343	342
	*			*		
Rockport	1867.4	1950.9	1965.2	1947.8	1958	1962
Copano	1570.5	1662.0	1672.3	1660.5	1667	1671
Bayside	455.2	524.8	548.73	531.4	540	541
White Pt.	460.9	490.9		486.5	513	497
		*		*		
Packery	956.4	994.8	1023.1	973.7	1012	1023
Bird Is.	709.4	731.0	799.3	690.7	758	788
Yarborough	1780.1	1766.9	1877.8	1698.8	1806	1862

†relative to Ingleside=900 mm

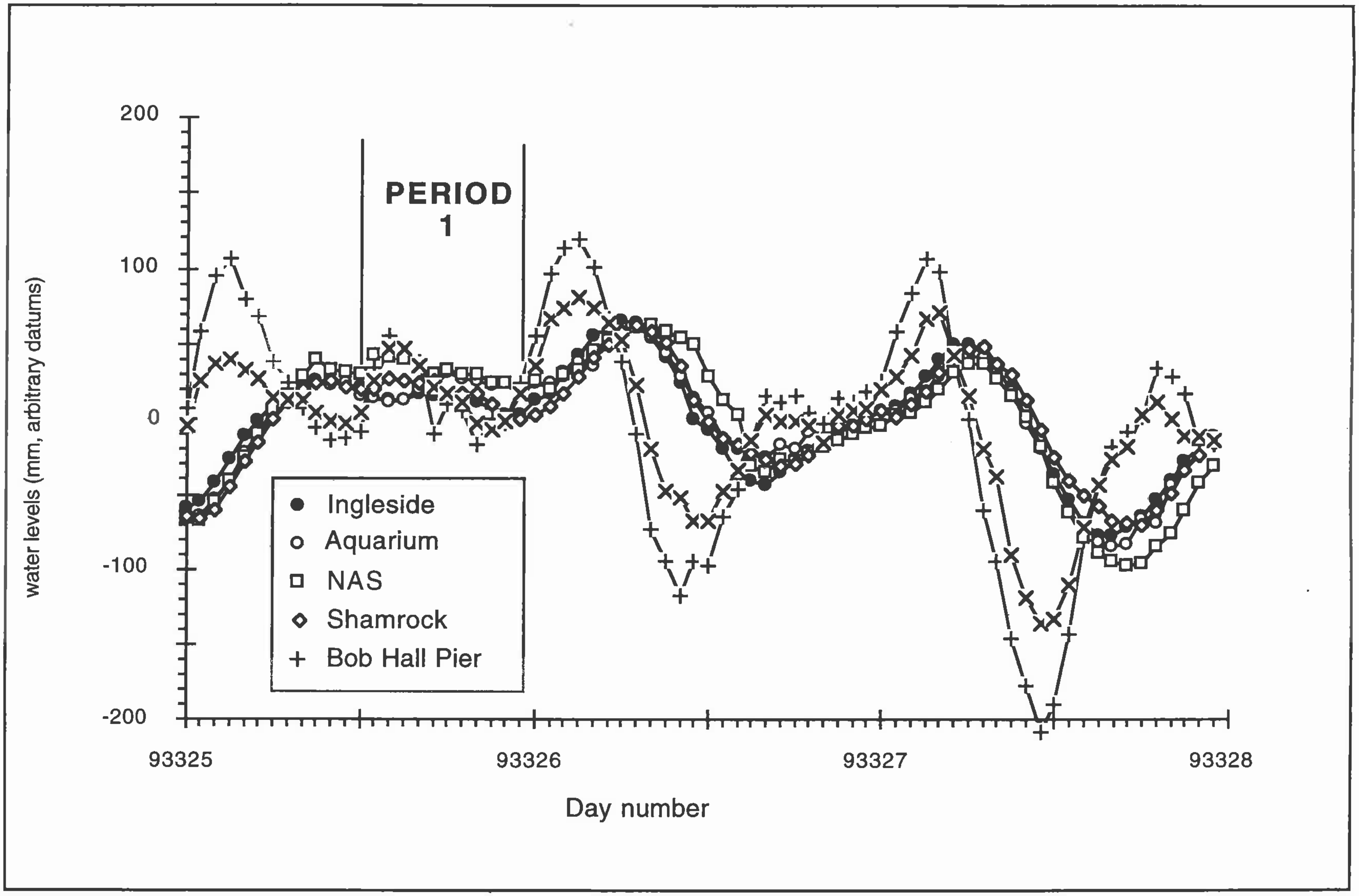


Figure C-1. Water levels and leveling period 1, Corpus Christi Bay

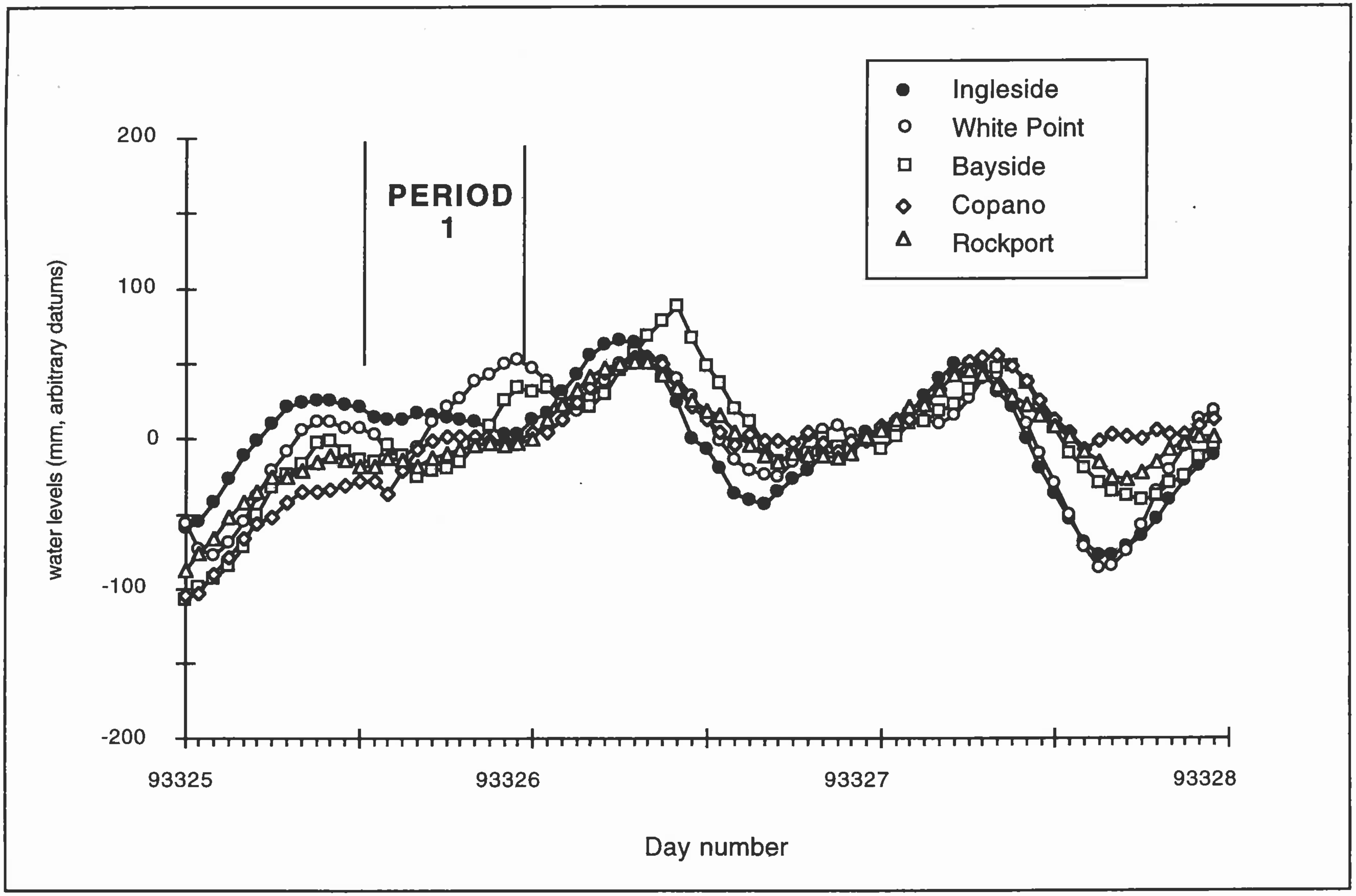


Figure C-2. Water levels and leveling period 1, upper bays

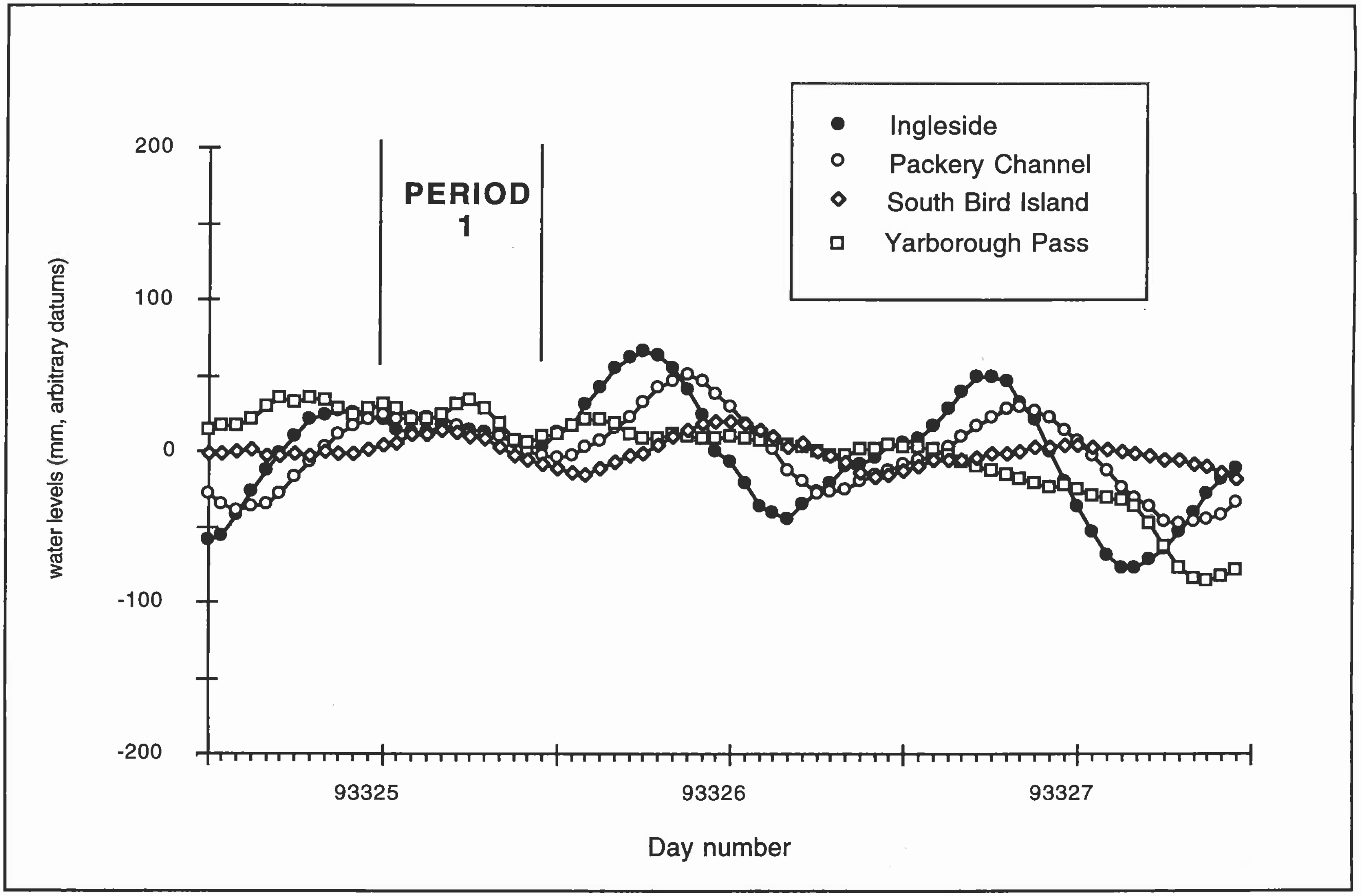


Figure C-3. Water levels and leveling period 1, lower bays

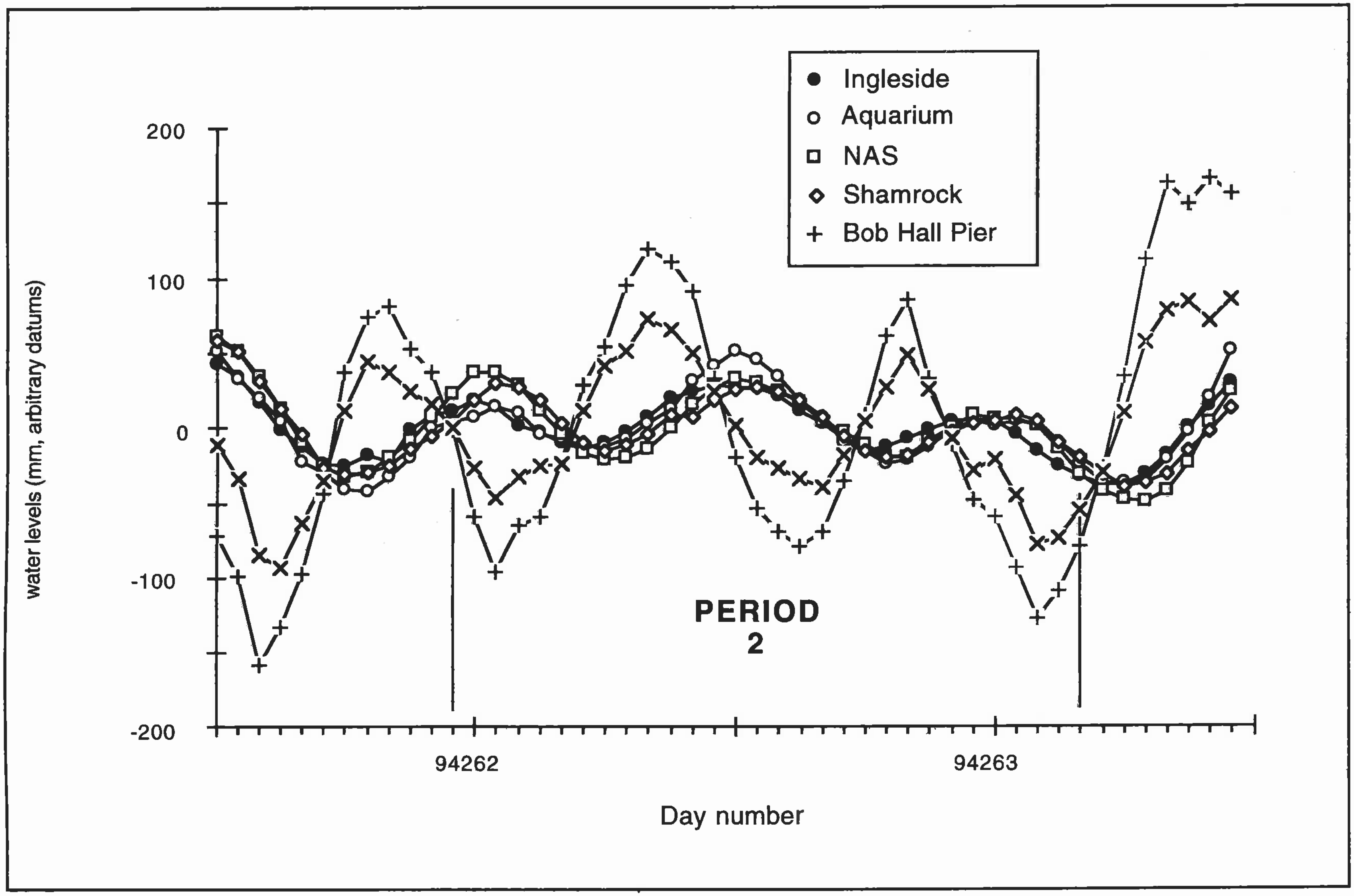


Figure C-4. Water levels and leveling period 2, Corpus Christi Bay

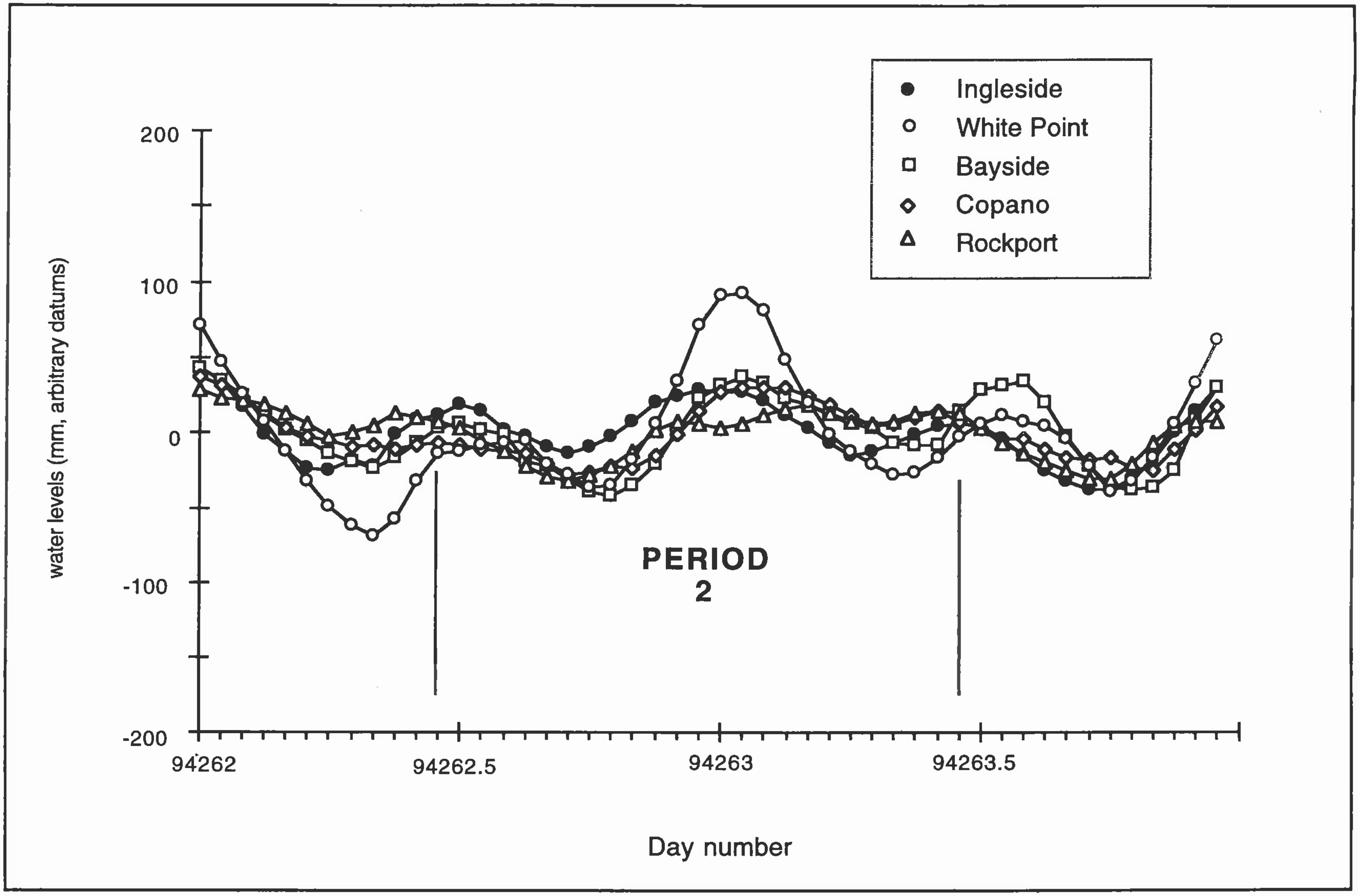


Figure C-5. Water levels and leveling period 2, upper bays

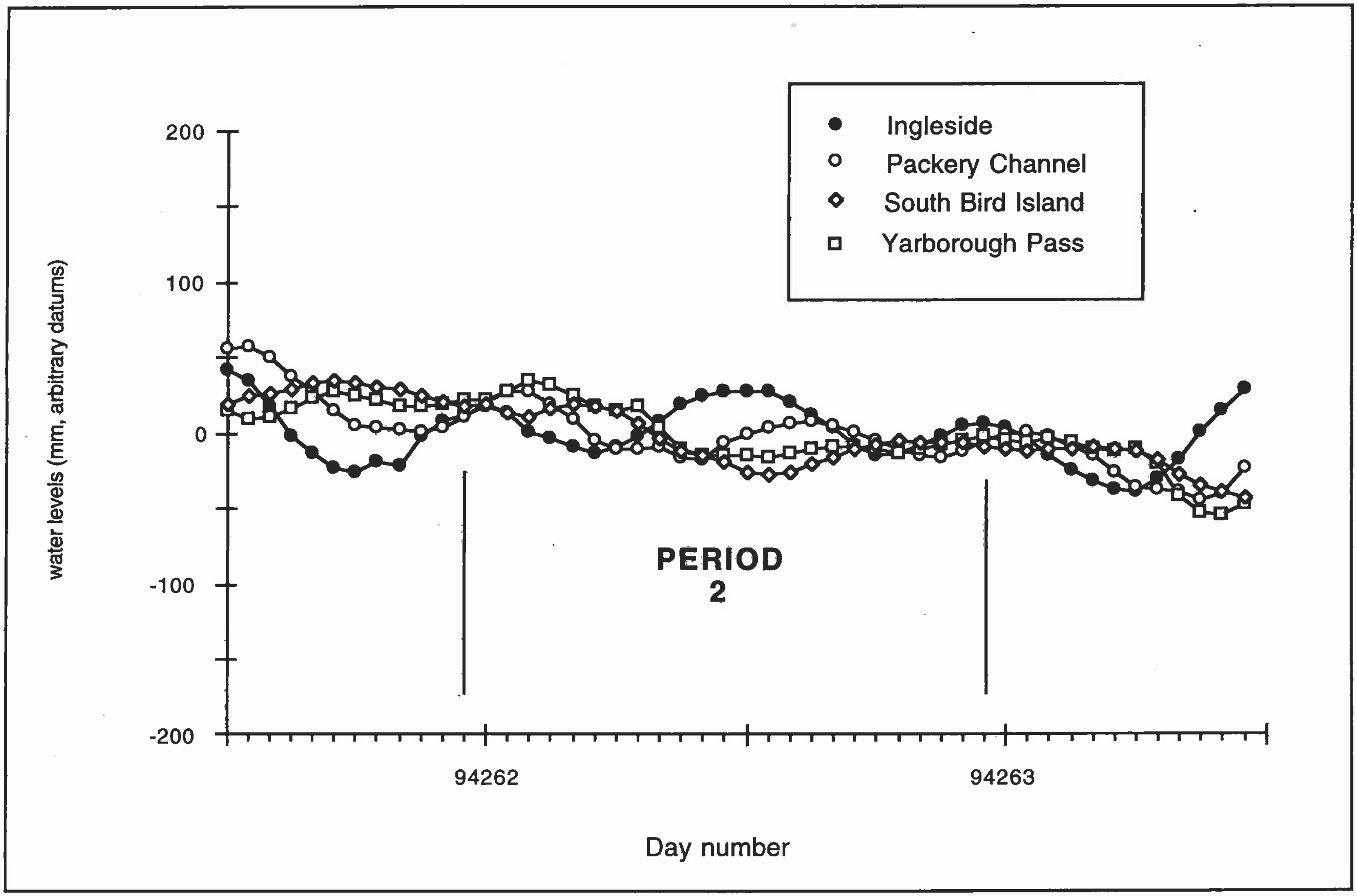


Figure C-6. Water levels and leveling period 2, lower bays

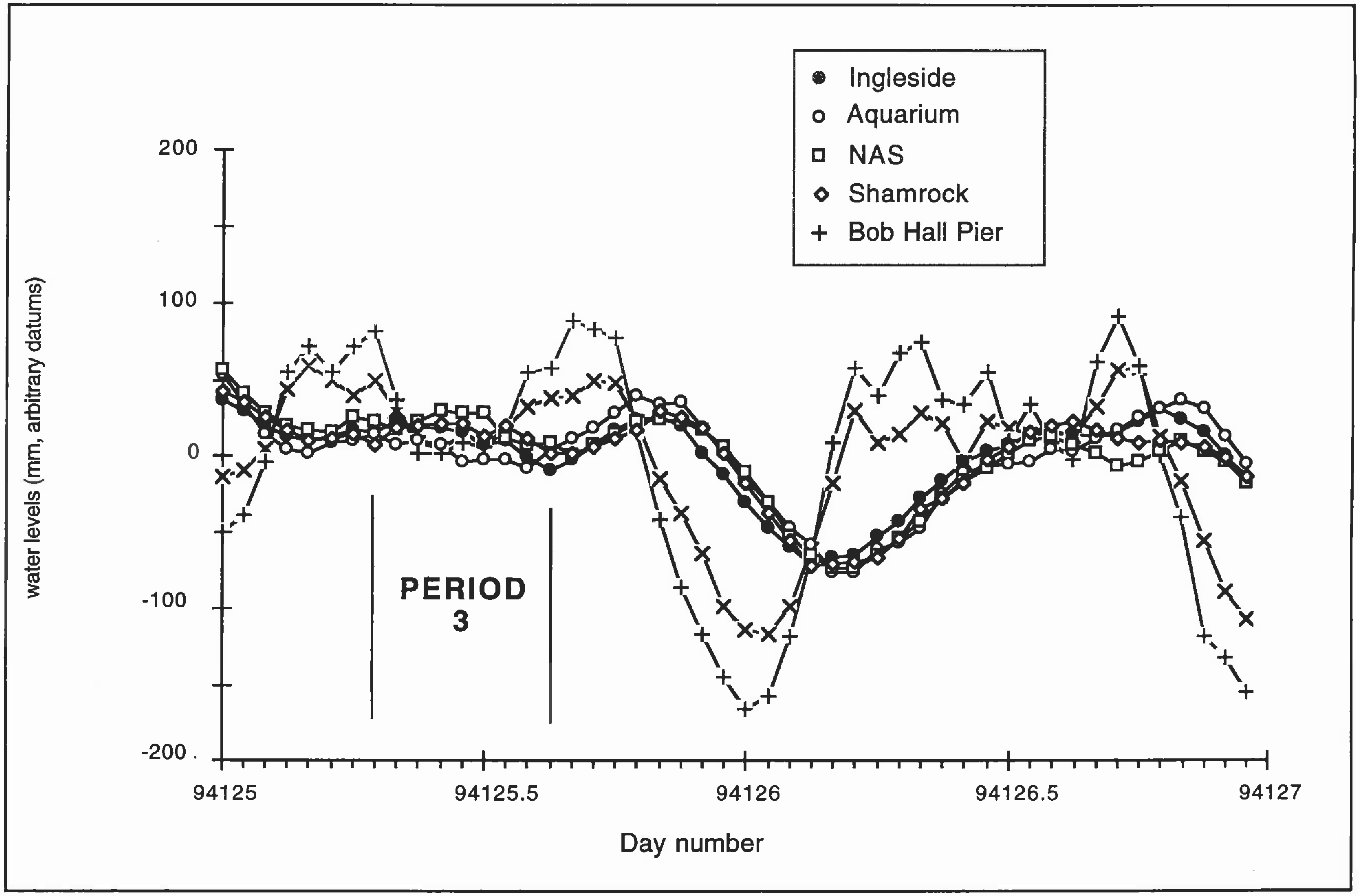


Figure C-7. Water levels and leveling period 3, Corpus Christi Bay

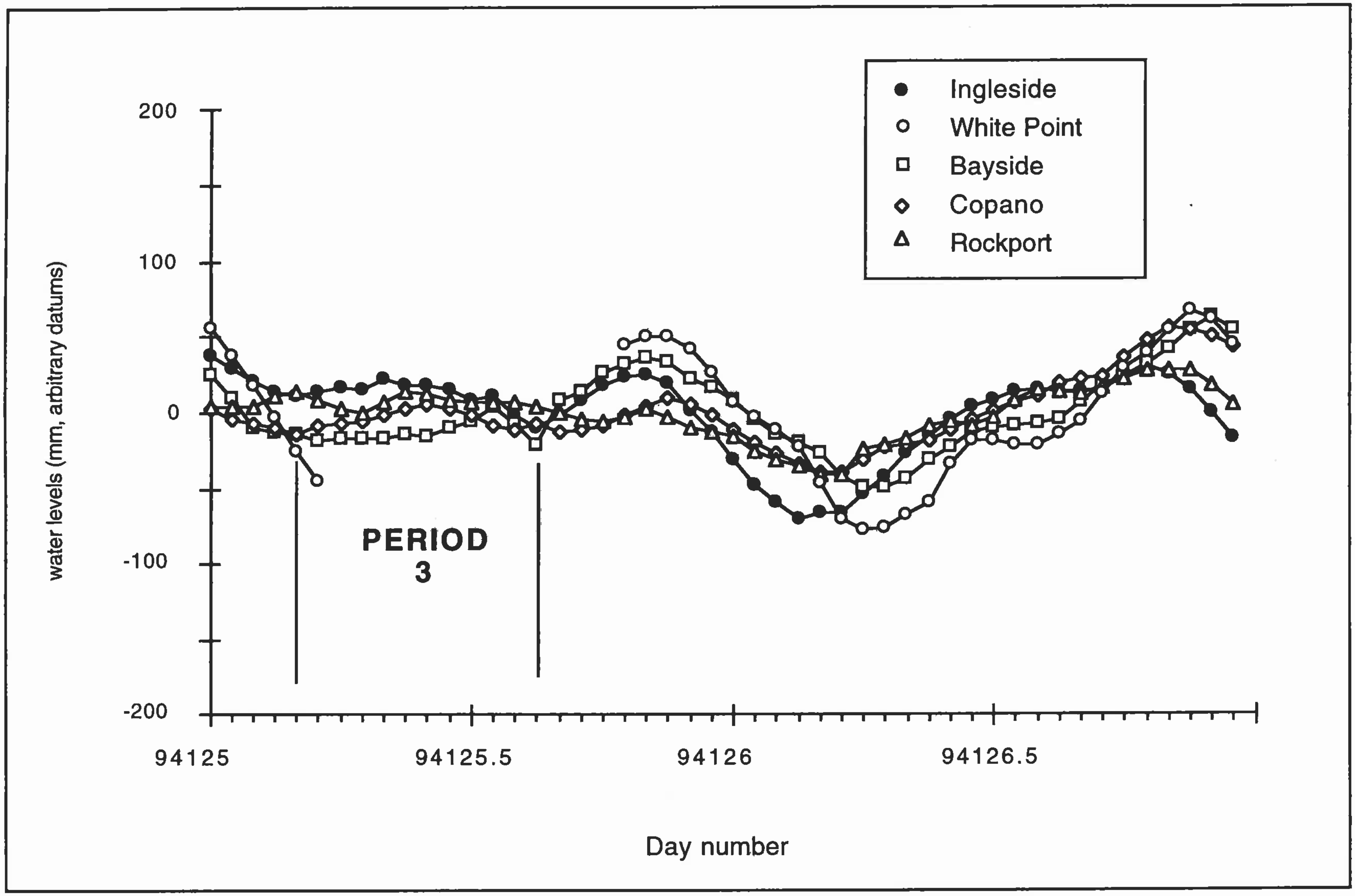


Figure C-8. Water levels and leveling period 3, upper bays

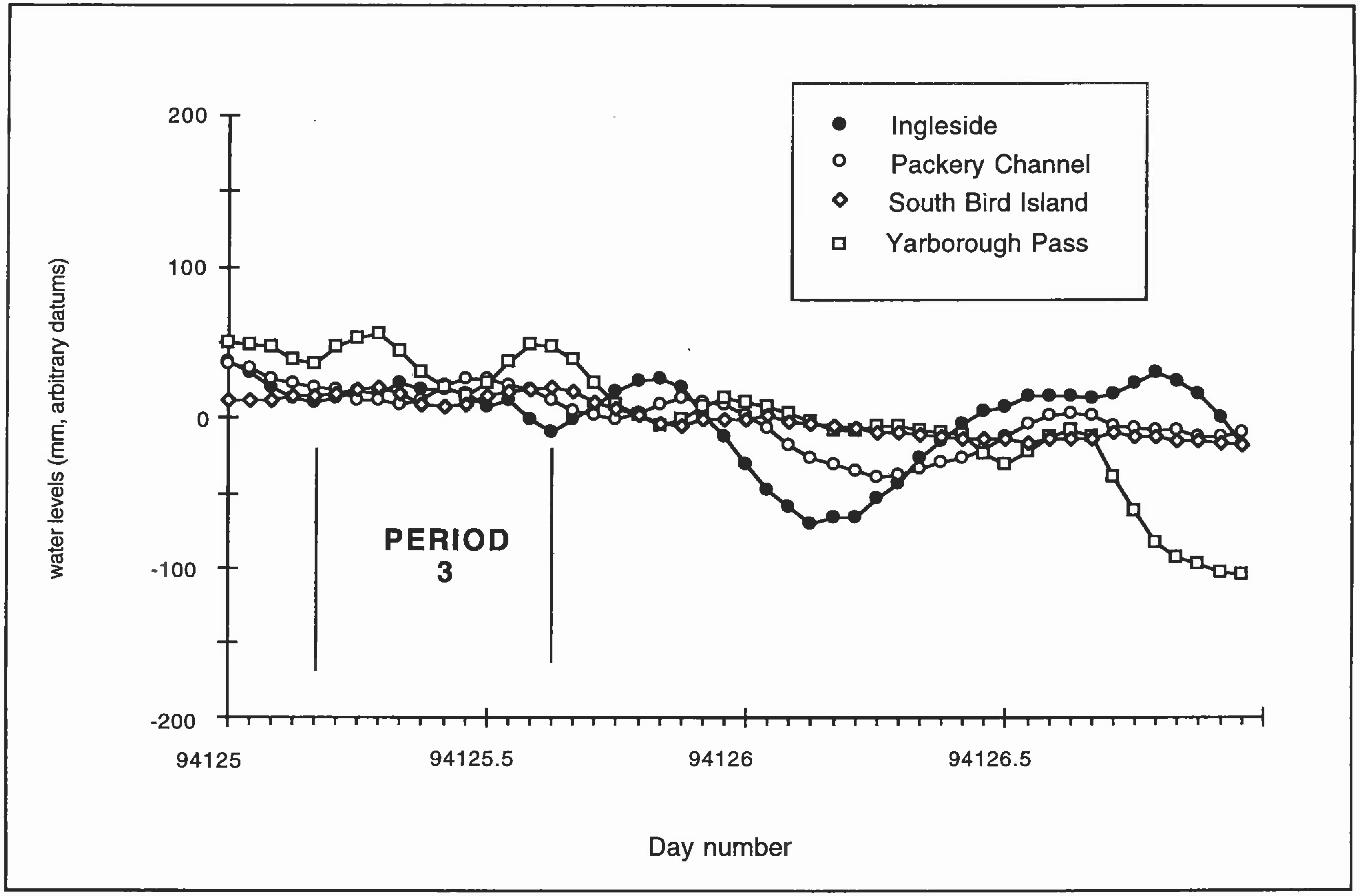


Figure C-9. Water levels and leveling period 3, lower bays

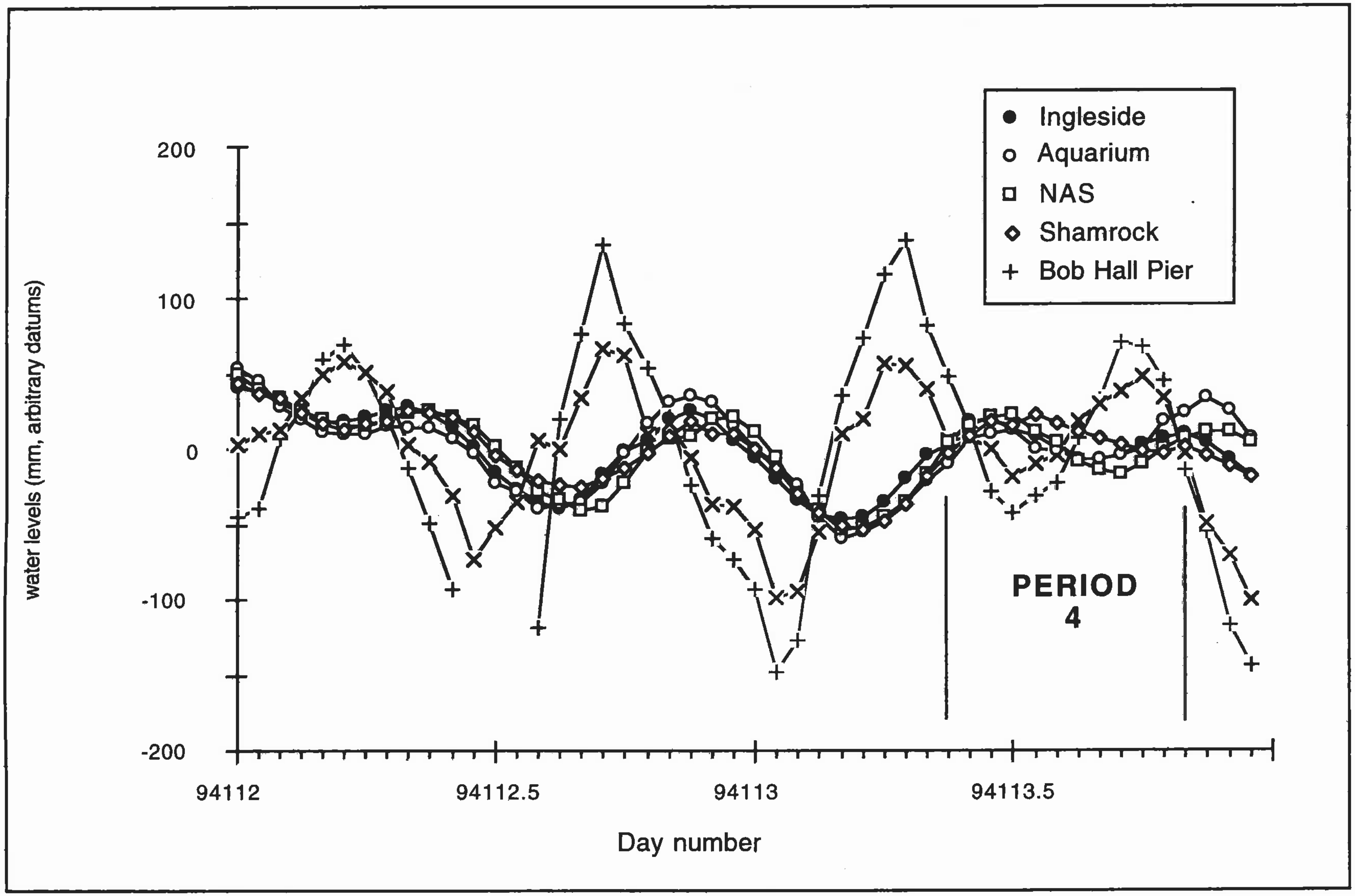


