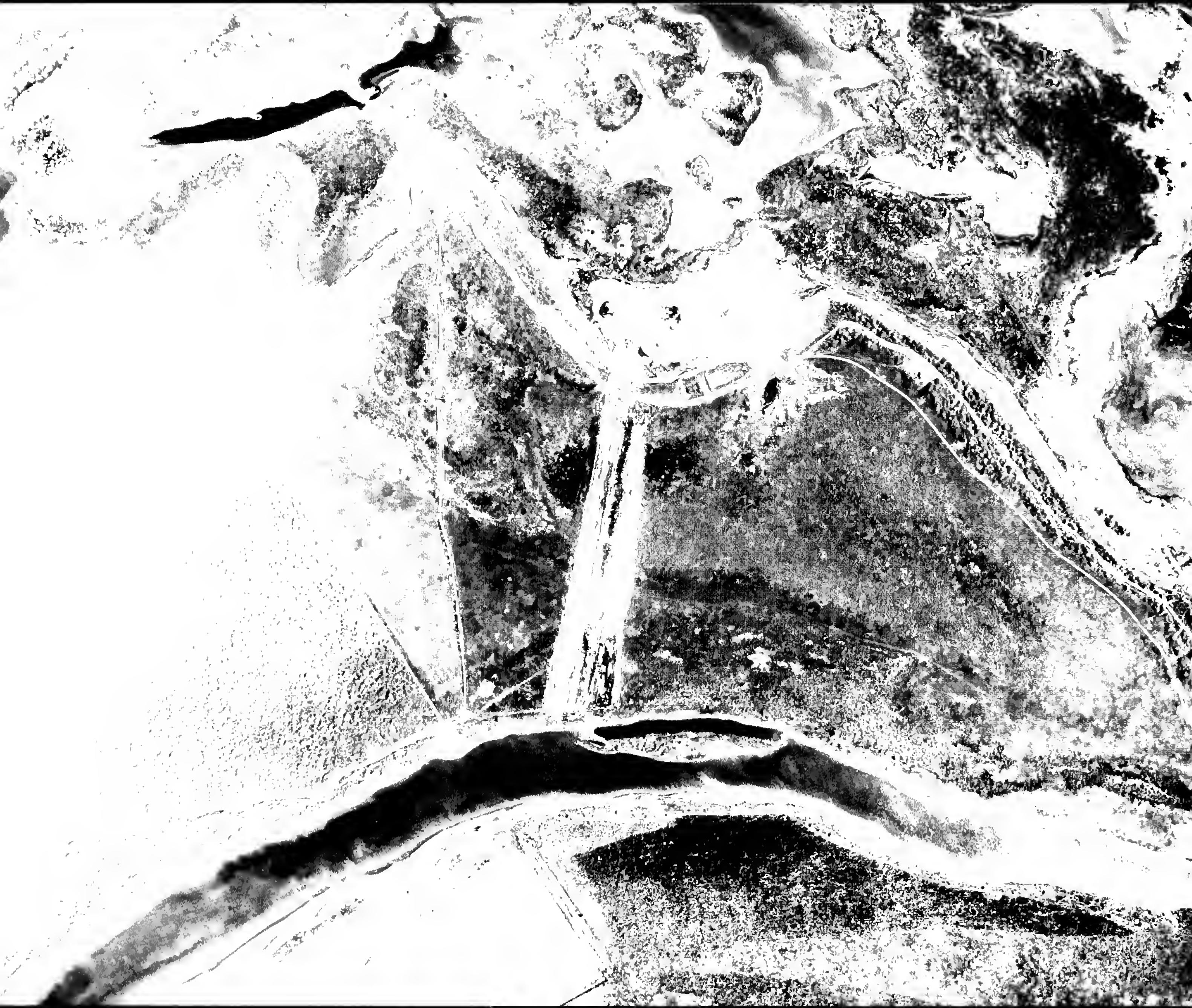
VOLUME II

Findings

RINCON BAYOU DEMONSTRATION PROJECT

Concluding Report



UNITED STATES DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
In Cooperation with
University of Texas Marine Science Institute

September 2000

Cover: Rincon Overflow Channel, September 1997

RINCON BAYOU DEMONSTRATION PROJECT

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CITATION

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Abstract

The Rincon Bayou Demonstration Project significantly lowered the minimum flooding threshold of the upper Nueces Delta, thereby increasing the opportunity for larger, more frequent diversions of fresh water from the Nueces River. During the 50-month demonstration period, the amount of fresh water diverted into the upper Nueces Delta was increased by about 732%. Five freshwater inflow events were sufficient to activate the project's Rincon Overflow Channel and inundate, to varying degrees, the tidal flats of the upper delta. These tidal flows would not have otherwise been directly freshened. As a result, in a relatively short period of time (only 4.2 years after the opening of the project's Nueces Overflow Channel), the average salinity gradient in the upper delta reverted to a more natural form, with average salinity concentrations in upper Rincon Bayou becoming the lowest in Nueces Delta.

The effects of the demonstration project on the ecology of Rincon Bayou and the upper Nueces Delta were positive to the environment. Single-celled plant communities in the water column (phytoplankton) and on the surface of the sediments (microphytobenthos) evidenced increases in primary productivity with the reduction of salinity concentrations. Benthic communities (composed of bottom-dwelling organisms) evidenced increases in abundance, biomass and diversity. And, vegetation communities evidenced increases in plant cover and decreases in bare area. In summary, it was observed that freshwater inflow controlled, to a great extent, the ecological function of the upper delta ecosystem by regulating critical biological mechanisms.

A significant degree of ecological function was returned to the Nueces Delta and Nueces Estuary ecosystems by the demonstration project. Prior to the project, persistently high salinity concentrations severely inhibited the function of the Nueces Delta, and the delta's natural contribution to the greater estuary ecosystem was limited to infrequent periods when natural flow events occurred. With the restored regular interaction between the Nueces River and Rincon Bayou, fresh water and nutrients were more consistently introduced into the upper delta. As a result, estuarine habitat in the delta component of the Nueces Estuary improved in both quality and quantity, and foraging opportunities for many estuarine species were increased.

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Introduction

"These waters of the seaboard exert an influence upon the affairs of mankind far out of proportion to their size, for it is here that land and sea meet, and the fresh and salt waters of the earth intermingle."

❖ E.J. Perkins

The Rincon Bayou Demonstration Project was conducted from 1994 through 1999 within the upper Nueces Delta, located northwest of the city of Corpus Christi, Texas. The delta was formed and is supported by the Nueces River, which passes along its southern edge as it empties into Nueces and Corpus Christi bays (Figure 1-1). Because of the dynamic nature of this natural system, the delta consists of a variety of habitats, including open water, marshes and mud flats and possesses a unique array of hydrological and biological characteristics.

Ecologically, the Nueces Delta is part of the greater Nueces Estuary, which is a brackish transitional zone situated between the freshwater riverine habitats of the Nueces River and the marine habitats of the Gulf of Mexico. Salt water from the bays regularly inundate the lower reaches of the delta during a variety of tidal and atmospheric events. The delta is also periodically inundated with fresh water when the Nueces River occasionally spills out of its banks. Such freshwater flooding events significantly contribute to the biological productivity of the delta by providing a medium for nutrient exchange and biochemical cycling, supplying fresh water to marsh plant communities, transporting detrital and other nutrient materials from the established marsh vegetation and sediments to the bay, and buffering bay salinity (Longley 1994). The Nueces Delta has therefore been considered one of the most important sources of nutrient material for the entire Nueces Estuary system (Texas Department of Water Resources 1981), supporting numerous plant and animal communities, including commercially important marine life.

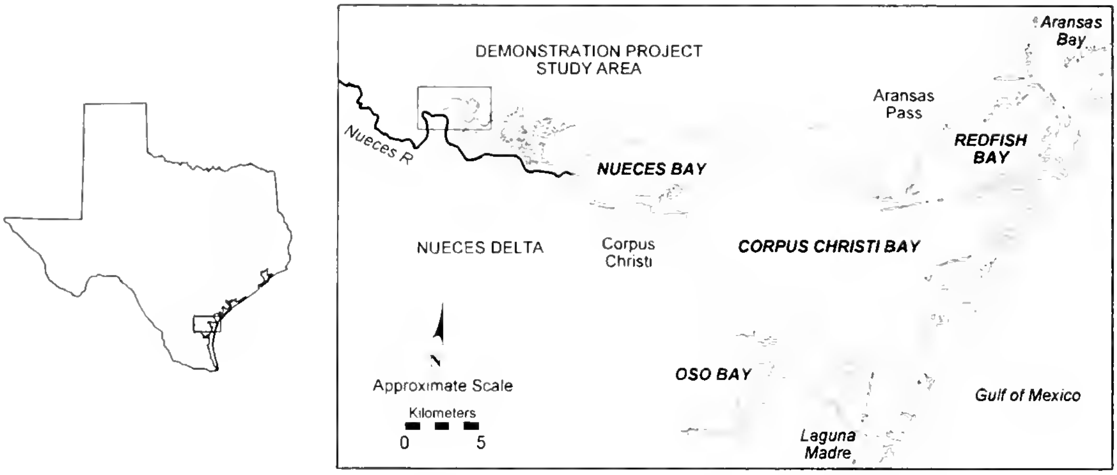


Figure 1-1: Location of the Nueces Delta along the Coastal Bend of Texas.

BACKGROUND

Since the beginning of the 20th century, the human population along the Coastal Bend region of Texas has substantially increased (Figure 1-2). As a result, the demand for fresh water to meet the growing municipal and industrial needs of the region also increased significantly. In response, two large reservoirs were constructed in the Nueces Basin for the purpose of storing flood flows. The first was Wesley Seale Dam (Lake Corpus Christi), constructed on the Nueces River by the City of Corpus Christi in 1958, and the second was Choke Canyon Dam (Choke Canyon Reservoir), constructed in 1982 on the Frio River by the U.S. Bureau of Reclamation (Reclamation) (Figure 1-3). Choke Canyon Dam was designed to be operated in conjunction with Lake Corpus Christi as part of one reservoir system.