Figure C-10. Water levels and leveling period 4, Corpus Christi Bay

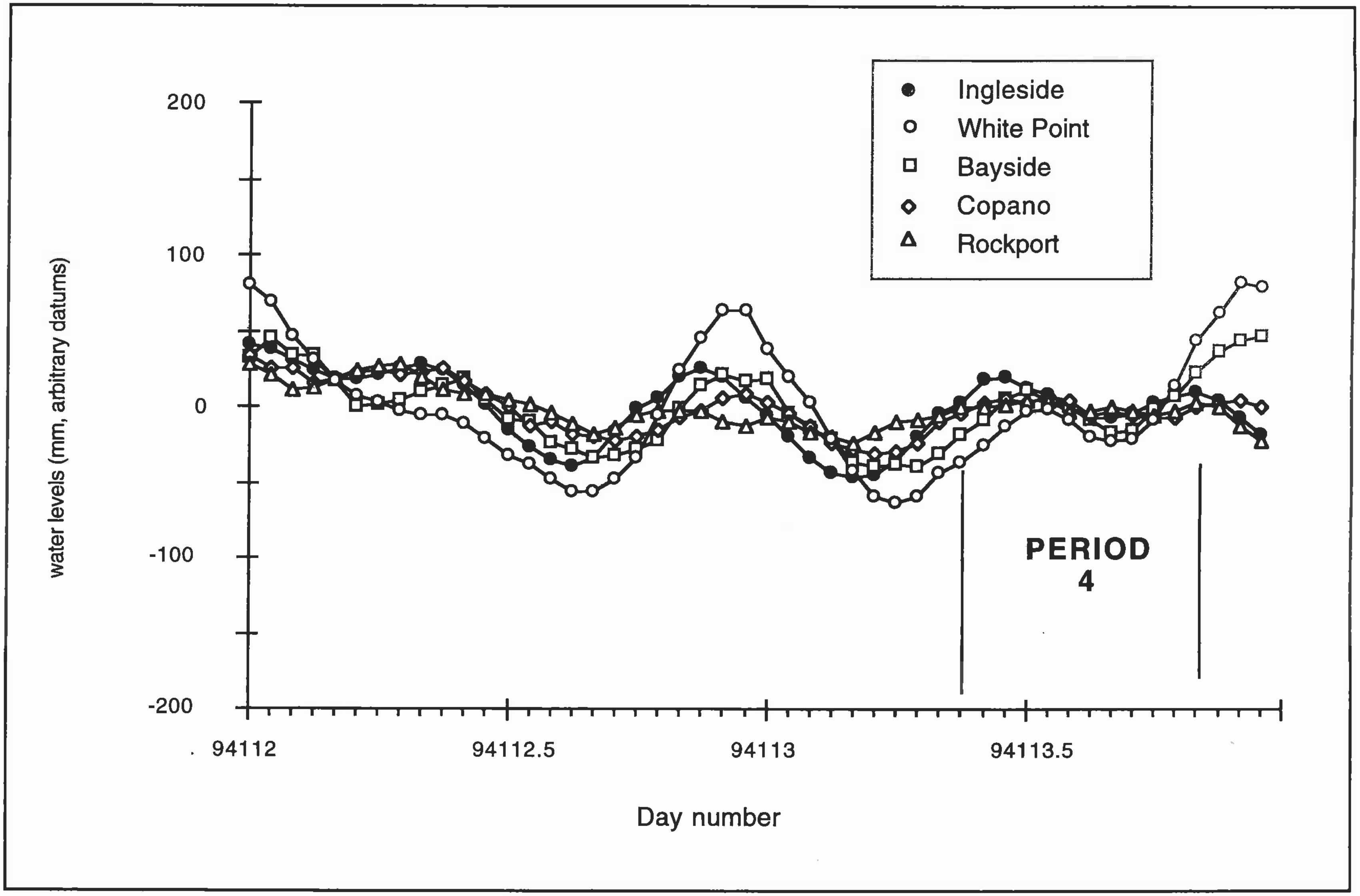


Figure C-11. Water levels and leveling period 4, upper bays

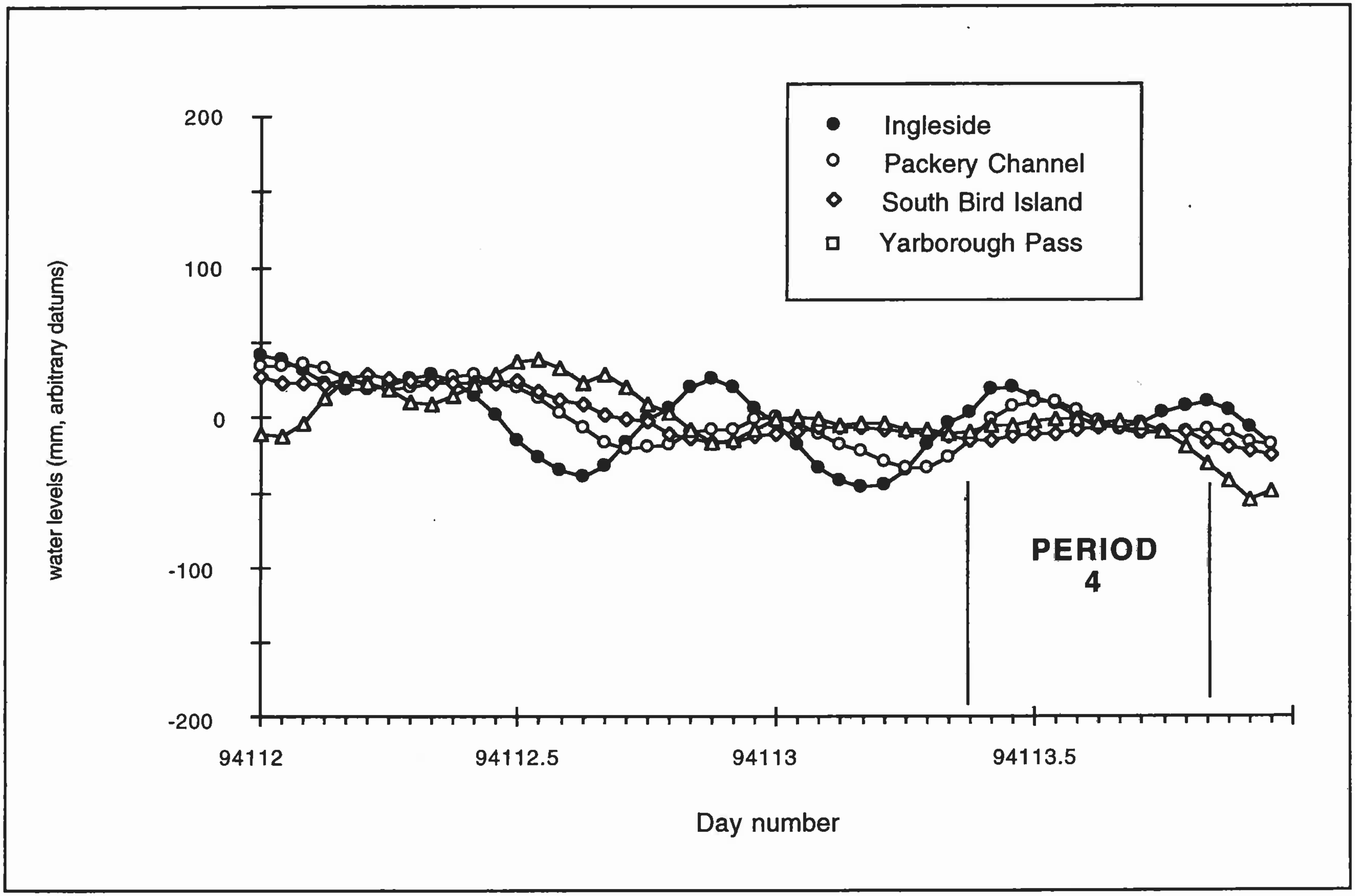


Figure C-12. Water levels and leveling period 4, lower bays

APPENDIX D

HYDROMECHANICS OF A CONNECTING CHANNEL TO A BAY

Consider a small bay in communication with a much larger reservoir through a small channel of uniform cross section. That the reservoir is "much larger" means that the exchange of water volume with the bay does not affect the water level in the reservoir. That the bay is "small" means that it is sufficiently deep in comparison to its surface area that its water surface can be considered to be level throughout. The water level of the reservoir is assumed to vary with time t according to some specified function F(t). This is a conceptual model of a stilling well communicating to a large body of water (the "reservoir") whose surface is disrupted by waves, of a coastal embayment connected with an inlet to the sea (the "reservoir"), and to a smaller embayment connected to a larger. We want to know how the flow through the connecting channel and the water level inside the bay will respond to the driving water level F(t).

The equation of motion for flow in the channel, in which u denotes the cross-sectional mean current, is:

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}\frac{1}{2}\overline{u^2} = -g\frac{\partial h}{\partial x} + \frac{1}{D}\frac{\tau}{\rho}$$

where the overbar denotes a section mean, D is the water depth in the channel, x is measured from the reservoir to bay, τ is the stress on the bed, h(x) is the water level along the channel, and the remaining symbols have their usual meanings. The only assumptions introduced to obtain this equation are that the water is incompressible and homogeneous, and that the only stress operating is that on the channel bed. We use de Chézy's expression for bed stress, with coefficient C, i.e.,

$$\tau = -\rho g\ |u|\ u / C^2$$

(Recall that the frictional stress increases with *decreasing* values of C, unlike the case for Manning, Kutter, or Darcy-Weisbach coefficients.) Integrating this equation from the reservoir x_0 to the bay x_1, where $\Delta x = x_1 - x_0$, gives:

$$\Delta x \frac{\partial u}{\partial t} = -\frac{1}{2}\left[\overline{u(x_1)^2} - \overline{u(x_o)^2}\right] - g\ (h_1 - h_o) - \frac{u\,|u|\,\Delta x}{DC^2}$$

where u now denotes the average value along the inlet, and the additional assumption has been made that the average τ can be computed from the average velocity u. So far, these simplifying assumptions do not undermine the approximation of the equation.