During the period when these two reservoirs were being planned, particularly in the case of Choke Canyon Dam, the potential adverse impacts of reservoir operations on the bay and estuary systems were a concern. It was generally suspected that these impoundments would reduce the amount of fresh water entering the Nueces Estuary and upper Nueces Delta, adversely affecting the natural productivity of these systems. However, there was very little specific information available regarding the needs of delta and estuary systems, or of their responses to changes in freshwater inflows. In recognition of the bay and estuary resources, the State of Texas required that, once Choke Canyon Dam was completed and filled, a total

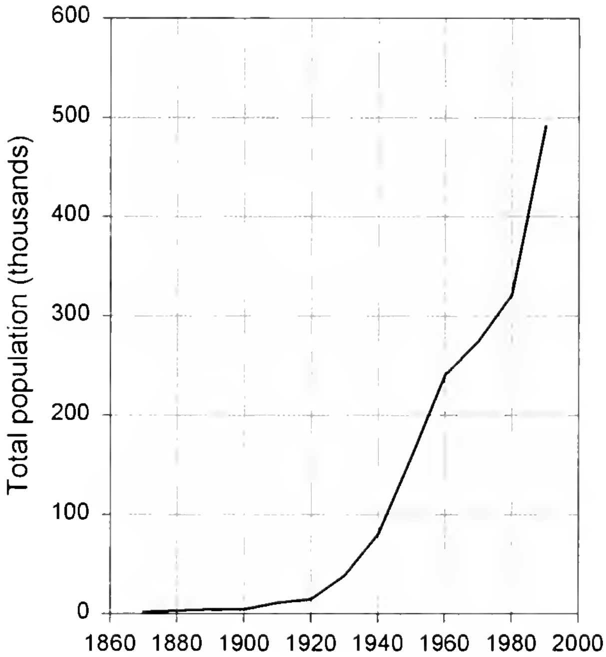


Figure 1-2: Historical population trend for the areas served by the Nueces River at Calallen.

Sources: City of Corpus Christi 1981 and Texas Water Board 1992.

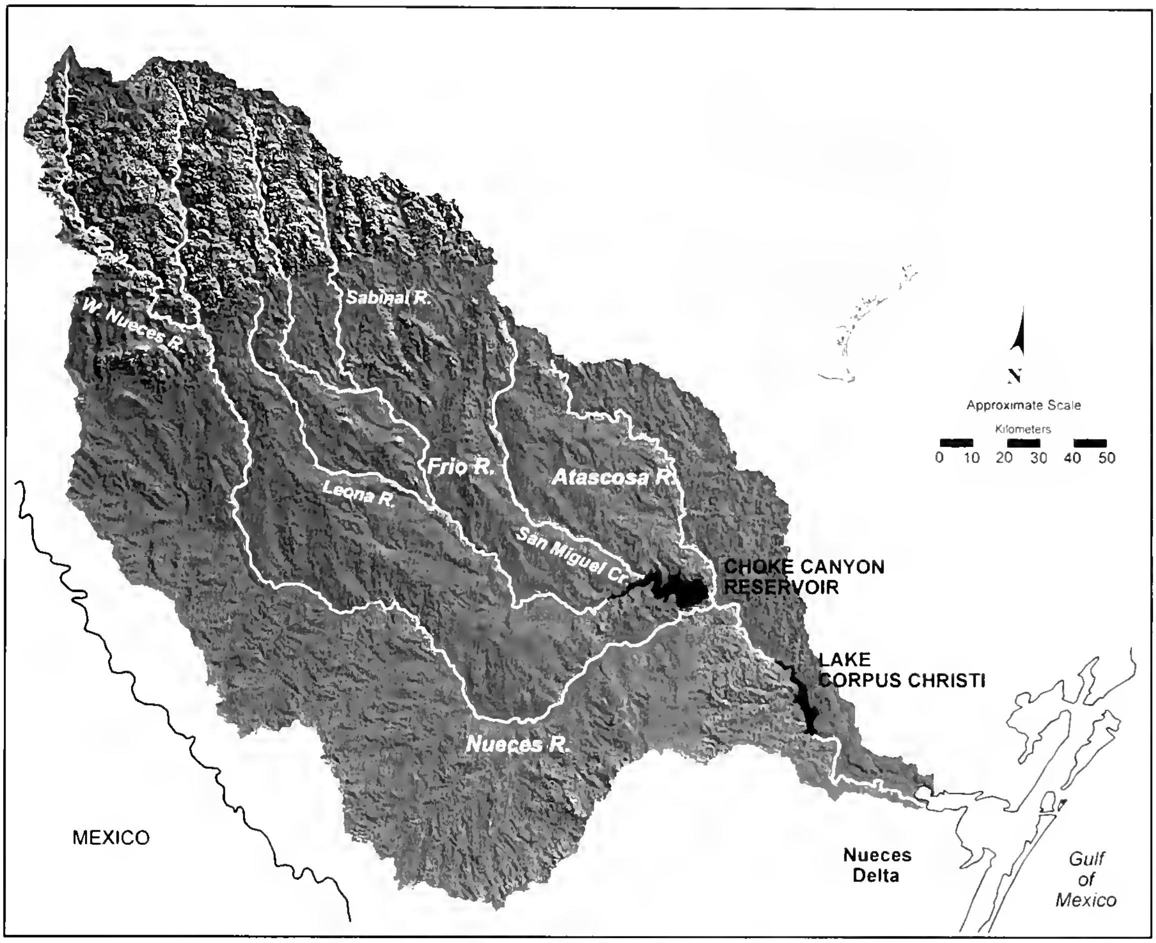


Figure 1-3: The Nueces River Basin, including major drainages and reservoirs.

Source of topographic base map: U.S. Geological Survey 1997.

of 186,274 10^3 m^3 (151,000 acre-ft) of water per year would be provided to the estuaries by a combination of releases and spills from the reservoir system at Lake Corpus Christi Dam and return flows to Nueces Estuary (Texas Water Rights Commission 1976). Although the dam was completed in 1982, flow into the reservoir was minimal for the first several years. However, in June 1987, record rainfall over the Frio River watershed filled the reservoir, and water was released as flood control for the first time.

During the mid-1980's, several entities initiated regular monitoring programs in the region. Salinity in the Nueces Estuary began to be sampled continuously by several State agencies and universities. Fish, shrimp, crabs and oysters in Nueces Bay were sampled during routine, State-wide coastal inventory surveys. Modest research efforts were also undertaken by university researchers to monitor the effect of the water releases on hydrography and benthos in the estuary.

By the early 1990's, it had become apparent that there had been a notable reduction in the freshwater inflow to the delta and estuary systems. For example, historically Nueces Bay had supported large populations of shrimp and oysters, which generally require salinity concentrations in the range of 10 to 20 parts per thousand (ppt) salt. During the relatively dry period of the late 1980's and early 1990's, the salinity of the bay had increased to hypersaline conditions (> 36 ppt), and consequently the shrimp and oyster populations were reduced. For example, from 1984 through 1989, shrimp harvest declined in Nueces

Estuary, even though it was stable in the Aransas Bay ecosystem to the north and the upper Laguna Madre to the south (Montagna *et al.* 1998).

Because of contention regarding the amount of fresh water dedicated to the bays and estuary from the reservoir system, releases had not been made for that purpose since Choke Canyon Reservoir filled. In 1992, the Texas Natural Resources Conservation Commission (TNRCC) implemented an operating plan requiring minimum mandatory inflows on a monthly schedule totaling 186,274 10^3 m^3 (151,000 acre-ft). As part of the same order, TNRCC also created the Nueces Estuary Advisory Council to provide oversight of the releases and monitor the operating plan, and to make recommendations for improving the plan. In April 1995, the original TNRCC order was revised to adopt a "target" minimum monthly inflow plan instead of a mandatory inflow amount. This change, which resulted in an annual inflow target of 112,258 10^3 m^3 (91,000 acre-ft), was intended to mimic natural hydrographic conditions in the Nueces Basin while providing some relief to the water customers of the reservoir system.

THE RINCON BAYOU DEMONSTRATION PROJECT

Beginning about 1993, a consortium of local, State and Federal entities began investigating alternatives to restore fresh water to the greater Nueces Estuary. In 1993, as part of this initiative, the Reclamation undertook a temporary demonstration project to provide detailed scientific information regarding the freshwater needs of the delta and its response to changes in freshwater inflows. The Rincon Bayou Demonstration Project had two primary objectives:

1) To increase the opportunity for natural freshwater flow events into the upper Nueces Delta; and

2) To monitor any resulting changes in the hydrography and biological productivity of the delta.

PROJECT FEATURES

The area selected for the demonstration study encompassed the northwestern portion of the upper Nueces Delta, or that area generally north of Rincon Bayou and west of the eastern-most railroad crossing (Figure 1-4). This area represents both the historic location of river inundation events and the western limit of the Nueces Estuary (*i.e.*, the tidally influenced portions of Rincon Bayou and a large area of tidal flats).

Water Diversion

Reclamation decided on a final demonstration project design after reviewing several different alternatives. The selected alternative provided an uncomplicated means of increasing the opportunity for freshwater diversion and distribution in the upper delta, while preserving the natural "event" mechanism to which the system had adapted. The physical aspects of the project included two principal features: the Nueces Overflow Channel and the Rincon Overflow Channel (Figure 1-4).