The left-hand term is the integrated local time tendency through the inlet. The second term on the right is basically a pressure gradient, or "head" gradient, giving the force (per unit mass) due to the difference in water level between bay and reservoir. The last term on the right represents the effect of frictional drag through the inlet. The first term on the right is inertial in origin, arising out of the field acceleration. It provides a contribution to the acceleration if (1) the distribution of current across the section is different at the two ends of the inlet, or (2) at a given instant the flow at one end differs from the flow at the other, i.e. there is a net storage or depletion within the inlet. This term is often referred to as "entrance" loss, though we must note that it is the *net* of "entrance" and "exit" losses.

In order to effect a solution of this equation, further—and more egregious—simplification is necessary. The single most troublesome term is the entrance loss, since to evaluate it rigorously requires the detailed distribution of current across the section. Harris and Bodine (1977) reversed the order of integration, i.e.

$$\overline{u(x_1)^2} - \overline{u(x_0)^2} \approx \overline{u(x_1)}^2 - \overline{u(x_0)}^2$$

so that if the inlet has a uniform area the difference becomes zero and the term drops out. Sometimes the entrance/exit loss term is represented as a coefficient multiplying $u^2/2g$ (e.g., Escoffier, 1977; Keulegan's 1967 definition of a repletion coefficient can be shown to be closely related), in analogy to the conventional expression in hydraulics of conduit losses from expansions or contractions. This can be incorporated into the drag term by adding a loss coefficient to C^2 in the denominator (Escoffier, 1977), but there is very little data from tidal inlets to justify such a formulation. Moreover, the analogy to hydraulics would suggest a range of coefficient K from 0.05 to 100 (e.g., Bober and Kenyon, 1980), depending upon the detail of the inlet structure, unlike the suggestion of Escoffier (1977) that the "uncertain" coefficient ranges around unity.

The essential feature of this entrance-loss term is the possibility it introduces for asymmetry in acceleration through the inlet depending upon the direction of flow. Both of the approximations just noted (Harris and Bodine, 1977, Escoffier, 1977) render the term *symmetric*: it will reverse sign but have the same value when the current reverses direction.

Even if the entrance loss term is neglected, the equation still does not admit an analytical solution. Other possible simplifications are to treat a steady-state flow, i.e. drop the time tendency term, on the argument that (apart from the period around the reversal of current) the current equilibrates to the head difference Δh across the inlet, or to drop the nonlinear frictional drag, assuming in effect an inviscid flow. For the steady-state problem, the equation reduces to the de Chézy relation equating head loss Δh to drag, which can be reformulated as Manning's equation. This approximation has increasing validity as the length of the inlet Δx increases, because frictional drag plays an increasingly important rôle. Brown (1928) used this approach with de Chézy stress formulation to derive elegant expressions for tidal amplitude in the bay and tidal prism of the inlet.

If both of these assumptions are applied, the section-mean equation becomes overconstrained. However, since a steady, inviscid flow is thereby assumed, one can fall back to the primitive three-dimensional momentum equation, which reduces to Bernoulli's equation for these conditions. All streamlines originate (or terminate) on the surface of the bay and pass through the inlet. Bernoulli's equation can be evaluated directly, therefore, between these two points, the inlet velocity being given by $u = \sqrt{[2g(h_o-h_1)]}$. Harris (1900) used this method to analyze inlet behavior as a part of his comprehensive treatise on tides. There is a logical flaw, however. While every streamline passes from the surface of the bay through the inlet, not every point of the inlet lies on a streamline, i.e. there may be dead areas or recirculating areas. The entire streamtube emanating from the bay and passing through the inlet must be considered. The discharge at the end of the inlet is the product of velocity times the cross section area of this streamtube, that is, $u A_c$. This area cannot be determined by simple *a priori* analysis, but must be determined empirically. For several inlets it has been found that $A_c/A < 1$, i.e. the exiting current is contracted. This ratio, the contraction coefficient, is analogous to the elementary hydraulic problem of gravity flow from a tank through a small opening, in which the area of the emanating flow at the *vena contracta* is substantially less than the cross section of the opening. This, again, is the manifestation of an exit loss, and illustrates that such a loss is an inertial, not a frictional, phenomenon.

With a conventional Bernoulli-type entrance-loss term, the one-dimensional momentum equation becomes:

$$\frac{\partial u}{\partial t} = -\frac{g}{\Delta x} h_1 - \frac{g\,u|u|}{DC^2} - \left(K_{in}\frac{1}{2}[\mathrm{sgn}(u)+1] + K_{out}\frac{1}{2}[\mathrm{sgn}(u)-1]\right)\frac{u|u|}{2\,\Delta x} + \frac{g}{\Delta x}F(t)$$

The sign convention is positive from reservoir (the ocean) to bay, so the loss coefficient K_{in} applies on the flood and K_{out} on the ebb. This formulation preserves the possibility of asymmetry in the entrance/exit loss term. The reservoir level $h_o(t)$ has been specified as the time function $F(t)$. To close the equation, h_1 is related to u by the following,

$$\frac{\partial h_1}{\partial t} = \varepsilon\, u(t)$$

where ε is the ratio of the cross sectional area of the inlet to the surface area of the bay. This equation, a version of the integrated continuity equation, invokes the assumption that the water surface elevation is level within the bay.

These coupled equations were solved by finite-difference time integration, using a second-order Adams-Bashforth scheme for the lefthand-side time derivative of the momentum equation, and a forward timestep for the continuity equation. This scheme is conditionally stable, and is known to have good accuracy for moderately nonlinear differential equations, as well as to be fairly effective in controlling nonlinear instabilities. This solution was coded in the executable EXHIBIT1, whose operation is described in Section 4.2 and in Appendix A.

While the complete momentum equation, with its full time variation and nonlinearity, is not capable of analytical solution, some insight into the implicit physics can be obtained from a linearized version of the equation. The nonlinear terms are replaced by a single "friction factor," which is rigorously a function of u, i.e.

$$\frac{\partial u}{\partial t} = -\frac{g}{\Delta x} h_1 - f u + \frac{g}{\Delta x} F(t)$$

$$f \equiv \frac{g\,|u|}{DC^2} + \left(K_{in}\frac{1}{2}[\mathrm{sgn}(u) + 1] + K_{out}\frac{1}{2}[\mathrm{sgn}(u) - 1]\right)\frac{|u|}{2\,\Delta x}$$

but we assume it to be a constant. Differentiating once and substituting the continuity equation result in the linear differential equation:

$$\frac{\partial^2 u}{\partial t^2} + f\frac{\partial u}{\partial t} + \frac{g\,\varepsilon}{\Delta x} u = \frac{g}{\Delta x} F'(t)$$

If this is driven by a periodic signal, $F(t) = H_0 \cos \omega t$, say, then the solution will be made up of a transient part that decays in time, and an equilibrium part of period $2\pi/\omega$. (See Baines, 1958, for a different but similar treatment.) Sparing the reader the arithmetic, the amplitude of the periodic part of the solution for water elevation in the bay is:

$$h_1 = \frac{g\,\varepsilon\,H_0}{\Delta x} \frac{1}{\sqrt{(\omega^2 - g\varepsilon/\Delta x)^2 + (f\omega)^2}}$$

so that the ratio of the amplitude inside the bay to that in the reservoir (the ocean) is:

$$\frac{g\,\varepsilon\,/\Delta x}{\sqrt{(\omega^2 - g\varepsilon/\Delta x)^2 + (f\omega)^2}}$$

This means that when the drag term—friction plus entrance/exit loss—becomes large enough to affect the exchange of water through the inlet, the inlet will act as a low-pass filter, passing the longer period motions through to affect water-level response of the bay, but filtering out the shorter period motions. This is precisely how a stilling well operates, filtering out the shorter-period surface waves but passing through the longer-period variations in water level.

APPENDIX E

WAS THE REACTION BREAKWATER (NORTH JETTY) A SUCCESS?

Background

In Chapter 3, the development of improvements at Aransas Pass was recounted. An important aspect of this was the design and construction of the Haupt jetty, which is now incorporated into the North Jetty of the inlet, and whose unusual shape is an identifying feature of Aransas Pass. Performance of the reaction breakwater has to be evaluated in the context of physical knowledge and political conflicts of its time.

In the main text (Section 3.1.1), the history of this project is outlined, primarily with respect to its physical modifications of the inlet. To summarize, the project began on the drawing board in 1895, when Brewster Cameron of the Port Aransas Harbor Company solicited a proposal from two consulting engineers, Haupt and Ripley, who were on the three-member Board of Consulting Engineers convened earlier to review work at the Pass. Haupt was an eminent coastal engineer with considerable experience in inlets and harbors. Ripley was a Corps veteran with two decades of experience on the Texas coast, and a familiarity with navigation projects around the world. The Harbor Company was working under the constraint that it had to achieve 20 ft over the bar by 1899 or its rights would revert to the federal government. (Although the Corps had a plan for a pair of straight jetties on the books since 1887, in fact work at Aransas had been virtually abandoned by the government, after the failures of the Nelson and Mansfield jetties.)

The Harbor Company began work on the first part of the project in August 1895, attaining about a 13 ft controlling depth over the bar as the work progressed. The foundations of the old Mansfield jetty were discovered, and prevented any further deepening of the channel. Though construction on the north jetty was continued, the old government jetty continued to be a problem. In winter of 1896, a 500-ft breach was blasted out, but much of the old jetty remained. The status of the inlet jetty constructions as of 1897 were shown in Figs. 3-3 and 3-4 of the text. Having failed to achieve the 20 ft controlling depth, the Harbor Company relinquished its rights to the government in 1899. In 1897 the Board of Engineers had declared the north jetty to have no value to the government (see Haupt, 1901b):

> There does not seem to be any probability that the jetty as now constructed will of itself secure and maintain any considerable increase of depths in a navigable channel of proper width. The Board is of the opinion that the value to the Government of the works for the improvement of Aransas Pass is nothing.

The Corps revised its existing two-jetty plan to incorporate the Haupt breakwater into a north jetty, while adding a straight south jetty.

Congress, however, in 1902 authorized only removal of the old Mansfield jetty, work on which progressed through 1904, then resumed from 1911 to 1915. Congress also directed the Corps to complete construction of the Haupt jetty as originally designed, which was completed in 1906. Almost immediately, in 1907 (Haupt, 1910), the Corps declared the channel to be deteriorating, noting that "a secondary channel, 600 feet wide and 6 feet deep, broke through the gap between jetty and shore with the result that for all practical purposes the channel was on the north side of the jetty instead of the south side, as intended... " (USCE, 1912). The north jetty was tied to St. Joseph's Island in 1909. At the same time, the south jetty was begun.

Fig. E-1 displays bathymetric charts compiled from Harbor Company, USC&GS, and Corps of Engineers surveys from 1895 to 1904, after the government assumed responsibility for the Pass (from Gillette, 1904b). See also the charts shown in the main text. Haupt's own assessment of the status of the jetty in 1904 is shown in Fig. E-2. In the main text, Fig. 3-5 shows the status of Aransas Pass in 1909. Note especially the passage marked "Flood Channel."

Was the reaction breakwater successful? Engineering evaluations at the time ranged from expansive to vitriolic. Symons (1899), based upon Haupt's (1899) paper, stated "Professor Haupt and all concerned are to be congratulated on the results obtained at Aransas Pass." Le Baron (1900) said, "... the jetty at Aransas Pass has proved a success in securing deeper water... ." Ripley (1901) referred to its "remarkable results." Haupt (1901a) declared it a "pronounced success," and quoted from the report on an 1899 survey by the USC&GS that, "...ever since its construction there has been a marked increase in the depth of water on the bar." Of course, Haupt and Ripley were on the Board of Consulting Engineers for Aransas Pass (along with Wisner), which conceived the project, so they were hardly independent reviewers. Cameron (1898), who convened the Board, agreed it was successful, but was more pointed:

> As already stated, it failed [to achieve the predicted 15 ft depth at the completion of the first part of the work] solely because of the obstructing Government jetty, which had been officially reported as having long since disappeared. Certainly, if there is anyone to blame for failure it would seem to be the United States engineers for not correctly reporting the facts as to the existence of the old jetty, and for taking advantage of this neglect to remove the obstruction erected by them, to condemn the reaction breakwater.

Corthell (1899), the project engineer for the Corps two-jetty design and Eads' right-hand man on the Mississippi jetties project, was skeptical, believing twin, straight, parallel jetties would function better. Gillette (1904a) flatly stated, "Very little improvement of the bar has resulted... ."

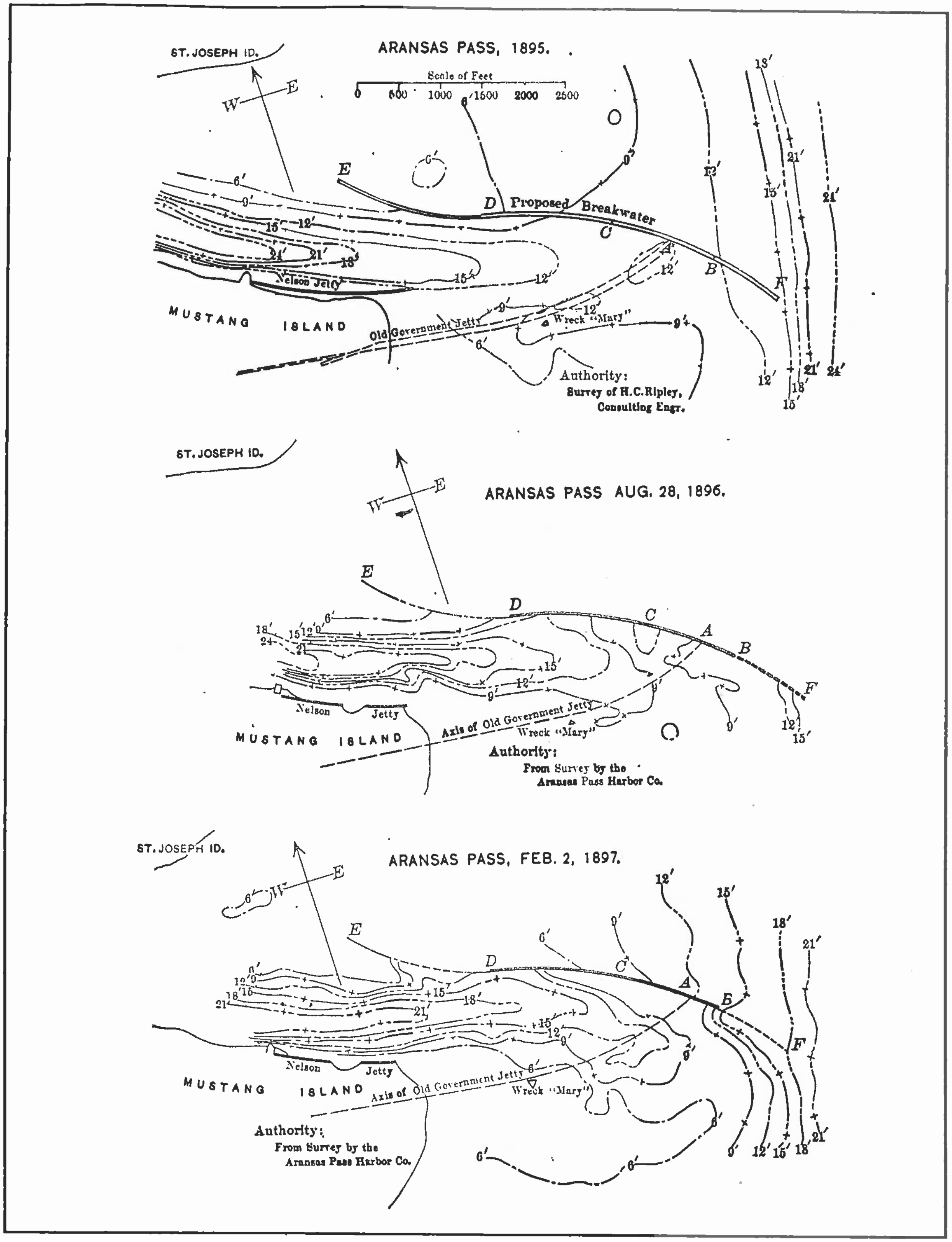


Figure E-1. Successive bathymetric surveys at Aransas Pass 1895-1904, from Gillette (1904b)

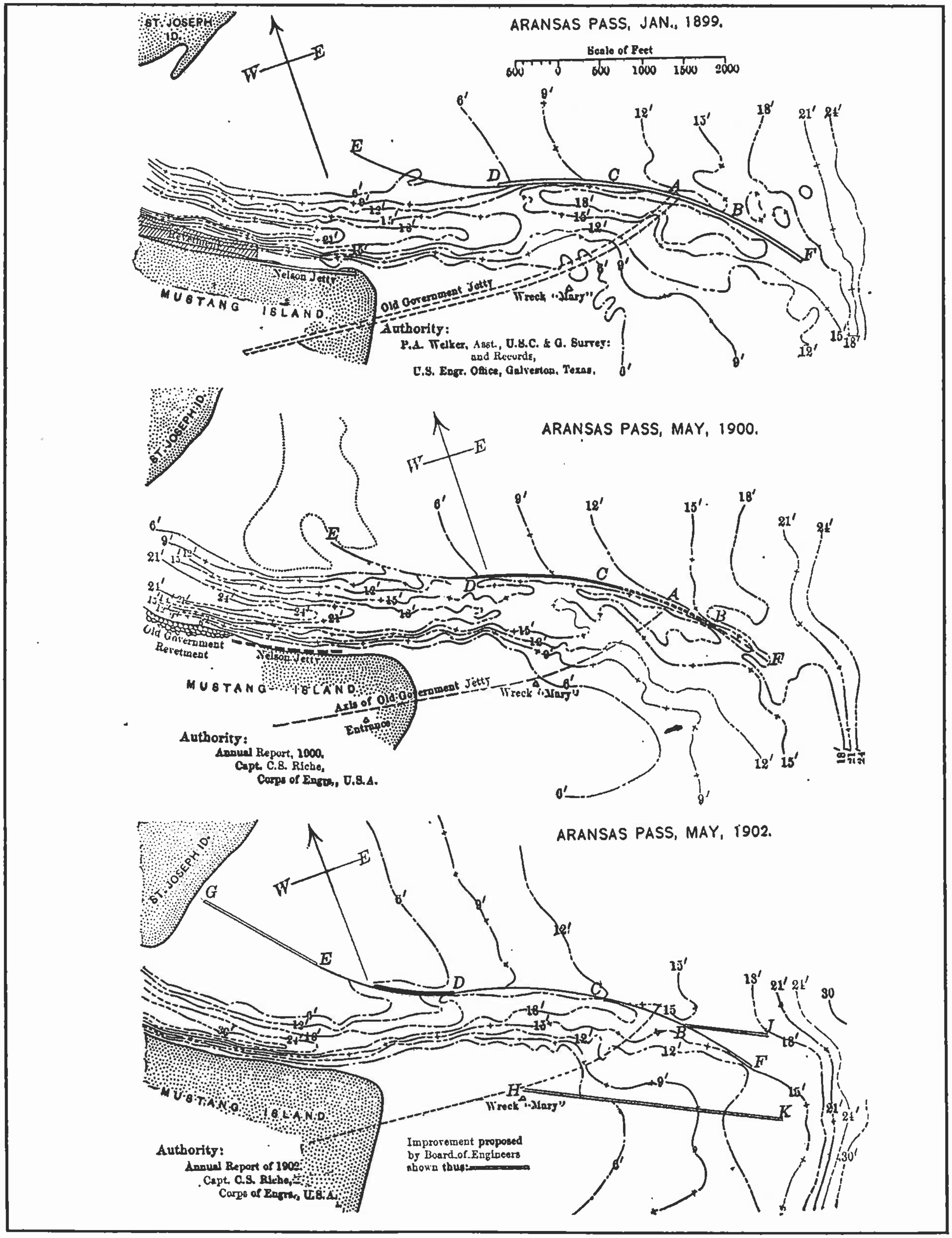


Figure E-1. (continued)

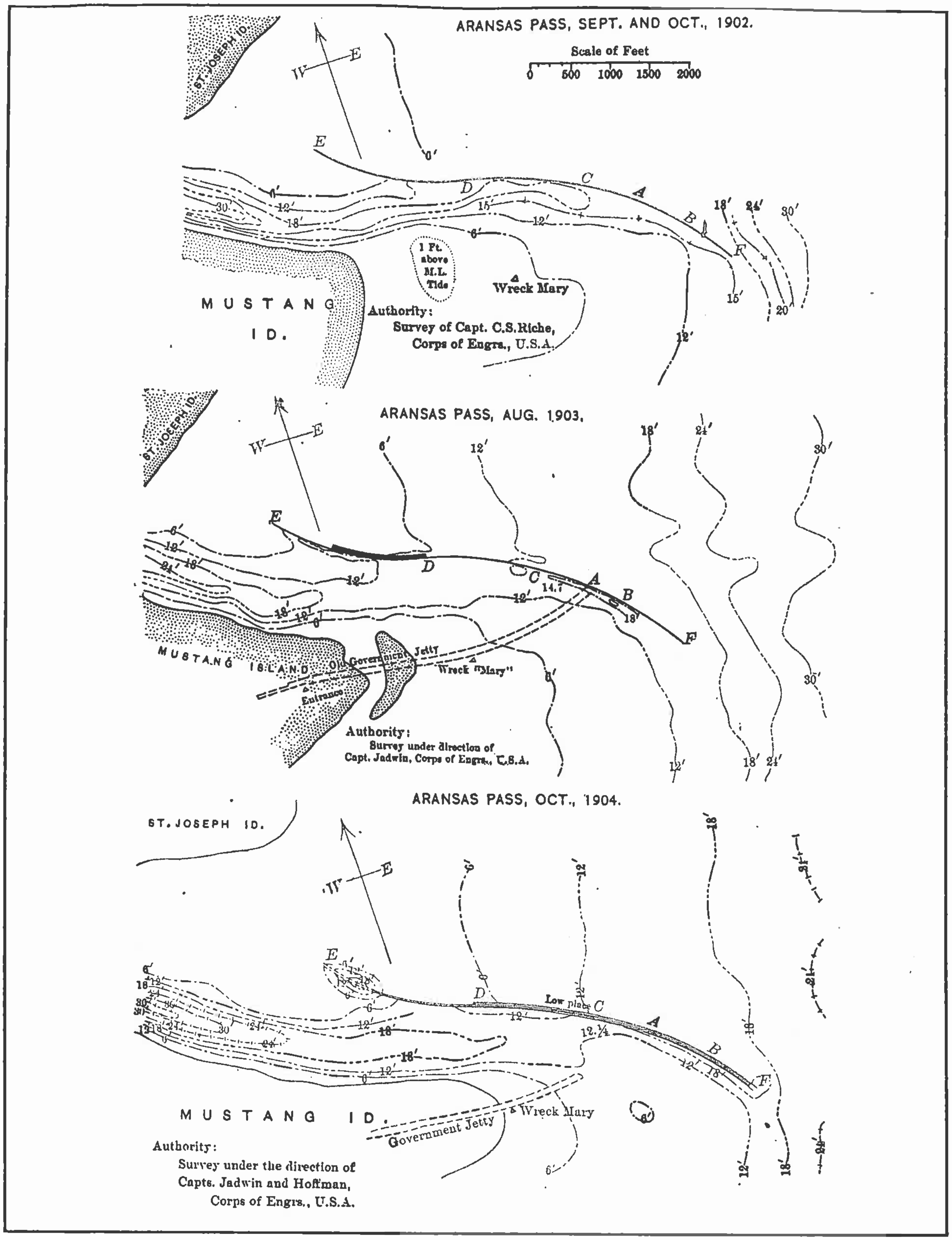


Figure E-1. (concluded)

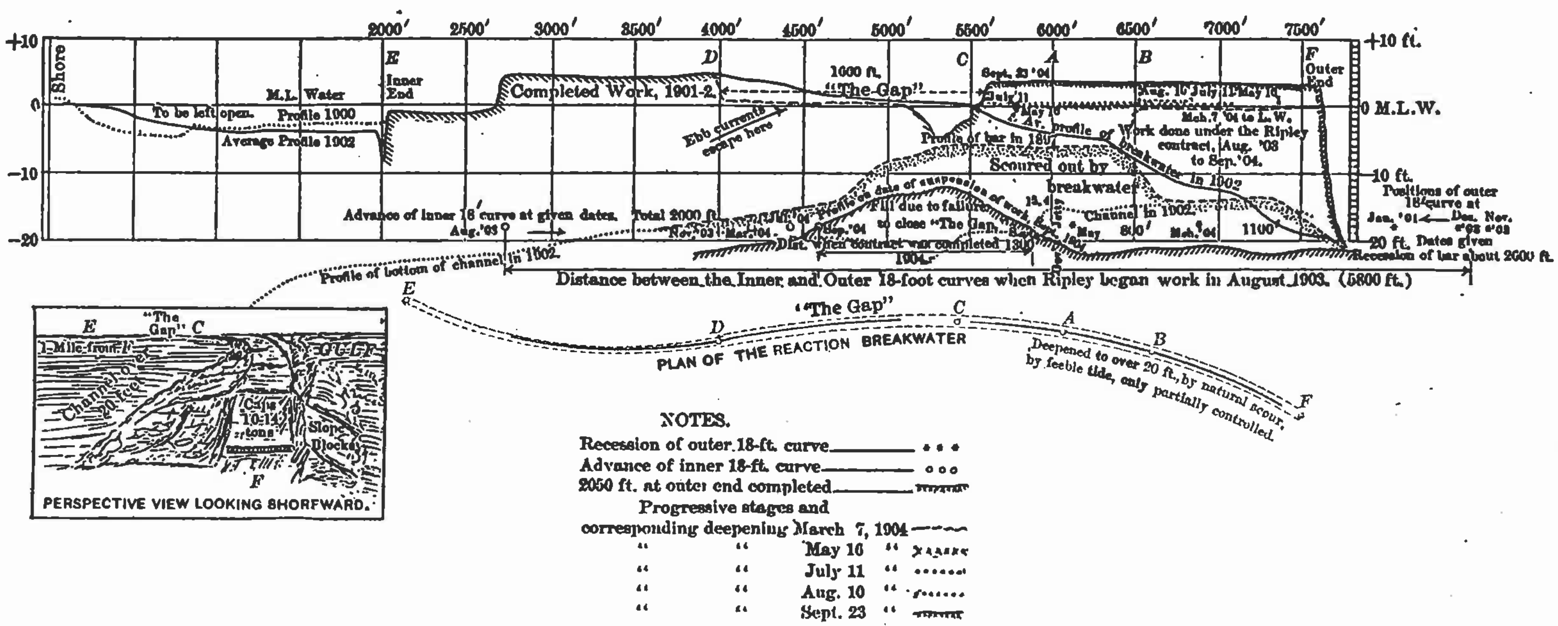


Figure E-2. Status of North Jetty construction in 1904, from Haupt (1904)

Basis for the design

The principal features of the reaction breakwater, as theorized by Haupt (1888), and designed by Haupt and Ripley (1895) were:

- an isolated, single barrier set on the updrift ("windward") side of the inlet
- concave toward the tidal channel in its outer end
- detached from the shore, by a gap of over 1500 ft
- elevation of the structure above high water, so no loss of flow over the structure would occur

The theory was that such a structure would obviate a second "leeward" jetty, thereby halving construction costs, that the detachment gap would permit full entrance of the flood tide into the bay, while the ebb current would be directed to the south of the breakwater thereby preserving its scouring capability, and the concavity would enhance scour of the channel by the ebb current. Other minor design features included the reverse curvature on the landward section of the jetty, which was intended to assure focusing of the ebb current to the south of the breakwater, and positioning of the breakwater itself along the windward shoal of the ebb bar paralleling the curvature of the natural channel.

The central design feature was the curvature of the breakwater concave to the bar channel. This was supposed to enhance the scouring ability of the ebb current by the "reaction" effect, which referred to the increased scour due to lateral impingement of the current, analogous to bank cutting on the outer side of a river channel bend. The mechanics of this process were, at best, obscure, and a matter of debate concerning the attributes of the reaction breakwater.

Haupt's (1888) original description of the process of bar formation and tidal inlet maintenance is diffuse, notwithstanding the view from a century later, replete with phrases such as:

> ...if the flood pressure and movement is from the south side of the entrance the channel will be to the north, as the banks will be more extensive on the former side, offering greater resistance and deflecting the ebb stream and crowding it in until it is supported on its opposite flank by the shore.
>
> The effect of this racing of the waves in search of an escape from the pressure of the flood tide is to scour off and prolong the sharper lip at the gorge and to flatten out and beat back the opposite shore, thus shifting the position of the "inlet" ...
>
> A typical plan for a breakwater ... would be one composed of curves whose cusps are pointed in the direction of the advancing flood resultant, and having an inshore flank to concentrate the flood upon the beach channel, where it is both possible and desirable to maintain

> one. The curves should have the semi-conjugate diameters equal to about one-fourth (1/4) of the transverse.

The original "theory" made much of the direction of the tidal flood wave, the so-called flood resultant, and the sketches of proposed breakwaters were, in fact, convex to the channel. Over the next few years, Haupt's concept evolved (one might even say reversed) to emphasize more the direction of wave attack and littoral drift, and reverse the curvature of the breakwater. Still, the physics were obscure: "It aims to utilize the well-known centrifugal force by the reaction developed by the resistance caused by a continuous change of direction so often manifested in the concave bends of streams, instead of the principle of concentration which has been relied upon so largely in the system of twin or convergent jetties, with such meager results. ... Manifestly, it is not velocity, therefore, that constitutes the working force to produce scour, but reaction ..." (Haupt, 1899). Some of this was an attempt on his part to retrofit his earlier work to conform to his later view. For example, he asserted that the phrase "flood component" really included the effect of surf as well as tidal propagation (Haupt, 1889), which only further obfuscated the discussion.

Other engineers of the time had difficulty with Haupt's descriptions. Gillette (1904b), apparently with tongue in cheek, commented "Professor Haupt claims that these waves are the offspring of the flood tide, and the above paragraph would indicate a desire to escape from their parent, but neither the method of their origin nor the cause of the desire are explained." Corthell (1899) who demonstrated that he was a far better engineer than a biologist when he characterized the Aransas breakwater as a "single-legged, worm jetty", said, "The terms used and the words coined by the author are not entirely understood by the writer, and he may not be correct in translating them into common language. ... The entirely new idea that 'it is not velocity ... but reaction' is so entirely opposed to all accepted ideas of river and harbor engineers and their experience, that it is difficult to understand." Harts (1901b) described Haupt's theory simply as "... the peculiar theory of erosion by 'impact' or 'reaction.'"

Ripley (1899) attempted to clarify, stating that a curved breakwater or jetty employs two principles:

> *First*.— That of reaction, by means of which, water, constrained to flow in a curve, excavates and maintains a greater cross-sectional area of channel than when flowing in a straight course... .
>
> *Second*.— That of centrifugal force, by which the particles of flowing water tend to hug the concave side of a channel. This principle makes it possible, by means of a single curved structure, to concentrate the ebbing waters of a tidal harbor... .

He also cited examples from European practice dating back three-quarters of a century of using curved jetties.

Despite Haupt's assertions that the breakwater "is composed of curves whose radii and centers are adjusted to the site in such manner as to cause deposits on the outer side of the structure, thus re-enforcing it, and scour on the inner side, where an excess of foundation material revets the slope..." (Haupt, 1899), nowhere does he explicate his methods. At most he provided general statements, such as (Haupt, 1900), "the success or failure of the engineer depends upon a proper adjustment of his radii to the local conditions; if too short, the channel will be too deep and narrow, and *vice versa*. The happy medium which is best adapted to all stages must be determined."

Contemporary evaluations

Some engineers argued the "theory" of the jetty, regardless of its performance. A matter of debate was the wisdom of detaching the jetty from the shore. Haupt's theory was based on admitting as much of the tidal inflow on the flood as possible, which he believed would be affected by the considerably reduced flow cross section of jetties connected to the land. Many disagreed, including Le Baron (1900), "An opening through which the flood tide can enter permits more or less of the ebb tide to go out, and by just that much we lose scouring power in the ship channel, and are likely to set up a dangerous scour in the subsidiary channel, which may endanger the stability of the works, or bring an undesirable amount of sand into the harbor." Corthell (1899) dismissed it as "of only theoretical advantage, and the writer believes it to be a positive, practical disadvantage."