The primary feature of the demonstration project was an overflow channel (Nueces Overflow Channel) excavated from the Nueces River to the headwaters of Rincon Bayou (Figures 1-4 and 1-5). The channel was located approximately 60 m downstream of the Interstate Highway 37 (IH 37) bridge along the north bank. The design dimensions of the Nueces Overflow Channel were approximately 274 m long and 12 m wide, with a bottom elevation of 0.6 m (2.0 ft) mean sea level (msl). This bottom elevation was selected so as to prevent regular tidal exchange between the Nueces River and the upper delta. However, early into the demonstration period, the channel's effective bottom elevation was lowered by flow events and tidal exchange to approximately mean sea level. Minor excavations were also made at two sites along the headwater channel of Rincon Bayou to remove channel-constricting sediment deposits, thereby allowing a higher diversion volume during flood events. Construction of the channel was completed on October 26, 1995. The purpose of the Nueces Overflow Channel and associated channel

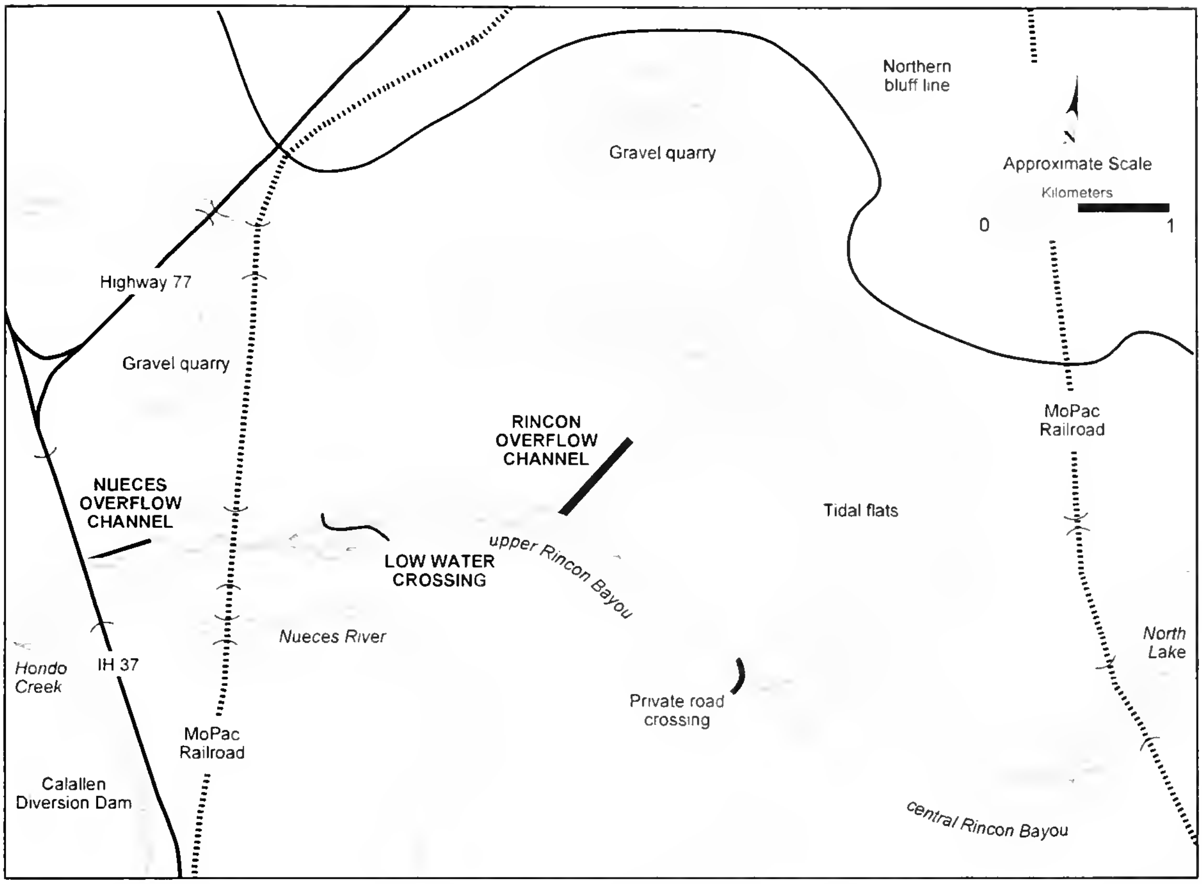


Figure 1-4: Study area for the Rincon Bayou Demonstration Project and location of project features. The pre-existing private road crossing separating the upper and central Rincon Bayou channels was not part of the demonstration project.

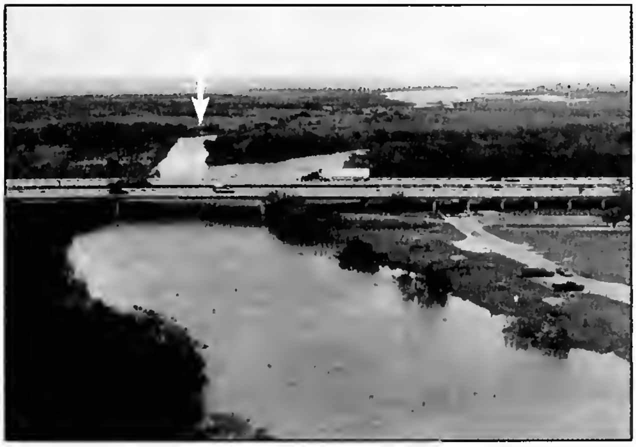


Figure 1-5: View of the Nueces Overflow Channel. The view is looking northeast, with the Nueces River in the foreground, and Rincon Bayou in the distant background. The photo was taken on June 26, 1997, during the first significant flow event.

Photo courtesy of the Bureau of Reclamation.

improvements was to lower the flooding threshold of the Nueces River, thereby increasing the opportunity for more frequent and higher magnitude flow events into the upper Nueces Delta.

During the design phase of the project, Reclamation determined that an existing private road crossing over Rincon Bayou would act as a partial dam during larger flood events, limiting the volume of water diverted into the delta and substantially reducing the proposed project's effectiveness (Figures 1-4 and 1-6). Therefore, a second overflow channel (Rincon Overflow Channel) upstream of this road crossing was designed which would connect Rincon Bayou to the tidal mudflat areas in the northern part of the delta (Figure 1-7).

The design dimensions of the Rincon Overflow Channel were approximately 610 m long and 30 m

Figure 1-6: View of the private road crossing separating the upper and central Rincon Bayou channels. This pre-existing structure (constructed between September 1992 and March 1993) was not part of the demonstration project. The photo was taken on June 26, 1997, during the first significant flow event. During larger events, the structure backed water up in the upper Rincon Bayou (left), as indicated by the difference in water levels on either side of the road.

Photo courtesy of the Bureau of Reclamation.

Figure 1-7: View of the Rincon Overflow Channel. The view is looking northeast from Rincon Bayou (foreground), showing the channel's outlet into the tidal flats (background). The photo was taken on June 26, 1997, during the first significant flow event.

Photo courtesy of the Bureau of Reclamation.

wide, with a bottom elevation of 1.22 m (4.0 ft) msl on the upstream (south) end and 0.91 m (3.0 ft) msl on the downstream (north) end. In addition, the downstream end of the channel was crossed with an elevated road over eight 24'-diameter HDPE culverts. The actual bottom elevations of the channel at the end of the demonstration period were about 1.14 m (3.75 ft) and 0.76 m (2.50 ft) msl, respectively. The primary purpose of the Rincon Overflow Channel was to provide a "spillway" during larger flow events that would divert floodwater around the private road crossing, thereby improving diversion and distribution of fresh water within the delta during larger events.

In addition to these two principal features, numerous access road improvements were made as part of Reclamation's agreement with the private landowners in the delta. These included the installation of cattle guards, placement of culverts in low areas, and rehabilitation of a low water crossing over the upper end of Rincon Bayou (Figures 1-4 and 1-8). This last feature was improved by raising the crest elevation from about 1.5 m (5.0 ft) msl to about 2.1 m (7.0 ft) msl, and adding thirteen 36"-diameter HDPE culverts in two locations to allow passage of flow events. The purpose of these road improvements was to preserve landowner access to the upper delta during the term of the demonstration project and to minimize the resistance to water moving into the delta during discharge events.

Several other diversion alternatives were considered at the beginning of the study. These included: 1) either a total or partial diversion of the Nueces River into the delta, 2) delivery of a continuous flow of fresh water from the existing municipal infrastructure of either the San Patricio Municipal Water District or the O.N. Stevens Treatment Plant, 3) diversion of either river or groundwater through wind or solar pumping, or 4) some combination of the above. A detailed analysis of each of these alternatives was presented in the Plan of Study for the demonstration project (Bureau of Reclamation 1993). Each of these alternatives would have supplied some measure of fresh water into the upper delta and estuary. However, none of the alternatives would have adequately met the first objective of the demonstration project, which was to restore the opportunity for natural freshwater flow events from the Nueces River into the delta.

Monitoring Program

The second objective of the demonstration project was to monitor any resulting changes in the hydrography and productivity of the delta from freshwater flow events. The data collection program was therefore designed to monitor hydraulic conditions in the study area, as well as those biological parameters that would be most responsive to project diversions: namely, water column productivity, benthic communities and vegetation communities. Each of these monitoring elements were regularly sampled at various stations in the upper delta (Table 1-1). The biological monitoring program was initiated in October of 1994, some 12 months before the Nueces Overflow Channel was opened. This initial 12-month period served as a baseline period before the effects of the demonstration project began. The hydraulic monitoring began with the installation of gauging instrumentation in April of 1996. In addition to the data directly collected as part of the demonstration project, the measurements of other monitoring and research efforts were also

Figure 1-8: View of the low water crossing at the head of Rincon Bayou. This access road was one of several road improvements made as part of the demonstration project. The photo was taken on June 26, 1997, during the first significant flow event.

Photo courtesy of the Bureau of Reclamation.

Table 1-1: Summary of the annual monitoring program conducted as part of the demonstration project.

Monitoring Element	Response Variables	Schedule	Stations
Hydrography	precipitation; and *stage*, *velocity* and calculated *discharge* through the Nueces Overflow Channel	Continuous	1
Water Column Productivity	water quality (conductivity, temperature, depth, dissolved oxygen, calculated density, total suspended solids and water clarity)	Monthly	8
	nutrients (orthophosphates, dissolved silicon, nitrate, nitrite, ammonium, particulate carbon and nitrogen (PC/PN), dissolved organic nitrogen (DON))	Monthly	8
	phytoplankton (species composition and size fractionation of major producing groups, biomass and growth rate of suspended species and of microphytobenthos (benthic phytoplankton))	Monthly	8
Benthic Communities	macrofauna (species composition, density and biomass)	Quarterly	6
	meiofauna (species composition, density and biomass)	Quarterly	6
Vegetation Communities	pore water and open water (salinity, nitrate, nitrite, ammonium and temperature)	Quarterly	3
	macrophyte communities (species composition, percent cover and leaf-area)	Quarterly	3
	macrophyte communities (above-ground biomass, below-ground biomass and calculated root/shoot ratios)	Bi-annually	3

utilized when available. These additional data sources included the Texas Coastal Ocean Observing Network marine monitoring system of Texas A&M University-Corpus Christi Conrad Blucher Institute, the weather station network administered by the National Weather Service, the national stream flow gauging program conducted by the United States Geological Survey and unpublished data from faculty at the University of Texas Marine Science Institute.

The study "treatments" were considered to be freshwater diversions into Rincon Bayou either through the Nueces Overflow Channel or over the bank of the Nueces River. A comparison site was needed that would be subject to the same general environmental conditions (*e.g.*, tide, evaporation, precipitation, runoff, *etc.*) as the treatment sites but would not be affected by the project's diversions. This site, located in the upper delta, served as an acceptable "reference" to which data from treatment sites could be compared. Therefore, the demonstration study included a total of four monitoring sites: one reference and three treatment (upper Rincon Bayou, central Rincon Bayou and tidal flats) (Figure 1-9).

This monitoring aspect of the demonstration project involved the time observation of responses in the biological resources of the delta to intended (though not fully controlled) applications of fresh water. As with many biological studies, assessment of treatment

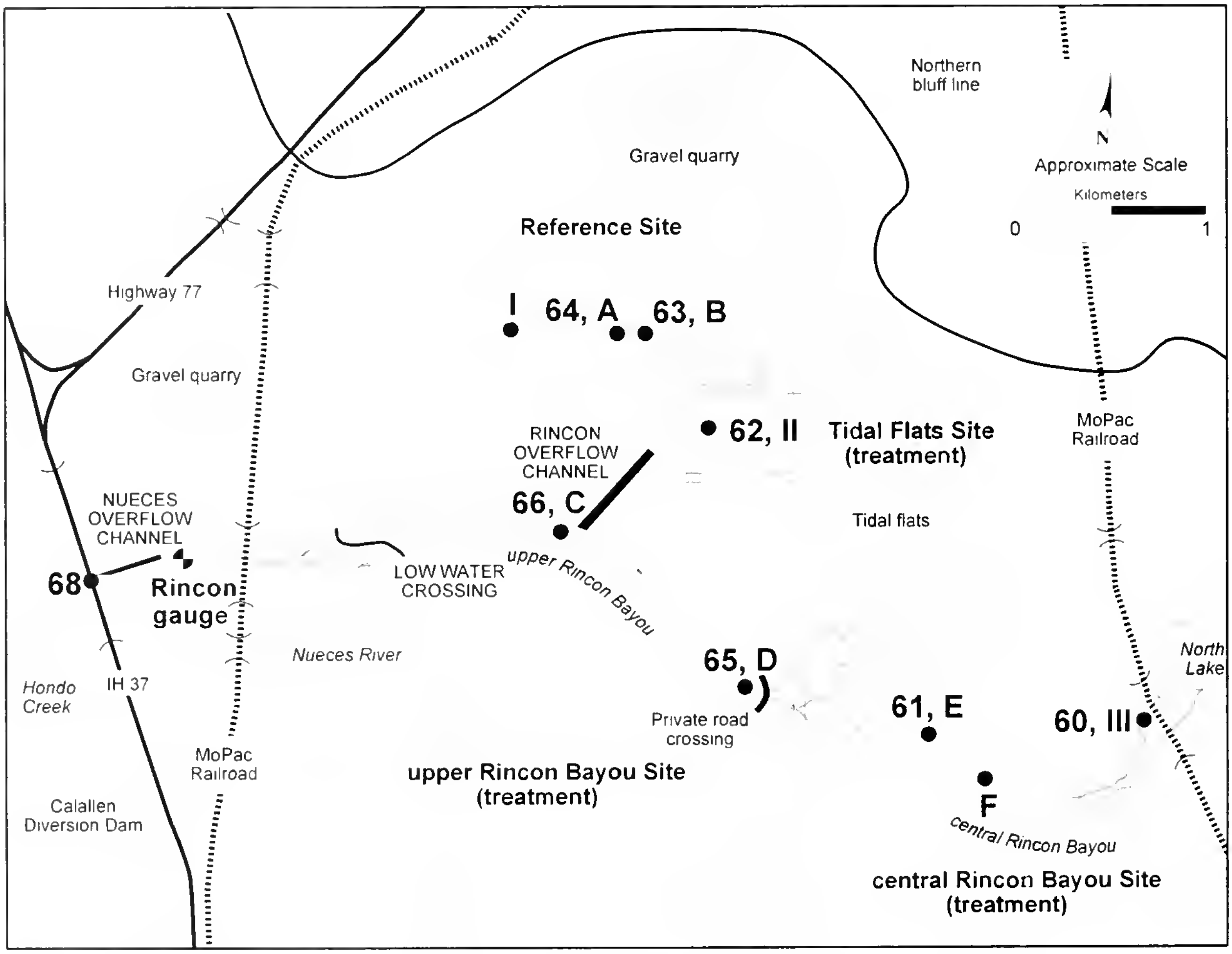


Figure 1-9: Overview of the monitoring sites and stations established for the Rincon Bayou Demonstration Project. In general, the study design included one reference site and three treatment sites (upper Rincon Bayou, central Rincon Bayou and tidal flats). The location and number of sampling stations at each site is indicated by numerals (60 through 68) for water column productivity, letters (A through F) for benthic communities, and Roman numerals (I through III) for vegetation communities.

applications is often complicated by the difficulty in establishing a suitable experimental control. Here, the establishment of a random control area was not practical. Consequently, the basis of comparison of responses in biological productivity and species diversity to freshwater applications was fashioned according several considerations. First, hydrographic and biological data collected from the delta and surrounding area in years prior to the start of the current study offered some credible information on the status of the delta. Analyses of such pre-study data have been or are in the process of being published elsewhere, thus providing some characterization of conditions in the delta prior to the start of this study. Second, studies by scientists on this project and others have previously established some biological response relationships to fresh water in Gulf Coast estuaries, and in particular, responses to changes in salinity. These known responses were an important tool in assessing the effects of the demonstration project. The experience of project scientists with conditions in the Nueces Delta and similar estuaries offered highly relevant expertise to project studies. Third, a site was selected as a reference (*i.e.*, comparison) point based on location and lower likelihood of impacts from freshwater inundations (*i.e.*, treatments). Obviously, the more affected by project diversions, the less useful the reference site would be in evaluating treatment effects. Finally, the duration of data collection (over five years) and the varying freshwater inputs to the upper delta allowed the study of relationships to the varying biological responses (*e.g.*, consistency in response). Consequently, the demonstration project monitoring program was quasi-experimental in design. Nevertheless, previously established biological and ecological relationships applied here enabled the opportunity for deductive conclusions central to the goals of this study.

In designing the monitoring plan for the demonstration project, Reclamation again considered several different alternatives. Most of these alternatives included using data on wildlife or fish use of the area (*e.g.*, mammals, reptiles, waterfowl, shorebirds, fin-fish, shellfish, *etc.*) as a measure of project success. However, considering the extensive non-estuarine migratory range of many of the species which utilize the study area, it was determined that these organisms would be subject to a variety of other forces not related to the demonstration project. Using such data to establish relationships between the direct effects of the project and observed changes in wildlife or fish populations or habitat use would have been difficult. For this reason, vertebrate wildlife use was considered to be an ineffective tool in evaluating the direct effects of the project on delta productivity.

PARTICIPANTS

There were several key participants in the Rincon Bayou Demonstration Project. The primary participants of the study, without whom this project would not have been possible, were the private landowners in the delta who granted Reclamation temporary permission to make the modifications and conduct the monitoring program. The design, coordination and funding of the project was provided by Reclamation. All of the biological data collection and analysis activities were conducted by researchers from the University of Texas Marine Science Institute, with support from the Texas Water Development Board. The hydraulic monitoring was conducted by the U. S. Geological Survey, who installed and maintained the data collection equipment, and hydrographic data analysis was provided by the University of Texas Center for Research in Water Resources.

AUTHORITY AND FUNDING

The Rincon Bayou Demonstration Project was conducted under the authority of the Federal Reclamation Act of June 17, 1902, as amended. Funding for the study was appropriated on a yearly basis by the United States Congress under Reclamation's General Investigations and Wetland Development programs.

CHAPTER TWO

Study Area

"If there are seventy-five square miles on this earth that disgrace it, those seventy-five square miles may be found here, Nueces Bay being one big slimy slough, only fit for the habitation of alligators and mud-snakes."