The tidal current channel that developed in the detachment gap, labeled "Flood Channel" in Fig. 3-3, which the Corps was quick to criticize, in fact was part of the design. The breakwater was intended to "freely admit the full tidal prism during the entire period of flood tide, that there might be no reduction of volume at ebb; consequently it was detached from shore, there being a gap of nearly 1 800 ft left open at the inner end" (Haupt, 1899). The key to whether this was functioning incorrectly was if the ebb current was also escaping through this channel, on which the Corps did not comment. Pitts (1899) reported on conditions at the Pass at that time:

> The purpose of the opening left from E to G [landward terminus to St. Joseph Island], was to give a greater width of flood tide entrance, and the speaker believes that it is of material value for that purpose. It is true that a considerable quantity of water is lost through G-E during ebb discharge, but here again the water is thrown against the Mustang Island shore by centrifugal force, and the loss is limited to a surface one only. This is proven to the speaker's satisfaction by the fact that since September, 1896, when the foundation was completed to E, and the jetty from D to E was brought to a partially effective condition, there has been no tendency to scour in this opening; in fact, the depths have decreased somewhat.

Unfortunately, no depths are given by Pitts, but the description sounds much like the flanking channel that led the Corps in 1907 to declare the pass as "deteriorating." In later years, Ripley considered the detachment gap to be less important than the curve of the jetty itself and the procedure by which it was constructed (i.e., from the sea toward the inlet), see Ripley (1924).

A curious part of this debate centered on whether the jetty was "windward" or "leeward," i.e. its relation to the prevailing winds and associated littoral drift. Corthell (1899) noted that no data had been presented to demonstrate that the "windward" side is the north and east side. His recollection was "that the preponderance of winds is from the south and west, and that the winds and the currents are up the coast during most of the year." Schweitzer (1898), in an eccentric paper replete with errors of fact, made specific mention of Aransas Pass, stating that he had determined "long before" that the littoral current was from the south. (Schweitzer performed the 1888 survey of Aransas Pass under contract to the Corps of Engineers that concluded the government jetty had disappeared.)

Gillette (1904a) wrote, "...the sand drift, while moderate in quantity, is undoubtedly to the north in the aggregate, and seems to be so in detail, seldom or never moving to the south." With respect to the historical southern movement of the inlet, he remarked, "... occasionally one will drift against it [sand drift] owing to peculiar conditions. Thus, at Aransas Pass, Texas, the entrance has moved south a long distance against the resultant drift, and work is now going on there, on the theory that the drift is from the north, whereas it appears to be distinctly from the south."

This ignored earlier statements to the contrary by experienced workers. Kastl (1898) stated, "During the four years, 1888 to 1891 inclusive, the writer was connected with the Brazos River Harbor Improvement, in Texas, as Principal Assistant Engineer and Engineer, and with the Tampico Harbor Improvement, in Mexico, as First Assistant Engineer. His observations were that the resultant direction of the littoral currents on the Gulf coast is southwestward at the mouth of the Brazos, and southward at Tampico. These currents are sand-bearing." Wisner (1899) commented that "On the Gulf Coast, the resultant of the littoral current is from the northeast to the southwest." Le Baron (1900) said, "The reason the [Haupt] jetty has succeeded and the Government jetty failed is, in the writer's opinion, entirely due to its location... as the main thing in this case was to protect the channel from the encroaching sands to windward." The most compelling case was presented by Ripley (1898) presenting wind data from Galveston and distilling his quarter-century experience on the Texas coast. This, too, was ignored by Gillette.

Haupt (1904) rebutted Gillette by the empirical observation of the failure of the Government jetty because it collected sand on the north side. He also noted that if the drift is from the northeast, the present jetty should evidence deposition on its upcoast side and increased depths on the channel side, both of which have occurred. (In the process of this remark, with respect to the north jetty, Haupt added, "now adopted by Congress and nearly completed," which was irrelevant to the argument but served to rub salt in the wound of the Corps.) He quoted an 1899 report of the U.S. Coast Survey Officer stating that the drift of sand was from northeast to southwest. Haupt continued, "Moreover, if the drift be due to the prevailing winds, it will be found far more reliable to trust to the physical record on the site, which is the result of centuries, than to go to the register of any Bureau and attempt to formulate their observations," in evidence of which he included a photograph of the famous wind-sculpted oaks at Rockport, stating that the "view is looking south-southwest, which is about at right angles to the axis of the foliage, thus indicating a strong east-southeasterly wind."

Gillette (1904b) responded that the movement of the inlet contrary to the direction of drift was "... being caused by the driving of the water out of the inner lagoons by fierce 'Northers,' a type of wind almost peculiar to that coast." He presented the analysis of one year of wind data at Corpus showing a prominent southeasterly resultant, about 14° south of the perpendicular to the coastline. (This was fallacious since it was based upon wind direction reported to only the eight principal points of the compass, i.e. to the nearest 45°, hence could not resolve a small departure—either positive or negative—from the coastline normal.) He was clearly unimpressed by Haupt's argument, and snorted, "The only evidence produced by Professor Haupt, to support his claim of a sand drift from the north, are the movement of the entrance and a photograph of some vegetation." His evaluation of the performance of the jetty remained based on the supposition that the drift was to the north.

To close his case, Gillette (1904b) performed a sand budget for subareas north and south of the jetty based upon surveys between 1895 and 1904, presented in his paper (and compiled in Fig. E-1 above). The entire area north of the jetty was one subarea, but excluded data inside the 6-ft contour (where much of the littoral accumulation would have been expected). For this subarea, he asserted that it exhibited net scour for the 1895-1904 period of nearly 2,000,000 cu yds. He reports over 600,000 cu yds for the subinterval 1900-1902 alone. A comparison of the 1900 and 1902 contour charts discloses nothing like the reported scour; indeed, within the accuracy of the soundings, apart from some minor changes immediately adjacent to the jetties, the charts appear identical. The 1895-1904 value is likewise a misrepresentation, being driven by a prominent reduction in slope of the entire face of the bar to the shelf break between 1895 and 1897, which moved landward all of the contours lying seaward of the 9-ft isobath. If the surveys are accurate, this would have been a large-scale adjustment due in all likelihood to Gulf of Mexico hydrographic conditions, and not the minor construction of the north jetty.

Yet another matter of debate was whether it was really a single jetty, i.e., what was the true extent that the Nelson and the Mansfield jetty contributed to channel deepening. McKinstry (1901) considered the short, lee jetty (the Nelson jetty) to be essential in the performance of the Haupt jetty by blocking drift to the north. Gillette (1904b) drew the same conclusion, that whatever success the Haupt jetty had was due to the fact that there was a twin south jetty on the other side of the Pass. The pragmatic Ripley, writing two decades later (Ripley, 1924), stated with regard to the design of a single curved jetty, "If this last condition [that the outgoing current must meet the curve of the jetty tangentially] cannot be met, a short jetty on the opposite side of the channel should be placed so as to give the current the proper direction to meet the curve. In some cases, a short second jetty may be required in order to give stability to the gorge and to retard the entrance of sand during flood tide." There is little doubt that he had in mind the situation at Aransas Pass.

The political setting

There was more than just the pride of an engineer's design in Haupt's insistence that the project was a success, but an investment of years in finding a test for his idea of a Reaction Breakwater. He had submitted his plans to the Board of Engineers as early as 1888, the year after his patent was granted, and later requested of the Chief of Engineers permission to make "a demonstration, at a site to be agreed upon." He was ignored, and learned later, purely by accident, that a critical report had been made and circulated by the Board on his theory, stating that his views "...are unconfirmed by experience and contain nothing not already well know, which has a useful application in the improvement of our harbors." He prepared a response to the criticism, but still received no reply from the Board (Haupt, 1899). Thus, a private enterprise appeared to be the only means of testing his Reaction Breakwater. This was afforded by the Port Aransas Harbor Company. According to Haupt, the Aransas Pass experiment, "an admittedly difficult and unpromising location," was "the result of about 25 years of research and over 11 years of effort to secure a practical demonstration... ."

His reaction to the 1897 Corps plan to incorporate the incomplete breakwater into a pair of jetties with straight extensions to the shore and the sea was critical: he lampooned this as the "old-time method," which, if adopted, "would destroy the effective energy of the currents and prevent the completion of the demonstration of the principles which have been applied thus far at this entrance with unprecedented success, and would further involve an annual expense for maintenance, which is not now required." Haupt was well-known at Congress, having provided advice and testimony several times, and probably used this influence to have Congress intervene, directing the Corps to remove the old Mansfield jetty and leave the new breakwater jetty undisturbed, then, later, to complete the construction of the Haupt jetty to his full specifications.

Corthell was critical of the project; he brought credentials of working on many jetty projects around the world, and had designed the twin jetties of the Corps' 1887 plan (Corthell, 1899). Maj. Symons (1899), on behalf of the Corps, made the remarkable statement, noted in Section 3.1.1 of the text, that there was nothing new in the design and the Corps "have been building just such structures for years." He congratulated Haupt on the results but questioned whether they were permanent. Maj. Gillette (1904a) of the Corps dismissed the project rather perfunctorily, "Very little improvement of the bar has resulted ... ."

Ripley (1899), much more understated than Haupt, was still unequivocal in his judgement of the project as a success. Pitts (1899) commented, "The speaker believes the results so far obtained show that the curved jetty on the north side of the channel, which was designed by the author, would be amply sufficient to control and direct the current, if completed. ... The speaker does not believe that a straight jetty would serve the same purpose in this location... ."

Wisner (1899) was supportive, and took direct aim in the Corps in stating that they "...conceived the idea that works which had produced beneficial results at other harbors must necessarily be the proper remedy to apply. The result has been that millions of dollars have been expended on jetties which have been of absolutely no use, except to form breakwaters for the protection of dredged channels. ... In spite of these repeated failures, the 1897 Board of Engineers not only endorsed the 1888 project for jetties 2 000 ft apart at Aransas Pass, but condemned the unfinished curved jetty [the Haupt jetty] as worthless to the Government, and as an obstacle to future improvements, when their own published charts show beyond question that the results predicted for the enterprise would be realized at once upon the removal of the old curved jetty [the Mansfield jetty], which the predecessors of the Board located, unfortunately, on the wrong side of the Pass." After discussing various aspects of this and other sites, he once again fired a shot at the Corps, with respect to failure of the jetties at Cumberland Sound:

> ... the local engineer in charge of the improvement, recommended that the project for parallel jetties be abandoned, and that a single curved jetty be constructed on the north side of the entrance, to shut out the sand drift from the north and guide the tidal flow across the bar on the line best adapted for maintaining a channel with natural forces.
>
> The deadly wisdom of the engineer board, whose consideration of a few hours outweighs the conclusions of the resident engineer who gives years of study to the conditions, proved fatal to the project.

Published judgments of the success or failure of the breakwater therefore generally fell along civilian-military lines, the proponents among the former and the opponents among the latter. As noted earlier, Haupt, Wisner and Ripley made up the Board of Consulting Engineers for Aransas Pass, and Pitts was Assistant Engineer on the project. Thus vested interests existed on both sides. This conflict was doubtless exacerbated by Haupt's being snubbed by the Corps, and pressing his case with Congress.

In Maj. Gillette's (1904a) paper on seacoast harbors, he made the above-quoted, rather dismissive statement about the Port Aransas work. Haupt (1904) reacted with uncharacteristic vehemence, taking Gillette to task at length (14 pages) for inconsistencies in his paper and other published and unpublished works, as well as case-by-case examples of failed projects that the Corps had labelled as successes, noting in passing those reports to which he (Haupt) was "denied access." He recounted the cold reception by the Corps of his own ideas, for which, he added at every opportunity, he had been awarded the Magellenic Prize.

Maj. Gillette's discussion closure (1904b) ran 76 pages, nearly three times the length of the original paper, all but three pages of which dealt with Haupt, beginning with Haupt's letters to the Corps almost 20 years earlier. It seems that

Haupt had, at last, provoked the response from the Corps which he had been seeking for so long.

Maj. Gillette provided, in the course of this, a wealth of information on the Aransas project from the files of the Galveston Corps office, reviewed and cited earlier. He also—unfortunately—concentrated mainly on Haupt's early papers and his patent application for the Reaction Breakwater, which (as noted above) were obscure and vague, and in some respects erroneous, but here he found easy prey. A point-by-point discussion of Haupt's 1888 paper was given, in which Maj. Gillette acidly notes at the outset and the conclusion that this is the paper "for which he received the prize from the American Philosophical Society," and with respect to the Corps' unwillingness to consider these papers, "Certainly, if Professor Haupt has nothing better than the ideas shown in 'Physical Phenomena,' etc., and 'Dynamic Action,' etc., and Boards [of the Corps of Engineers] have refrained from presenting them to Congress, the time of Congress has been mercifully saved." He concluded:

> *First.*—That Professor Haupt's theories, promulgated in 1887-88, have little or nothing to do with his present "reaction breakwater" theory, and, in addition, are almost wholly erroneous.
>
> *Second.*— The "reaction breakwater" theory has never been practically tested.
>
> *Third.*— The theory is so palpably wrong as not to be worth such test.

The key word in each of these is "theory" and each of these conclusions is *prima facie* correct because of that word. However, Gillette gave relatively little attention to the more important question of whether the reaction jetty was actually working. He instead focused on the degree to which the jetty as designed conformed to Haupt's "theory." Also, many of the comments of Gillette had already been anticipated by Haupt (1901b).

Judgements

Many aspects of the arguments of Haupt and Gillette appear quaint to the modern engineer. But to appreciate the debate, one must recognize that coastal engineering a century ago represented a different culture entirely. Analytical methods were rarely used, equations were of little value being mainly limited to the discharge relation of de Chézy, Bernoulli's equation was practically unknown, and the viscous-stress formulations of Navier and Stokes would have smacked of science fiction. Engineers instead had to cultivate an intuition based upon accumulation of field experience and their own conceptual model of the processes.

The fact is that neither Haupt nor Gillette had a "theory" in the modern sense of the term with which the Aransas north jetty could be compared or validated. Much of Haupt's 1888 and 1889 exposition was conceptually wrong, such as the secondary rôle he assigned to windwaves and surf. Haupt was basically correct in recognizing that a pair of jetties could diminish the flood prism (what would be termed an "entrance loss" nowadays), but his attempt to explicate this by appealing to the direction of approach of the flood "wave" was flat wrong. Moreover, the long tidal periods and small amplitudes at Aransas would have rendered this effect unimportant anyway, so the detachment of the jetty was unnecessary. But Gillette was equally off base in embracing a view of littoral drift to the north at Aransas despite the observational evidence to the contrary. Ripley (1898) and Pitts (1899) were exactly correct in identifying the predominance of the southward component and in describing the equally important seasonal shift of drift.

Of course, both Haupt and Gillette, and the other protagonists on both sides of the debate, tended to polarize their positions in the charged atmosphere of competition between the private consulting engineers and the public military engineers. The military engineers viewed the consulting engineers as arrogant, inexperienced, and extravagant. The civilian engineers viewed the military as wasteful, inept and stubborn. This had recently come to a head in the confrontation with Eads regarding his works on the South Pass and his proposal for Galveston (see, e.g., Corthell, 1884, and the discussions of Merrill et al., 1886). Corthell (1884), whose allegiance was clearly with Eads, remarked in the *Transactions*, "... the Government should summon to its aid the best engineering talent within its reach, and should not give the general or exclusive charge of public improvements into the hands of engineers educated to conduct works of a totally different character," a statement barbed with enthymemes. Haupt had not been neutral on this debate, but had provided reports to Congress and in learned journals (e.g., Haupt, 1891) highly critical of the Corps. The friction between the two camps clearly exhibited itself in the Aransas Pass situation.

Ripley, whose long career spanned the transformation of coastal engineering to its modern form, addressed the question of bar deepening once more late in his life (Ripley, 1924):

> There are two methods of attacking the question of bar deepening, the deductive and inductive. Mr. Freeman regrets that the former method was not used in this paper, whereas the writer is firmly of the opinion that the latter method is the better one in the solution of these problems. ... The final plan for the improvement of the entrance at Aransas Pass, Texas, was designed by the inductive method. ... As regards the cut-and-error method referred to by Mr. Freeman, it may be stated that, by the inductive method, Nature performs this part of the operation and indicates exactly what results may be secured by the proper control of the forces available and the engineer is thus enabled to design a plan for the improvement with the utmost confidence of success.

This paper provoked a response from retired Brig. Gen. Davis, one of the veterans of the Aransas curved-reaction-jetty debate, who trotted out some of the same criticisms of the project used by Gillette, Black and others. In his reply, the consummate southern gentleman Maj. Henry Clay Ripley evidently could not resist one more shot at his old protagonists:

> Some years ago, an eminent engineer of extensive experience, likewise an able mathematician, studied this question by the deductive method. In accordance with his results, he designed plans for the improvement of the entrances to a number of important harbors, including Galveston, Tex., St. John's River, Florida, Cumberland Sound, Georgia and Florida, and Charleston, S.C. Several million dollars were expended in the execution of these works and yet in no single instance did the plan prove to be successful.