❖ Dr. A.C. Peirce (1894)

BACKGROUND

THE NUECES ESTUARY

There is no universally accepted definition of an estuary, though these systems are generally considered to share the following properties: a 1) coastal water body, that is 2) semi-enclosed, with 3) free connection to the open sea, with both 4) an influx of seawater, and 5) an influx of freshwater, and which is 6) of small to intermediate scale (*e.g.*, Pritchard 1967; Ward and Montague 1996). The property of scale differentiates an estuary from larger systems, such as the Mediterranean Sea, the Baltic Sea, and the Gulf of Mexico, which satisfy the other properties but clearly are not estuaries. These properties do not necessarily occur all of the time, as in many estuaries, the relative influence of freshwater and seawater influxes varies with season. In essence, an estuary is a transitional system between a purely freshwater and a purely marine system. It is, therefore, influenced by processes that are terrestrial and marine, but there are also hydrographic features unique to the estuarine environment and a consequence of its transitional character.

The boundaries of the Nueces Estuary include four bay systems (Texas Department of Water Resources 1982): one primary bay (Corpus Christi), one secondary bay, (Nueces), and two tertiary bays (Oso and Redfish) (Figure 2-1). In terms of geomorphic classification, the estuary is considered a coastal plain estuary (Pritchard 1967), being composed of a drowned river valley lying perpendicular to the coastline. However, the Nueces Estuary also shares characteristics of lagoons with large, bar-built bays parallel to the coastline, like

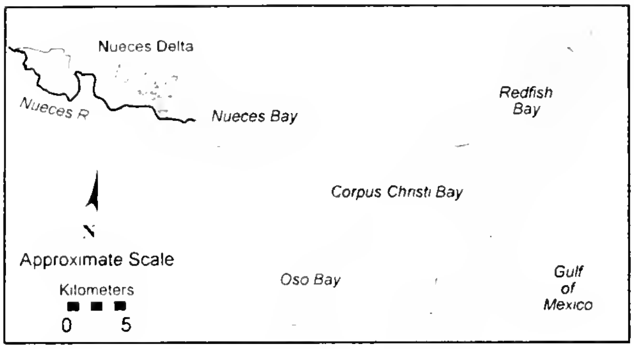


Figure 2-1: The Nueces Estuary and Delta.

Redfish Bay. The total estuary has an average depth of about 2 meters (m) and covers approximately 500 square kilometers (km^2) (Orlando *et al.* 1993). The bays are protected from the Gulf of Mexico by a system of barrier islands, and the only significant tributary of the estuary is the Nueces River. As a transition between continental and oceanic environments, the Nueces Estuary is subject to the effects of both marine and fluvial (riverine) elements. Included in the boundary of the Nueces Estuary are the tidally influenced portions of the Nueces Delta, which lies immediately west of upper Nueces Bay.

THE NUECES DELTA

The Nueces Delta (or Nueces marsh) is a complex area of vegetated marshes, mudflats and open water that covers approximately 75 square kilometers (km^2) (Figure 2-2). Along its northern boundary, the delta is separated from a large expanse of agricultural land by a steep bluff that reaches heights of about 20 m. To the south, the delta is separated from the municipal and industrial areas of the City of Corpus Christi by a similar bluff. The eastern limit of the delta is delineated by the upper segment of Nueces Bay, and the western limit by Interstate Highway 37 (IH 37) where it crosses the Nueces River. Upstream of this

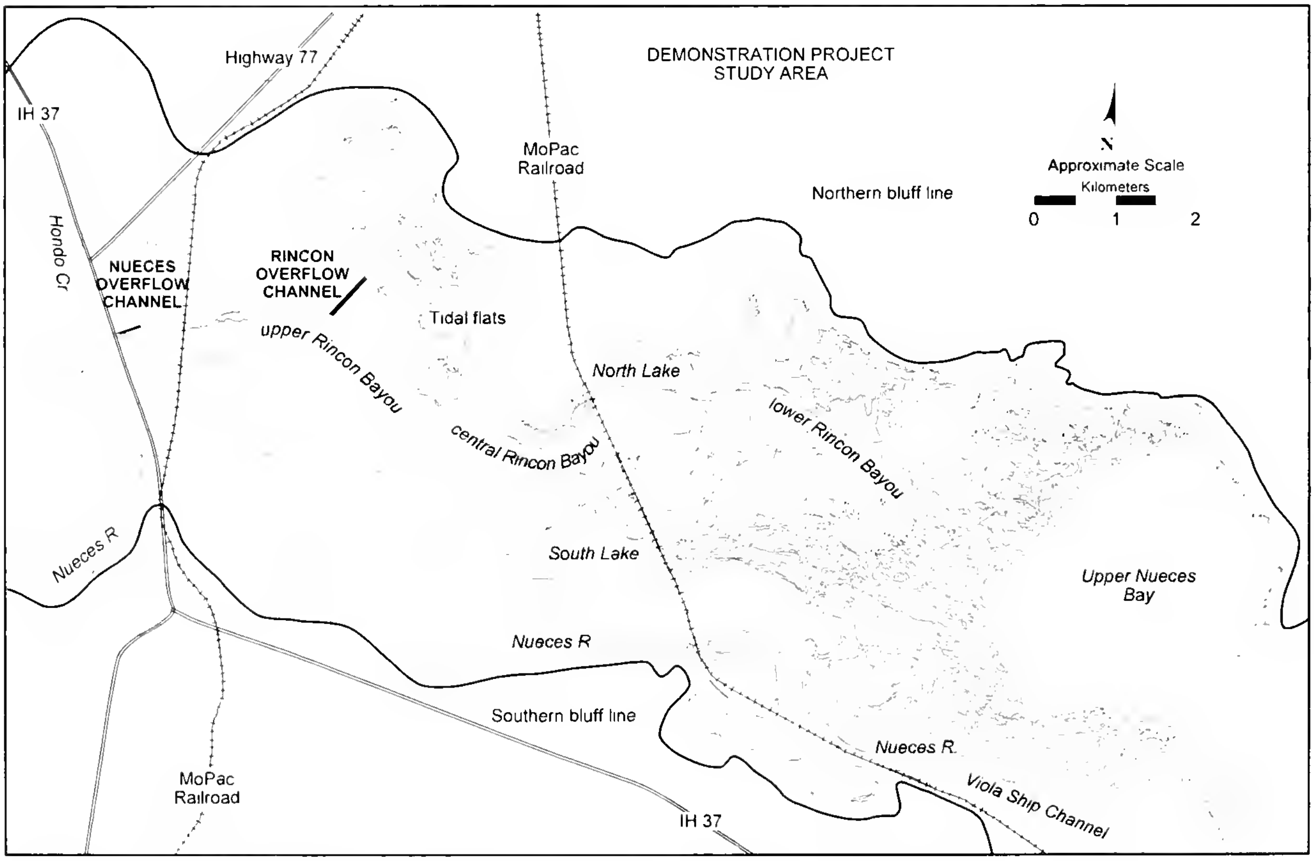


Figure 2-2: The Nueces Delta. Generally depicted are open water (shaded) and tidally influenced areas.

Source of base map: Salas 1993.

point, the broad Nueces floodplain extends for several miles in a northwest direction, being confined to a width of approximately 2 to 5 km.

Along the southern edge of the delta, the Nueces River flows west to east for approximately 15 km and empties into Nueces Bay. The banks of the river along this reach, which are generally about 1.5 to 2.5 m high, are steep and wooded. At higher flows, the river spills into the delta through numerous depressions along its northern bank. Within the delta itself, the two dominant hydraulic features are Rincon Bayou and South Lake (Figure 2-2). Rincon Bayou, which was likely once a course of the Nueces River, stretches along the entire northern portion of the delta to the bay. The depth and width of this channel varies greatly along this reach, at times being confined to just a few meters wide and at other times opening up into several large, shallow lakes or pools (*e.g.*, upper Rincon Bayou, central Rincon Bayou, and North Lake). South Lake is a large pool located in the south-central portion of the delta and is connected to the upper Nueces Bay by numerous tidal channels.

The delta is crossed latitudinally by two Missouri-Pacific (MoPac) railroads. The western-most railroad is located just downstream of the IH 37 bridge, crossing only the extreme western portion of the delta. The eastern-most railroad divides the delta roughly in half, with a majority of the lower (eastern) half being regularly inundated by water from upper Nueces Bay. The upper (western) half of the delta is generally higher in elevation, and only the lower channels and pools are regularly inundated by the bay. Both railroad crossings are elevated 3 to 5 m above the ground by fill material for most of their span, with the exception of a few bridged crossings over the more significant channels.

Generally, habitat features are quite diverse within the Nueces Delta, ranging from wooded upland areas to open bay waters. The western (upper) half of the delta is primarily dominated by rangeland and improved pastures, with brush thickets dominating the higher elevations, and a mixture of intertidal mud flats, marshes, shallow pools and channels dominating the lower elevations (Figure 2-3). The eastern (lower) half of the delta is almost exclusively dominated by brackish and saltwater marshes (Figure 2-4). Along both the northern and southern bluffs, remnants of diverse coastal forests exist where they have not been displaced by agriculture or development (Salas 1993).

Figure 2-3: Typical view of the upper Nueces Delta. The view is looking northeast, with North Lake in the background.

Photo courtesy of the Bureau of Reclamation.

HYDROGRAPHY OF THE NUECES ESTUARY AND DELTA

The Nueces Estuary and associated river delta are greatly influenced by water originating from riverine,

Figure 2-4: Typical view of the lower Nueces Delta. Nueces Bay is a short distance to the right, and the bluff along the northern boundary of the delta is in the distant background.

Photo courtesy of the Bureau of Reclamation.

estuarine and marine aquatic environments. Therefore, key hydrographic indicators like water level and salinity represent the combined effect of hydro-meteorological forces, including tides, wind, precipitation and local runoff, and river inflow.

WATER LEVEL

Water level variations in the Nueces Estuary are generally the result of interactions between (astronomical) tides, long-term secular excursions of the Gulf of Mexico and meteorological forcing (winds) (Ward 1997).

Tides

Of the many Fourier tidal components, four in particular account very well for the observed variation in the Nueces Estuary (Ward 1997). The three astronomical tides, which are generally short-term influences, include a semidiurnal (12.4-hour) and diurnal (24.8-hour) tide, each of which is then modulated by a 27.2-day lunar tide (*i.e.*, the variance of water level resulting from variations in the declination of the moon). The physical causes of fourth tidal component, a long-term secular variation in the Gulf of Mexico, are not well understood. In a "normal" year, there are clear *maxima* in the spring and autumn, and clear *minima* in winter and summer. The semi-annual variation is generally considered to be dominated by the winter minimum and autumn maximum (Chew 1964). Ward (1997) has summarized the features of this secular variation to include the following characteristics: 1) there are considerable year-to-year differences in the seasonal water-level variation, 2) the autumn maximum is usually the highest mean water elevation of the year and the winter minimum is usually the lowest, 3) the summer minimum in July and the autumn maximum in October are the most consistent in terms of seasonal regularity, 4) both the winter (December to March) and spring (April through June) extremes have a considerable seasonal range in which they occur and can exhibit multiple extremes during these periods, and 5) despite reference to a semiannual period, the signal is not harmonic, as both the autumn maximum and the summer minimum, especially the former, tend to be more sharply focused in time and extend over two-six weeks in duration.

This semi-annual variation is a prominent component of water level variation in the Nueces Estuary, and becomes increasingly important, compared to the other tidal components, with distance into the upper reaches of the bays, especially in Nueces Bay and Delta. The filtering properties of the inlets, shallow bays and channels greatly attenuate the shorter period frequencies (*e.g.*, semidiurnal and diurnal signals), but pass the longer periods with virtually no attenuation. As a result, water level variations caused by the cyclical lunar tide and the semi-annual secular rise and fall of water level in the Gulf represent the predominant long-term mechanism of water exchange with the Nueces Estuary. These two factors also account for most of the (greatly attenuated) tidal variation of water level within the upper Nueces Bay and Delta.

Wind

On a shorter time scale, meteorological forcing (wind) is a prominent mechanism for water-level variation. The principal process is the response of a free surface to an imposed stress, referred to more colloquially as "setdown" or "setup" of water levels. Where there are adjoining bay systems (such as Nueces and Corpus Christi bays, or Corpus Christi Bay and the Gulf of Mexico), winds cause a direct downwind set-up of water levels across component bays. This difference in water levels causes a direct and an indirect water exchange between the water bodies. The direct effect is that of wind stress on the bay itself. The indirect response of the same bay is that resulting from wind stress on the adjacent water body, which forces water into or out of the former. The area over which the winds operate and their duration are both important in the magnitude of the estuary's response.

There are three types of meteorological forcing elements common to the Nueces Estuary: frontal passages, sea breezes and storm surges. 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. Ward (1997) differentiates two classes of fronts: the relatively short-lived low-energy "equinoctial" frontal passages that do not force a response in the large water body of the Gulf, and the large-scale, longer duration "outbreak" fronts that result in exchange between the Gulf and the interior bays.

The response of the Gulf of Mexico during frontal passages is the single most important factor determining the total response of the interior bay systems. For Nueces Bay there is a two-step response, the response of the bay to setdown of Corpus Christi Bay, and the response of Corpus Christi Bay to setdown in the Gulf of Mexico. 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 (Ward 1997). The cross-bay transports, on the other hand, occur much more quickly but entail smaller water level changes and smaller volumes (generally on the order of 1% of the volume of the bay).

Another short-period force affecting water levels in the Nueces Estuary and Delta is the sea breeze cycle. A sea breeze 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). It is ultimately caused by the difference in thermodynamics of sea water and land surface and is most pronounced along their boundary. As the sea breeze circulation begins to develop, it imposes an organized circulation in the lower atmosphere that spreads inland and increases the wind speed. The reverse circulation develops in the evening as a land breeze, spreading out to sea from the coastline. In the coastal zone itself, the sea breeze 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 wind-waves (chop) are well-known features of summer hydrography in these bays attending the sea breeze.

The sea breeze is a relatively weak circulation, and its importance depends on other factors affecting wind. The effect of the sea breeze on water levels in the estuary may be minimized 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. The sea breeze is therefore best developed during conditions when these other influences are uncommon, which is typically during summer.

Finally, the most extreme water level responses of the Nueces Estuary to meteorological forcing are associated with the storm surges of tropical depressions. These intense organized tropical systems, the most extreme representative being the hurricane, are characterized by a cyclonic circulation with intense swirling winds around a center of extremely low pressure. The low pressure center and the circulating winds combine to create an elevated mound of water (storm surge) that moves with the depression, but the wind stress on the water's surface is the more important determinant of the magnitude of the surge.

As the cyclone and associated storm surge make landfall, the volume of water in the surge behaves as any long-period shallow-water wave, slowing due to shoaling water depths and steepening. As the surge propagates into bays and estuaries, it is subjected to various local physiographic modifications. In some regions, this can lead to further amplification of the surge height, and some of the highest recorded surges on the Texas coast have occurred on the inland side of the bays, the largest being Hurricane Carla surge measured at Port Lavaca in excess of 6.7 m. While a hurricane can inflict damage through high winds, tornadoes and intense rainfall, it is the surge, perhaps in concert with wave attack, that is responsible for most of hurricane-related impacts on the Texas coast.

In extreme instances, tropical storms may also have a secondary effect upon water levels in the estuary due to heavy precipitation. Such was the case with Hurricane Beulah, which made landfall in the autumn of 1967.

Inflow resulting from the record-setting flood event in the Nueces River caused a substantial rise in water levels in Nueces and Corpus Christi bays of up to 0.6 m above that of the Gulf of Mexico (Grozier *et al.* 1968; Corps of Engineers 1968). Grozier *et al.* (1968) went on to report that water levels in the bay were slow to fall (it took several days) because of the enormous amount of runoff from the rains inland, even though Corpus Christi Pass and two other new channels were opened between the bays and the Gulf by the storm.

SALINITY AND FRESHWATER INFLOW

In general, salinity concentrations in estuary systems are stratified horizontally and vertically, both of which are primarily determined by the size and location of the freshwater source(s). Over the area of the estuary (horizontal), the gradient of fresh to brackish to marine salinity concentrations (which is 0 to 15 to 30 parts per thousand (ppt) salt, respectively) progresses from the areas closest to the freshwater source (*i.e.*, river's delta and mouth), to the secondary bay(s), then to the primary bay. The degree of salinity stratification in the water column (vertical) depends upon the intensity of mixing.

In Nueces Estuary

As in most estuaries, there are substantial spatial gradients in salinity across the Nueces Estuary, not only because of the great range in hydro-climatology, but also because of the location of the river drainages and the variable influence of the sea (Ward and Armstrong 1997). Based on evaluation of long-term data, seasonal variations in the salinity of the Nueces Estuary, other than a proclivity for slightly higher salinity concentrations in the summer, were not readily evident (Ward 1997). Salinity variations within the water column (*i.e.*, stratification) in the Nueces Estuary was found to be minimal (less than 0.5 ppt), but the largest values of this (small) gradient typically occurred in Nueces Bay, nearer to the freshwater source (Ward 1997). One exception to this generalization is evaporation stratification, which typically occurs in stagnant portions of Corpus Christi Bay during the summer. In this case, the salinity gradient in the water column can be as much as 6 ppt and often associated with hypoxia (Ritter and Montagna 1999).

Short-term vacillations of salinity values within the greater Nueces Estuary are primarily in response to water-mass changes. 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 event diminishes (intrusion). These two mechanisms involve different physical processes, and therefore are not symmetric events. Extrusion is effected by a replacement of water volume due to the rapid influx of the inflow (river) hydrography, commonly called a "freshet" event. Intrusion is accomplished by the internal circulations gradually returning higher salinity water to the upper reaches of the bay and delta. 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, displacement of salt water by fresh is assisted by both wind forcing (frontal cross-bay transports and efflux to the Gulf) and surface precipitation surfeit. Intrusion, occurring over a longer time frame, is assisted by the typical evaporation deficit at the surface.

One factor of the regional hydro-climatology 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. 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 Corpus Christi Bay or even the Gulf of Mexico. Intrusion, on the other hand, is the combined effect of smaller water mass transfers, such as tidal exchanges and internal transports, whose cumulative behavior is more of a diffusive process, operating to mix out and 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 characteristics of the freshet response.

In Nueces Delta

In the Nueces Delta, variations in salinity concentrations of the pools, channels and marshes are driven by the same mechanisms as in the bays (*i.e.*, water-mass exchanges involving both intrusion and extrusion processes), with two significant differences. First, because much of the water in the delta is segregated into shallow pools and channels by higher land formations, many of these become frequently isolated from the bay due to water level fluctuations. This seclusion magnifies the effect of evaporation, resulting in the concentration of salts from bay water into the soils and water of the delta. The opportunity for continuous dilution by very large volumes of bay water enjoyed elsewhere in the estuary is not readily available in the delta.

Second, the magnitude, frequency, duration and timing of freshwater flow events (or freshets) into the Nueces Delta are burdened by one additional condition not applicable to Nueces Bay. This condition is that the stage (water level) attained by the flood event in the river must exceed the minimum flooding threshold of the river in the delta segment of the stream (determined by the elevation and dimensions of the lowest portions of the river bank) (Figure 2-5). Therefore, unlike Nueces Bay, the opportunity for freshets in the delta are limited to discrete periods of time when the river hydrograph sufficiently meets this condition. If the flooding threshold is not met, the flow event in the river will bypass the delta, providing Nueces Bay with an intrusion event without the same courtesy for the delta.