The more pertinent question with respect to Aransas Pass is, whatever the theory or design basis for the breakwater, did it succeed in clearing and maintaining a navigable channel? This question cannot be answered, because at no point in its existence, for a period of time sufficient to unequivocally determine the response of the channel contours to the breakwater, was the breakwater free of the influences of other constructions in the pass. The Mustang Island revetments, the Mansfield jetty and the Nelson jetty all antedated the Haupt jetty, and significantly affected the currents in the Pass. When the Haupt jetty was built up to specification, the foundation stones of the Government jetty remained affecting scour of the tidal channel. Before these stones were finally removed, construction had already begun on the modern south jetty, and the Haupt jetty had been tied to the shoreline. Maj. Gillette (1904b) himself concluded that "the breakwater, in connection with the other works at this place, acts simply as one of an imperfect pair of twin jetties," the second jetty being the combined structure of the Nelson jetty and the Government jetty. He argued, probably correctly, that the "south jetty" holds the current near the "reaction breakwater" and "... prevents the formation of a deep channel anywhere except near the breakwater." He also asserted, probably correctly, that without the revetment of Mustang Island, "the entrance would have long since traveled to the south and left the breakwater out of the problem."

The contours of the inlet from the time prior to the jetty extension project, see Fig. E-1, clearly indicate a talweg emerging from the inlet throat and approaching the breakwater, as its designers predicted. This was the demonstration, in the view of the proponents of the jetty, that it succeeded in its fundamental purpose, and validated the claims for the reaction principle. Ripley (1924) commented:

> This jetty has secured and maintained a 20-ft. navigable channel along its trace* continuously since its completion [in 1909]. With a strange persistency the channel has maintained itself along the

* By "trace" is meant *tracé*, the curved section of the channel, a term introduced into Nineteenth Century hydraulics by the French practice of river regulation of maintaining curves and bends, in contrast to the German method of channel straightening. In American practice the word was generalized to mean the plan of any curved structure. For example, Symons (1896) refers to the "slightly curved direction given to the jetty trace."

> concave face of the curved jetty and has baffled the efforts of those attempting to dislodge it. A second jetty was built on a straight line to the south about 1 250 to 1 700 ft. distant, but this failed to budge the channel. Then dredging operations were undertaken; but the channel continued to hug the curved jetty. Finally, four spur jetties were built from the face of the curved jetty into the channel, thus forcing it away from and out of the influence of the curved structure, thereby inviting deposits. The effect of these spurs will be to put a stop to the further demonstration of the effectiveness of a single curved jetty to maintain a channel without dredging or bar advance and to convert the scheme into a two-jetty plan supplemented by dredging with the inevitable bar advance and continuous expense for maintenance.

Was this due to Haupt's so-called reaction principle? Probably not. The more likely explanation is the effect of the revetments along the north end of Mustang Island deflecting the ebb current back to the northeast against the Haupt jetty. Impingement and convergence of the current against the jetty would scour a deeper channel. Pitts (1899), who brings considerable observational experience on the conditions at Aransas, remarked a century ago, "In fact, the ebb current is deflected to the north by the revetment laid by the Government between 'Co. Wharf' and Turtle Cove, and trends away from the shore line of Mustang Island before reaching the inshore end of the south or Nelson jetty." The same phenomenon has been operating in Bolivar Roads in the Galveston system to the present day, where a deep hole, 60-70 ft at times, has been scoured for many years along the toe of the north jetty. (Kieslich, 1981, observes that single updrift jetties tend to exhibit a talweg migrating toward the jetty, which he attributes to deposition of littoral drift approaching from the downdrift side. At Aransas Pass there is a substantial drift from south to north, its relative importance varying seasonally. To the extent that the various south jetty structures do not intercept this northward directed drift, this represents an alternative explanation.)

More importantly, where the Aransas Pass inlet channel was deepest it was also nearest the breakwater, too close to permit safe navigation. No sailing vessel could tack this close to the jetty, and steam-propelled vessels were subject to the bank-suction phenomenon, being drawn into the stonework. While navigable depths were achieved, a navigable channel was not. Even this does not condemn the reaction principle, because the effect of deflection and impingement of the ebb current against the jetty would have dominated and obliterated any effect of the reaction jetty. Even in this most fundamental determinant, maintenance of a channel across the bar, the reaction jetty at Aransas is still untested.

APPENDIX F

ESTIMATION OF EVAPORATION

The conventional method of measurement of evaporation is by accurately determining the loss from a pan of water. Since the same phase change from liquid to vapor is proceeding in the pan, where it can be precisely measured, as is operating in a natural waterbody (like a lake or bay), subject to the same environmental factors such as wind and humidity, this would presumably qualify as a direct measurement. Unfortunately, the thermodynamics of the pan differs from that of the waterbody. The exposure of the pan to wind and overwater conditions are not the same as the natural system, the fetch of air movement across the pan is shorter than that of the waterbody, and the exposure of the sides of the pan to heat exchange is greater than the equivalent surface volume in the waterbody. All of these produce different rates of evaporation from the pan and the natural system, necessitating a "pan-to-lake" or "pan-to-bay" coefficient to convert the former to the latter. Over the years, several experimental pan constructions have been employed, including land-based pans of various diameters and shapes, mounted above the ground or below the ground with the water surface flush, and pans floating in the watercourse itself, finally evolving to the National Weather Bureau Class-A pan. The usual method in hydrology is to postulate a correction that is in turn based upon rigorous water budgeting of a lake in the general area. For lakes in temperate climates, the pan-to-lake coefficient for a class-A pan is typically 0.7, but can vary from 0.2 to 1.5. This value of 0.7 was adopted for application to the Corpus Christi Bay system, but we note that there is considerable uncertainty in its applicability.

For the present study, evaporation records available from the National Climatic Data Center, in its "Summary of the Day" data file for Texas, were employed. There are two useful stations in this data file. The first is the pan that has been operated at Point Comfort since 1957. Most pan stations in Texas are located in proximity to reservoirs, or located well inland. Point Comfort is the only pan located in a truly coastal setting. The second useful station is that of Beeville, which is approximately central to the coastal watershed of the study area (i.e., excluding the Nueces basin); unfortunately, data from this station extend back only to 1979.

As noted in Section 2.2 of the main report, we require a means of extrapolating data from pan sites removed from the study area, and of extending the available period of record. In conventional reservoir simulation this is almost universally approached by constructing an "average year" monthly evaporation sequence which is then applied uniformly to the simulation period. The problem with this approach in the case of Corpus Christi Bay is that evaporation is a major element of the water budget and varies strongly with hydroclimatology. There is clearly a substantial year-to-year variation in both the summer maximum and the winter minimum. Especially during droughts, the higher temperatures (and lower humidities) increase the rate of evaporation and therefore the deficit at the surface of the bay. We believe this effect needs to be explicitly quantified.

This was approached by using air temperature as the basic hydroclimatological predictor. This is because there is a good record of air temperature at several stations in the Corpus Christi watershed, and because, from basic physics, temperature is one of the primary drivers of evaporation. The Dalton formulation of evaporation from a water surface is given by

$$E = \rho M W [e_s(T_W) - e_a(T)]$$

where E is evaporation in depth/time (cm/mo, say), T_W is water temperature (K), T is air temperature (K), e_s saturation vapor pressure, e_a atmospheric vapor pressure, W wind speed at a standard elevation, ρ water density, and M is a constant for the site. Vapor pressure is given by $r\, e_s(T)$ where r denotes relative humidity (as a dimensionless fraction). Using air temperature as an estimator for water temperature, which is quite satisfactory in this subtropical climatology, this equation simplifies to

$$E = M W (1 - r)\, e_s(T)$$

in which all of the constants as well as any approximation errors are absorbed in the constant M. Using the Clasius-Clayperon equation to evaluate e_s (see, e.g., Hess, 1959, Ward, 1980a) and some algebra results in the functional form

$$\mathit{log}\, E = a\, T\, \mathit{log}\{M W (1 - r)\}$$

where *log* denotes the base-e (natural) logarithm and *a* is a constant which can be computed from the Clasius-Clayperon equation. This functional form guides the statistical analysis of pan evaporation data. Most of the variation in E would be due to the factor T (since W and r enter the equation as logarithms, and moreover have a smaller range of variation than T). To a first approximation, therefore, we seek a linear dependence of log E on mean air temperature.

The 353 measurements of monthly pan evaporation data (November 1957-February 1991, with some months missing) at the Point Comfort site were log-transformed and regressed against air temperature (computed as the average of the measured minimum and maximum). A scatterplot of these data and the resulting regression, given by

$$E = 0.400\, \mathit{exp}\{ 0.0386\, T \} \qquad \text{(Point Comfort)}$$

for E in inches per month and T in °F, the reporting units of the measurements, are shown in Fig. F-1. As a predictor, this relation achieves a linear correlation with the observed monthly pan data of 93%, and explains 86% of the variance in the data, the resulting scatterplot shown in Fig. F-2. A further correction could be made for dependence upon relative humidity r by noting that the range of daily air temperature (i.e., maximum minus minimum) is in fact a measure of humidity, the daily range increasing with diminishing humidity. However, the single regression on air temperature is clearly a satisfactory predictor, especially in view of the intrinsic noise in the pan evaporation data.

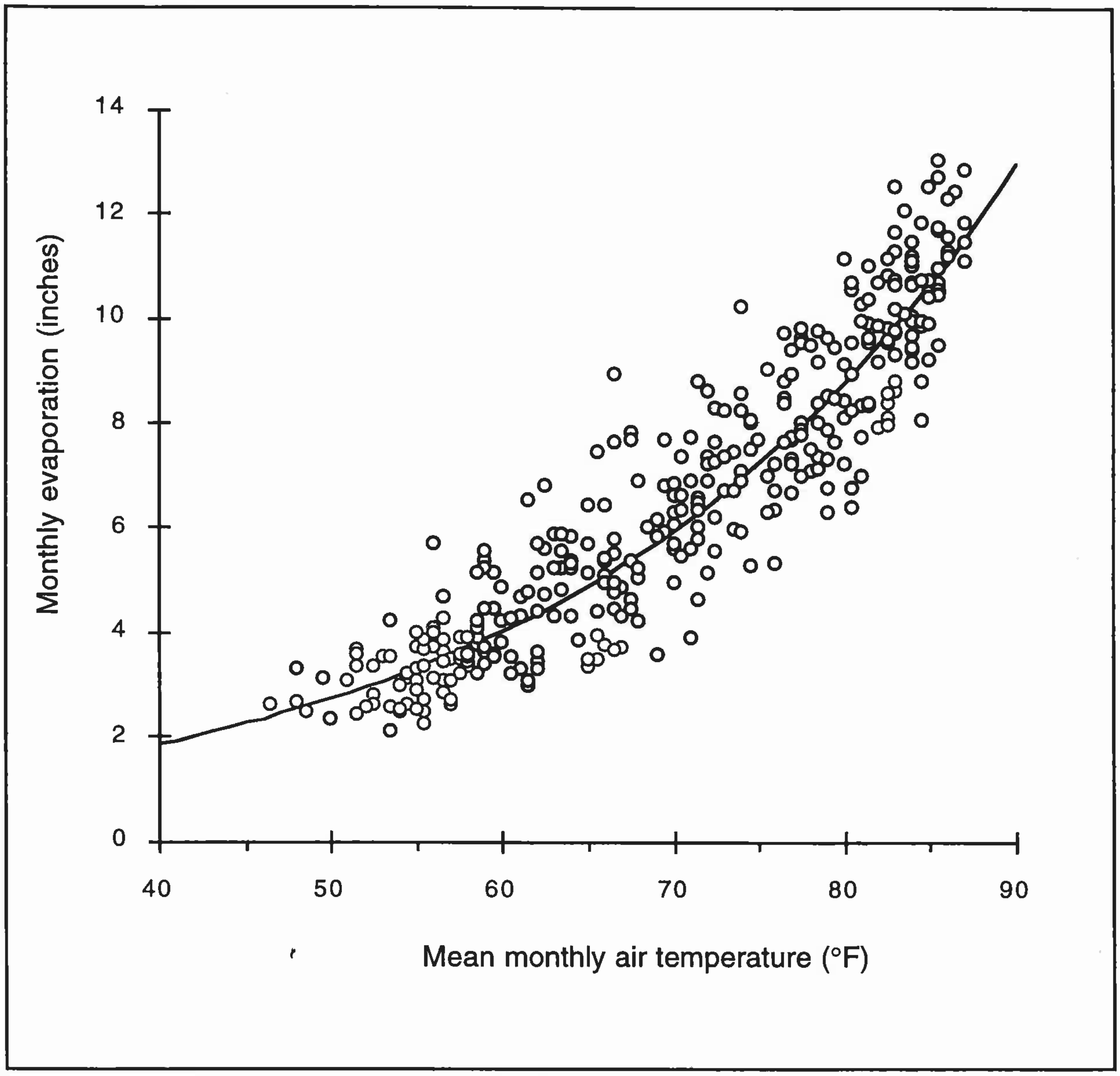


Figure F-1. Monthly pan evaporation and mean air temperature at Point Comfort, with Dalton-law regression line

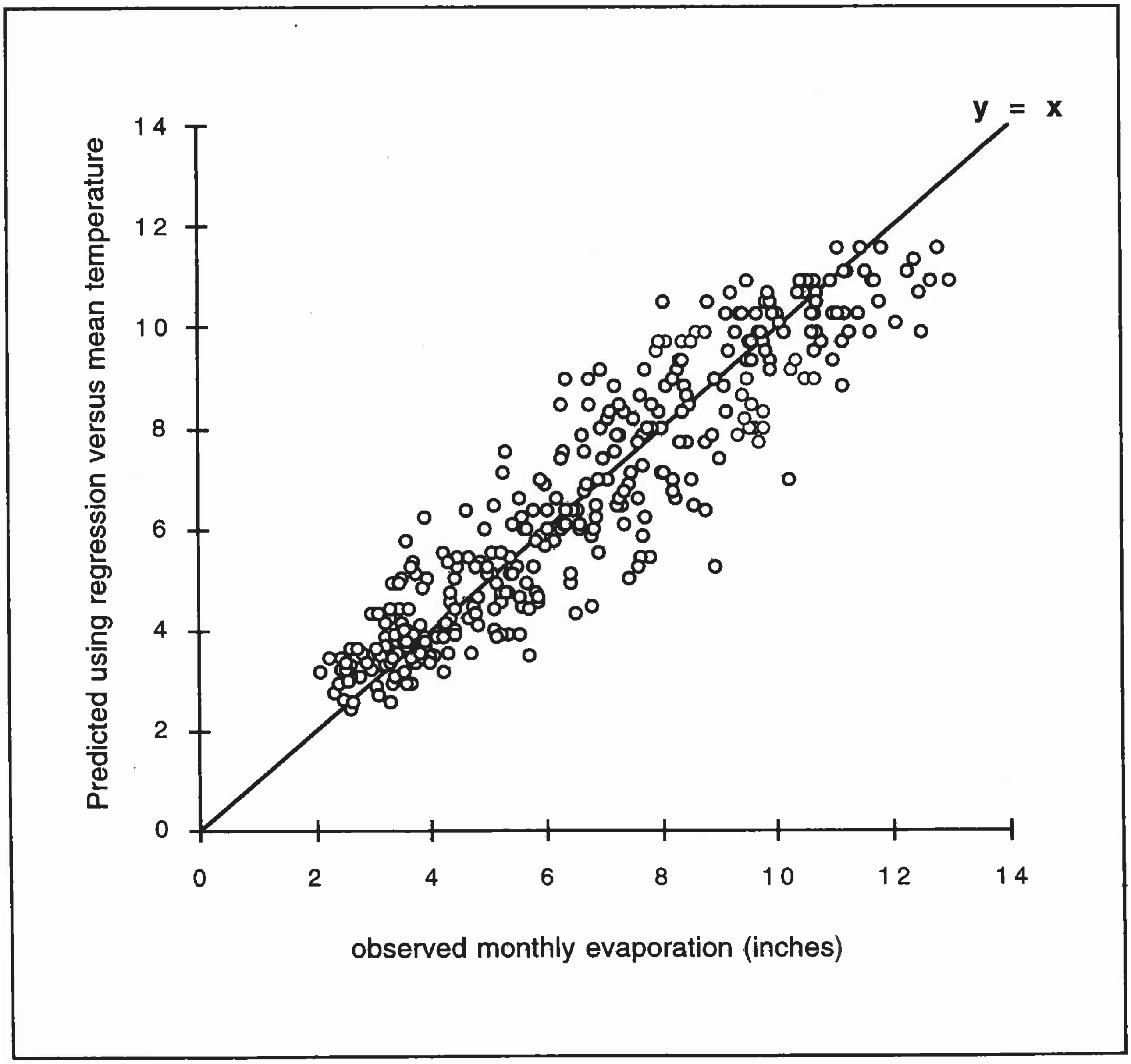


Figure F-2. Predicted versus observed monthly pan evaporation at Point Comfort

The same analysis was carried out for the Beeville station. There are fewer data points here, 134 over a ten-year period of record, but the regression turned out to be nearly identical to that at Point Comfort.

$$E = 0.575\, exp\{\, 0.0336\, T\,\} \qquad \text{(Beeville)}$$

At this station, the above relation as a predictor is 90% correlated with the observed monthly pan data, and explains 81% of the variance in then data. A comparison of the two, see Fig. F-3, shows that they are virtually identical

It is interesting to compare the same regression form for the pan data from Amistad, as the two regressions should bound the evaporation on the more arid Edwards Plateau, characteristic of the upper Nueces basin. This relation turns out to be

$$E = 0.624\, exp\{\, 0.03637\, T\,\} \qquad \text{(Amistad)}$$

which is a much higher rate of evaporation, Fig. F-3, not unexpected given the much lower humidities in the Amistad region.