These periodic deltaic inundation events usually coincide with tropical storm activity in early autumn or with the passage of frontal systems in late spring (Texas Department of Water Resources 1982). Such flooding events flush the numerous channels and ponds of the delta, and inundate large areas to an extent and depth governed by the volume and duration of the flood event (Ward 1985) (Figure 2-6). These discrete events also serve as a mechanism whereby salts, as well as organic materials and other nutrients produced in the delta marsh, are exported from the delta into the greater Nueces Estuary. Because of

Figure 2-5: Nueces River (looking downstream) just below the IH 37 bridge under flood conditions (April 1992). During such high-flow events, the river spills fresh water into the upper Nueces Delta from several low points along the north (left) bank.

Photo courtesy of the Bureau of Reclamation.

Figure 2-6: Natural flooding of the upper Nueces Delta, April 1992. Such freshwater inundation events significantly contribute to the biological productivity of the delta by providing a medium for nutrient exchange and biochemical cycling, supplying freshwater to marsh plant communities, transporting detrital and other nutrient materials from the established marsh vegetation and sediments to the bay, and buffering bay salinity.

Photo courtesy of the Bureau of Reclamation.

these events, the Nueces Delta is one of the most important sources of nutrient material for the entire estuary system (Texas Department of Water Resources 1981).

ECOLOGY OF THE NUECES ESTUARY AND DELTA

Montagna *et al.* (1996) has described eight different types of habitat subsystems occurring in the Nueces Estuary: salt marshes, beaches, the water column, muddy bottoms, sandy bottoms, oyster reefs, seagrass beds and algal mats. Although each subsystem is described separately, it is noted that there are many interconnections among them, as water currents, waves and tides transport organic matter, energy and even animals pass between habitats (Montagna *et al.* 1996).

According to a conceptual ecosystem model developed for the Nueces Estuary (Montagna *et al.* 1996), these eight habitat subsystems may be organized by their relative relation to the tidal water level. Intertidal habitats (those within the range of high and low tides) include salt marshes and beaches. Salt marshes are important sources of organic matter for the estuary, serve to buffer shorelines and provide habitat for important fish and wildlife species. Beaches support a low diversity of species because they experience high energy from waves, wind and currents which mix and transport detrital matter (plant and animal tissue) from the estuarine and marine environments.

Subtidal habitats (those below the average low tide level) include the water column, muddy bottoms, sandy bottoms, oyster reefs and seagrass beds. The water column (*i.e.*, the vertical portion of open water areas) supports a complex and productive food-web comprised of small, often single-celled organisms (plankton) that move with currents, and their predators, which are larger organisms (nekton), like fish. Beneath the water column, the substrate of the estuarine floor may be muddy or sandy. Muddy bottoms are more common in the estuary and support shrimp and other commercially important species, while sandy bottoms, which occur near the shoreline, are less common and support a number of large animals. Oyster reefs are associated with high diversity because they provide substrate, shelter and foraging opportunities for many different species. Seagrass beds are very diverse and productive, and serve as an important nursery ground for larval crustaceans, fish and invertebrates.

Supratidal habitats (those above the average high tide level) include algal mats. Algal mats occur in isolated pools only periodically inundated by tide or rainfall and are comprised of nitrogen-fixing mats of filamentous blue-green algae living in colonies on the sediment surface. These habitats provide nutrients to shoreline environments and foraging habitats for wading birds.

ESTUARINE HABITATS IN THE NUECES DELTA

The most predominant estuarine habitat subsystems in the Nueces Delta are salt marshes, the water column, muddy bottoms and algal mats. The following more detailed description of these habitat types were primarily derived from Montagna *et al.* (1996), except where noted.

Salt Marsh

Salt marshes are located in the shallow or intertidal regions of the estuary and delta, often near a source of freshwater input (*e.g.*, river mouths and secondary bays), and are dominated by marsh grasses and other plants (Figure 2-7). The salt marsh of the Nueces Delta is the most extensive within the Nueces Estuary. Salt marshes trap soft sediment and organic material from the water column between individual plants. Beneath the plants are strong reducing conditions, and often low oxygen levels due to decomposition of organic matter. Areas with a higher frequency of freshwater inflow have higher diversity, higher rates of primary production and higher net community production. The biomass of producer and consumer organisms can also be high, but species diversity can be low because of fluctuating salinity.

Figure 2-7: View of salt marsh habitat in the upper Nueces Delta. The vegetation transect for Station I is in this vicinity.

Photo courtesy of the Bureau of Reclamation.

Like seagrass beds, salt marshes are also an important nursery and feeding grounds for a variety of invertebrates and fish. Because of the amount of dead and decaying plant matter in salt marshes, their contribution of detritus to the food-web of adjacent habitats is important. The plant litter is utilized by micro-organisms and other small estuarine animals (Marples 1966) and serves as a critical link between primary and secondary trophic levels (Burkholder and Burkholder 1956; Odum and Wilson 1962; Teal 1962). Marsh plants also provide shelter for a variety of small organisms, including crustaceans, avians and mammals, and serve to stabilize marsh sediments. Because of these functions, the marsh subsystem in the Nueces Delta supports numerous estuarine organisms, including shrimp, crabs and fin-fish, by providing large amounts of food and structure.

One of the primary variables affecting the distribution and abundance of vegetation species in the delta marsh is salt. Salt is generally imported into the delta from Nueces Bay by a variety of tidal and wind forces, and generally exported from the delta by infrequent freshwater inundation events resulting from over-banking floods in the Nueces River. Water and soil salinity can be highly variable, depending upon precipitation, tide level and temperature (Henley and Rauschbauer 1981), especially because evaporation often exceeds precipitation for several months a year (Longley 1994). Elevation and proximity to channels and creeks are also factors that affect salinity, which often results in distinct vegetation zones (Chapman 1960; Chapman 1974; Nixon 1982).

Although most marsh plant species in the delta are salt-tolerant (halophytic), excessive salt concentrations can cause hypersaline conditions which are adverse to plant survival. For example, although halophytic species can survive in intermittent hypersaline environments, prolonged periods of salinity stress can stunt active growth and reproduction, leading to decreases in abundance and productivity (Deegan *et al.* 1986; Bertness *et al.* 1992). Ultimately, decreased vegetative coverage can create bare areas, which are then directly exposed to evaporation, leading to further increases in salinity (Zedler 1983; Bertness 1991). Successful re-colonization of bare areas requires at least a short-term lowering of salt concentrations in the soils, which allows re-invasion by vegetative (rhizomes) or reproductive (seed germination) growth.

Water Column

The water column habitats of the Nueces Estuary and Delta are shallow and are often only as productive as their substrate (Figure 2-8). This is in contrast with marine environments, such as the Gulf of Mexico, where the water column habitat is very deep and more productive than the bottom. Because fresh water mixes with salt water in the bays, the resulting salinity concentrations are often brackish (10 to 25 ppt). However, when evaporation exceeds freshwater inflow and flushing by the ocean, salinity concentrations can become saltier than the ocean (> 35 ppt). During dry periods in the delta, where supratidal pools and channels may become isolated for extended periods of time, salinity concentrations may exceed that of the ocean by several times. The estuarine water column is usually well oxygenated but can become quite turbid as sediment is re-suspended by wind or human activities. Mixing, due to the consistent high winds and shallow depths, prevents significant stratification of the bay water column.

Figure 2-8: View of water column habitat in central Rincon Bayou.

Photo courtesy of the Bureau of Reclamation.

The water column food-web consists of phytoplankton (single-celled plants) being eaten by zooplankton (single-celled animals), which in turn are eaten by fish. Primary production (the conversion of solar energy to chemical energy by photosynthesis) by phytoplankton in estuarine water can be relatively high but is typically much less than in salt marshes. There are two cycles of energy in the water column food-web. The first may be referred to as the "microbial loop," which includes only small flagellated phytoplankton and zooplankton and bacteria. Flagellates are a very diverse group of plankton that can travel short distances by beating their whip-like flagella. The small phytoplankton are preyed upon by small zooplankton, and, when the small phytoplankton and small zooplankton die, they may be decomposed by bacteria in the water. This food-web cycle is small, transfers energy rapidly, and its components are tightly coupled. However, energy cycled in this microbial food-web are not usually transferred to higher trophic levels (*e.g.*, fish).

The second food-web cycle of the estuarine water column consists of the larger phytoplankton, such as diatoms, which are eaten by zooplankton and some fish. In addition, some zooplankton are eaten by larger zooplankton and the larval and adult forms of some fish. Even larger predatory fish (*e.g.*, red drum, *Sciaenops ocellatus*) then eat these plantkivourous fish. This food-web cycle is larger, and it transfers energy slower than the microbial loop cycle, but both cycles are important in nutrient processing within the estuary.

Open Water, Muddy Bottom

The most common benthic habitat in the Nueces Estuary is the unvegetated muddy bottom (Figure 2-9). Movement of water over the surface of the mud keeps the sediment oxygenated to about one centimeter in depth. Below this region is a strongly reduced environment due to the presence of oxygen-consuming microbial animals. Mud is easily re-suspended, and muddy bottoms may therefore experience frequent erosion or deposition of sediment. Turbidity tends to be high at the surface, which restricts the presence of light-dependant primary producers and filter feeders. Deposit feeders, however, can be present in high abundance, diversity and biomass.

Detritus is the most important source of carbon for muddy bottom habitats. This material may originate from terrestrial sources transported by freshwater inflow, marine sources derived from marshes, seagrasses or sedimented phytoplankton. In the benthic muds, there are three types of animals which utilize detritus, including non-selective deposit feeders,

Figure 2-9: View of muddy bottom habitat in upper Rincon Bayou during a period of low water.