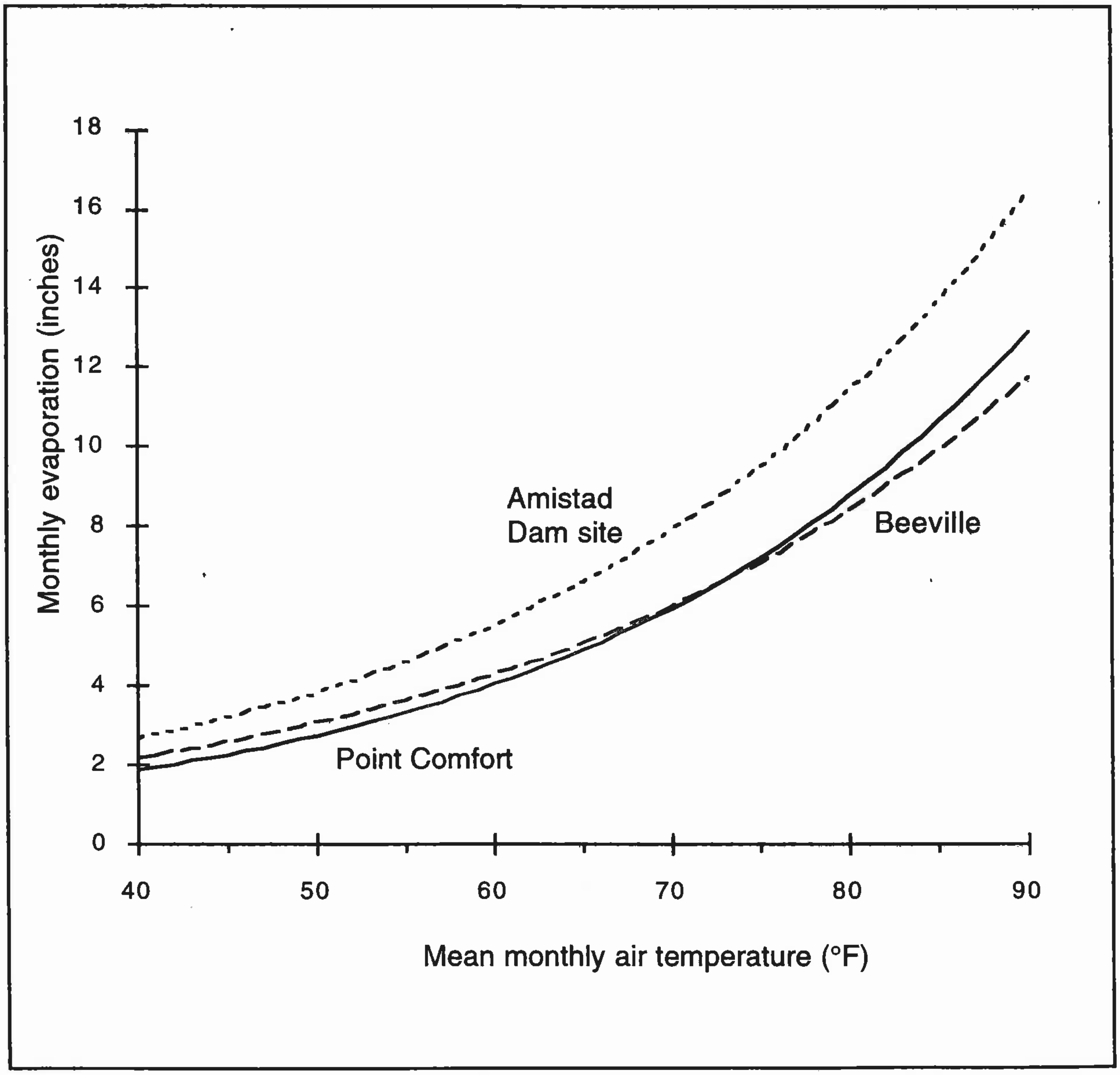


Figure F-3. Comparison of prediction relations for evaporation at Point Comfort, Beeville and Amistad Dam

APPENDIX G

SHELL DREDGING

Raw data on permitted shell excavation are presumably in the archives of the Texas Parks and Wildlife Department, but the resources of this project did not permit compilation and analysis of this data. Instead, shell dredged from the study area was estimated from more readily available sources. Kerr (ca. 1970) compiled total dredged volumes from the entire Texas coast back to 1912, and also provided data for the major bay systems including Nueces and Copano Bays for state FY's 1960-66. Gilardi (1942) presented data from Galveston Bay for 1933-40. Anderson (1960) gave data for Nueces Bay for FY 1958, and Mitchell (1959) for Columbia Southern (née Southern Alkali Corporation) in 1954. This information together with the historical development of the industry (see also Ward, 1993) allowed a reasonable reconstruction of the dredging activity in Nueces Bay.

From the Gilardi (1942) data on Galveston Bay, it was estimated that through 1932 and from 1941-54, Galveston Bay accounted for about 85% of the total shell dredged from the Texas coast. For 1955-59 this portion is taken to be 70%. After 1966, as the industry slowed in Galveston Bay, an annual value of 7,000,000 cu yds was used. With these data, the non-Galveston Bay volume for the Texas coast could be calculated. This is the source for the data in Fig. 3-14.

Major dredging is assumed to have begun in Nueces Bay with the Southern Alkali plant in 1934. Production of this plant was no doubt variable, in response to the market. In 1954 the plant used 120,000 tons of oyster shell from Nueces Bay according to Mitchell (1959). The equivalent volume, assuming a specific gravity of shell of 1.8, is about 80,000 cu yds. This is of clean, washed, compacted shell. The dredged shell with mud and voids would have been at least twice this. We conclude that the plant could easily use several hundred thousand cu yds, depending upon production. Through 1949, half of the non-Galveston production from the coast was assumed to be taken from Nueces Bay. The Southern Chemical operation could easily account for the bulk of this. The data on actual Nueces Bay production from 1958 and 1960-66 shows Nueces to account for 35% of the non-Galveston volume relatively consistently from year to year. This ratio was used to fill in the data for 1950-57 and 1959. For 1967-68, when the industry began to taper off in Nueces Bay, we assume an annual volume of 1,000,000 cu yds. These data and calculations are summarized in Table G-1, and are the source for the estimated Nueces Bay data of Fig. 3-14.

Table G-1

Annual volumes of shell dredged (cu yds) by geographical area, estimates in italics (see text)

	Texas coast	Galveston Bay	Non-Galveston	Nueces Bay		Texas coast	Galveston Bay	Non-Galveston	Nueces Bay
1912	535	*461*	*74*		1940	2102	1861	241	*120*
1913		*479*	*74*		1941	3485	*3004*	*481*	*240*
1914	576	*497*	*79*		1942	5196	*4479*	*717*	*358*
1915	904	*779*	*125*		1943	5486	*4729*	*757*	*378*
1916		*682*	*100*		1944	4599	*3965*	*634*	*317*
1917		*584*	*100*		1945	3456	*2979*	*477*	*238*
1918		*487*	*100*		1946	4500	*3879*	*621*	*310*
1919	452	*390*	*62*		1947	5482	*4726*	*756*	*378*
1920	724	*624*	*100*		1948	6228	*5369*	*859*	*429*
1921	746	*643*	*103*		1949	7174	*6185*	*989*	*495*
1922		*788*	*108*		1950	7527	*5442*	*2085*	*717*
1923	829	*715*	*114*		1951	8462	*6118*	*2344*	*806*
1924	1213	*1046*	*167*		1952	9159	*6622*	*2537*	*872*
1925	1205	*1039*	*166*		1953	10030	*7251*	*2779*	*955*
1926	1952	*1683*	*269*		1954	10823	*7825*	*2998*	*1031*
1927	1983	*1709*	*274*		1955	10055	*7039*	*3017*	*1037*
1928	1705	*1470*	*235*		1956	11366	*7956*	*3410*	*1172*
1929	1773	*1528*	*245*		1957	12043	*8430*	*3613*	*1242*
1930	1750	*1509*	*241*		1958	11470	*8029*	*3441*	1175
1931	1522	*1312*	*210*		1959	11296	*7907*	*3389*	*1165*
1932	1186	*1022*	*164*		1960	11449	8538	2911	1145
1933	538	505	33		1961	11701	8230	3471	1184
1934	768	607	161	*80*	1962	12131	8798	3333	1224
1935	808	698	110	*55*	1963	11534	8517	3017	1228
1936	1628	1492	136	*68*	1964	11753	8252	3501	1060
1937	2205	1839	366	*183*	1965	12095	8263	3832	1028
1938	2147	1901	246	*123*	1966	11548	7240	4308	1295
1939	2256	1762	494	*247*	1967		*7000*		*1000*
					1968		*7000*		*1000*

Appendix H

COMPUTATION OF VOLUME OF DREDGED CHANNEL

Theoretical dredged dimensions of a channel can be computed from the project dimensions, given as a project depth below the water surface and a bottom width, i.e. D x W, if account is made for the sides in which the channel depths slope up to the natural bathymetry. This requires an estimate of natural (i.e., before dredging) water depths. Fig. H-1 sketches the geometry of the channel cross section relative to natural water depths, from which the "affected" width, i.e., the width of the project at the bay bottom, not the channel bottom, is computed from

$$w = W + 2\,(D-d)\,a$$

For simplicity the channel side slope was taken to be 1:2 in the computations. (Actual side slopes in the Corpus Christi Bay channels range from 1:2 to 1:3.5 in the open bay, and may be steeper within the Inner Harbor.) An estimate of channel volume is then $(W+w)(D-d)/2$ times the length of the reach. Table H-1 tabulates the computed volumes of new work for each major channel reach in the Corpus Christi Bay system.

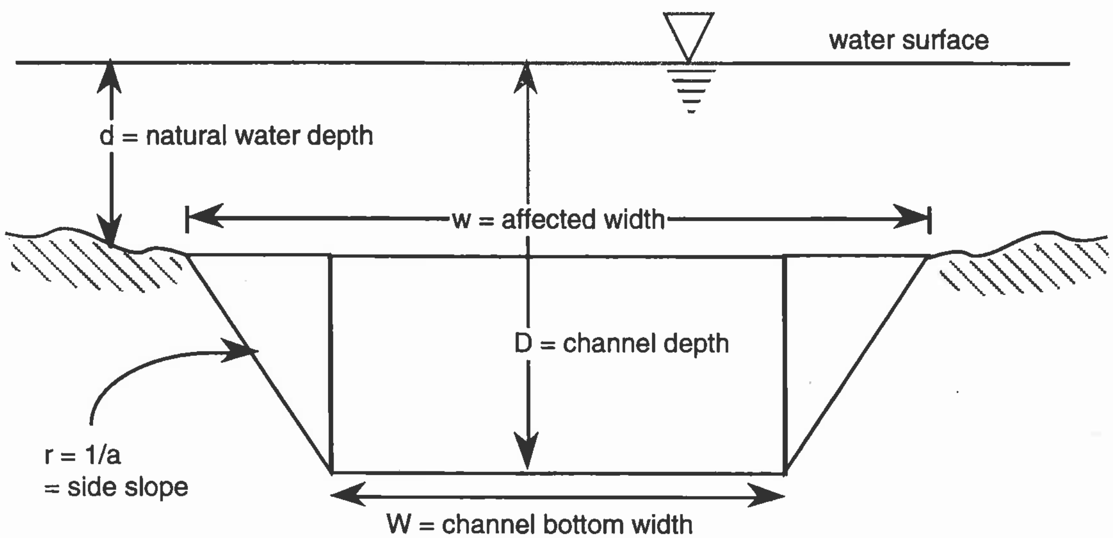


Figure H-1. Definition sketch.

Table H-1
Computed New Work Volumes

Date completed	proj dims (ft) depth	width	natural depth (ft)	affected width (ft)	length (ft)	volume (cu yds)	Notes
Entrance & Jetty Channel							
1926	27	250	15	298	10000	1217778	
1931	32	250	15	318	10000	570370	
1937	34	250	15	326	10000	1456296	
1946	36	500	15	584	10000	2759259	
1958	38	500	15	592	10000	1891852	
1966	42	500	15	608	10000	3648148	
1979	47	500	15	628	10000	3036296	
Turtle cove							
1908	8.5	75	3	97	30000	525556	across flats
1912	12	100	7	120	60000	696667	to McGloins Bluff
CCSC							
1926	25	200	13	248	108000	10752000	to Marker 82
1931	30	200	13	268	108000	5160000	at Breakwater
1937	32	200	13	276	108000	12928000	
1946	34	400	13	484	108000	24200000	
1958	36	400	13	492	108000	16832000	
1966	40	400	13	508	108000	32200000	
1979	45	400	13	528	50000	11396296	West reach
1979	45	500	13	628	58000	22669778	East reach
Encinal							
1941	30	200	14	264	44000	6049185	
La Quinta							
1955	32	125	7	225	27000	4375000	private project
1958	36	300	7	416	27000	6007000	federal project
1966	40	300	7	432	27000	6071000	
1979	45	300	7	452	27000	8217000	
Inner Harbor							
1926	25	800	1	896	3000	2261333	Turning Basin
1966	40	800	1	956	5000	4079778	
1934	30	150	0	270	7500	1750000	Industrial canal
1958	36	200	0	344	7500	970000	
1966	40	400	0	560	7500	4363333	
1934	30	800	0	1000	1000	1000000	Avery Point TB
1958	36	800	0	1000	1000	200000	
1966	40	1000	0	1160	1000	1400000	

Table H-1
Computed New Work Volumes
(continued)

Date completed	*proj dims (ft) depth*	*width*	*natural depth (ft)*	*affected width (ft)*	*length (ft)*	*volume (cu yds)*	*Notes*
Inner Harbor (continued)							
1945	18	100	0	172	18500	1677333	Tule Lake Chnnl
1958 ?	36	200	0	344	20000	5576000	
1966	40	200	0	360	20000	2720296	Tule Lake (incl
1990	45	300	0	480	20000	10279704	Chem TB Channl)
1958	36	1000	0	1144	1200	1715200	Tule Lake TB
1966	40	1000	0	1160	1200	204800	Tule Lake TB
1990 ?	45	1000	0	1180	1200	1975200	
1958	36	200	0	344	10000	3626667	Viola Ch
1966	40	200	0	360	10000	521481	
1990 ?	45	300	0	480	10000	5978519	
1958	36	1200	0	1344	1200	2035200	Viola TB
1966	40	1200	0	1360	1200	240356	
1990 ?	45	1200	0	1380	1200	2339644	
GIWW							
Upper Bays:	**Galv to CC**						
1915	5	40	3	48	90000	293333	to Mesquite Bay
1941	9	100	3	124	90000	1946667	
1945	12	125	3	161	90000	2343333	
1960	12	125	3	161	90000	4290000	new route
Lower Bays:	**CC to Brownsville**						
1948	12	125	1	169	186000	11139333	to Murdock Basin