Photo courtesy of the Bureau of Reclamation.

selective deposit feeders and omnivores. Non-selective deposit feeders (*e.g.*, polychaetes) process bulk sediment by extracting organic matter from the mud. Selective deposit feeders (*e.g.*, mollusks) usually have tentacles to pick and choose specific particles of material for ingestion. Omnivores (*e.g.*, edible shrimp, *Penaeus* sp.) eat detritus, microphytes or any small animals that they can catch. These benthic animals, in turn, provide prey items for many other estuarine animals, particularly fish.

Algal Mat

Algal mats are unusual features of the supratidal zone that occur in some locations within the Nueces Estuary and Delta (Figure 2-10). They occur when rain, wave surges or higher tides collects in low spots near the shore, often in areas with higher elevation than salt marshes. The trapped water is very shallow, and often becomes quite warm and saline with solar radiance and evaporation. However, these conditions allow a bloom of photosynthetic bacteria (cyanobacteria, or blue-green algae) that live on the sediment surface. These producers are very important to the bay ecosystem because they have the ability to fix atmospheric nitrogen (N_2) into forms more usable by other producers and bacteria like ammonia (NH_3), nitrate (NO_3) or nitrite (NO_2). When this material is transported back into the bays, it represents a nutrient spike that can enhance primary productivity in the estuary. However, aside from the cyanobacteria, there are not many species endemic to the relatively harsh conditions of the algal mats.

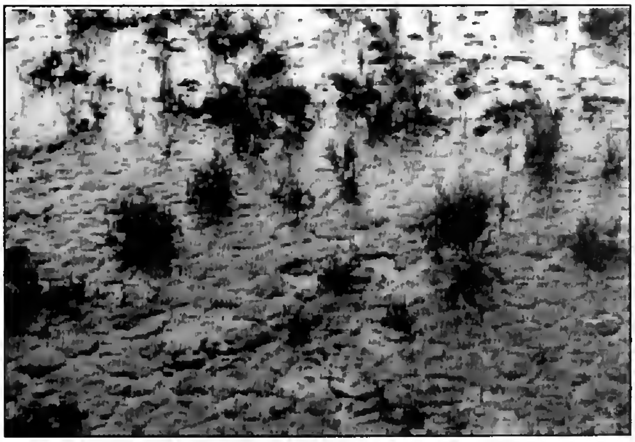


Figure 2-10: View of algal mat habitat near South Lake. This mat is comprised of colonies of filamentous blue-green, unicellular green, flagellated and diatomaceous algae, bacteria and a minor assemblage of worms, crustaceans and ciliates. The vegetation is approximately 6 to 10 inches tall.

Photo courtesy of U.S. Fish and Wildlife Service.

HISTORY OF THE NUECES ESTUARY AND DELTA

Just over a century ago, Dr. A.C. Peirce, a Bostonian naturalist intent on collecting bird species from the coastal regions of Texas, traveled to the Corpus Christi area. At that time (about 1890), Corpus Christi was still a primitive settlement on the western bayfront, accessible to the mainland by ferry across the Nueces near San Patricio, by fording El Rincon at Indian Point or by rail (Ward 1998). Peirce's book (1894) describes the travels of he and his guide (a local Corpus Christi resident and hunter), and includes several accounts of excursions into parts of the Nueces Estuary, particularly the Nueces Delta and upper bay. Although it reflects the values and judgements of the late 19th-century, the work provides a picture of the study area prior to many of the human activities that have changed it since:

> "*About a week after my arrival at Corpus Christi,... we started for the Nueces Flats. Our road was mostly through a country covered with a low growth of mesquite and weesatche* [sic] *brush, where pasture fences were much more numerous than houses, of which we saw few. . .. The land all about this part of the country is divided up into pastures containing many square miles each, which are occupied by thousands of sheep, goats, horses and neat cattle. . .. Twelve or fifteen miles from our starting place, we left the beaten road, and traveling four or five miles over a rough and hilly stretch of land, crossed the Nueces River and camped a few miles beyond.*
>
> "*Above the junction of the river with the bay is a large area of low marshy surface: this is the Nueces Flats, which include several thousand acres of land and water. In hundreds of places on the north side of the river, the earth is depressed below the level of the stream: and these depressions, filled with water, are, in places, only*

> *separated from each other and the large stream by slight elevations. . .. As a rule, the bottoms of these small bodies of water are firm, but a few of those nearest the river are decidedly boggy. On each side of the river, and between the water and the grass-covered land, is a space perhaps twenty yards in width, which is made up of bottomless mud. To venture on to this mud is simply to venture into it, and as it is seemingly without limit in depth, one might better try to walk on the ocean, so far as danger is concerned.*
>
> "*We found wild geese and ducks in abundance; nearly every one of these small ponds was well stocked with them. . .. Gulls and terns were also plentiful. . .. These birds frequent the place in search of food, which they find about the strip of mud next the river.*" (Peirce 1894).

From Peirce's description, the north bank of the Nueces River within the delta was very low. At present, the river bank in the upper delta is about 1.5 to 2.1 m (5 to 7 ft) above that of the elevation of the river under low flow conditions. Several factors could have contributed to this change, including river channelization and the intentional deposit of fill material. Evidence of the later, in the form of scattered concrete rubble and re-bar, was found by Reclamation during construction of the Nueces Overflow Channel (Figure 2-11).

Given the lower flooding threshold for delta inundations and the expanse and condition of the described mudflats adjacent to the river, the occurrence of freshets into the delta from the Nueces River were likely much more common at the turn of the century than at present. However, as can be observed today, the Nueces River in the delta was not continually fresh, as Peirce testifies that, "*the water of the river was not strong of salt, but was just brackish enough to fail completely to quench thirst*" (1894). That the Nueces River frequently experienced dry or low-flow periods prior to 1900 was also observed by others (Hollon 1956; Collins 1878).

Other evidence that the delta was much fresher than at present is the presence of *Rangia* middens (Figure 2-12). These piles of bivalve shells are the remains of foraging activities by Native Americans and may be found in the Nueces Delta at several locations along Rincon Bayou. *Rangia cuneata* is the dominant animal in Gulf coast estuaries where salinity concentrations continuously range from 0 to 15 ppt (Hopkins *et al.* 1973). Although adults can survive higher salinity values, larvae require concentrations in the range of 2 to 10 ppt for survival. The presence of large adult *Rangia* in the Nueces Delta indicates that the habitat there had been primarily oligohaline. At present, adult *Rangia* are only found only in the Nueces River just below the Calallen Dam (Kalke 2000).

Figure 2-11: Example of concrete rubble found at several points along the north bank of the Nueces River downstream from the IH 37 bridge. It is speculated that this material was intentionally placed in low portions of the bank to reduce flooding of adjacent pastures and was probably acquired from the highway bridge renovation during the late 1950's.

Photo courtesy of U.S. Bureau of Reclamation.

Several weeks later, Peirce and his guide made a second excursion, only this time they ventured into the delta by boat from Nueces Bay:

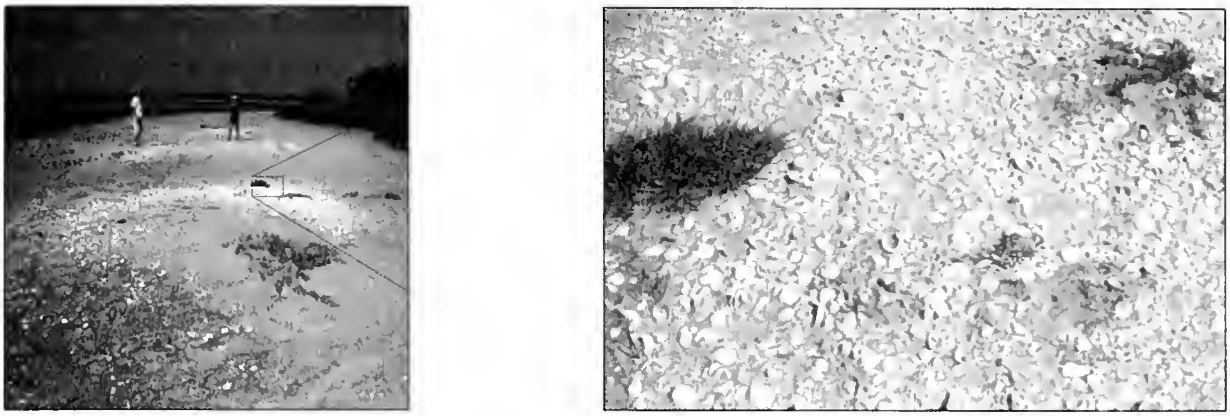


Figure 2-12: Example of *Rangia* middens (*i.e.*, piles of bi-valve shells) found in Nueces Delta. This location is along the southern edge of the central Rincon Bayou channel.

Photo courtesy of University of Texas Marine Science Institute.

> *"From a man who lived by the waters of Nueces Bay we rented a sail boat, at four bits a day. . .. Into this bay empties the Nueces River, and at the junction of the two is a mud flat, miles in extent. The river is deep and narrow, but at its mouth spreads out, as it were, to cover this great surface with an inch or two of water. The amount of water over the flat depends in a great measure upon the wind; a breeze from the east sending the water from the bay over the shoals, while a strong current of air from the west will have an opposite effect and leave the crest of the flat above the water's edge.*
>
> *"From various sources I learned that years ago the bay had extended several miles further back than now, and that the boggy soil on the sides of the river was at that time just such a flat as the one I have described. If this is true there is no reason why the whole bay may not in time be replaced by land. Such a radical change as this is to be hoped for, for if there are seventy-five square miles on this earth that disgrace it, those seventy-five square miles may be found here, Nueces Bay being one big slimy slough, only fit for the habitation of alligators and mud-snakes" (Peirce 1984).*

Peirce's description of the dynamic rate of siltation in the delta indicates that there was, during that period, a very large amount of sediment was moving down the Nueces watershed and into Nueces Bay. In fact, Morton and Paine (1984) have reported that the shoreline of Nueces Bay had been accreting (advancing) into the bay for much of the period between 1867 until the time of their research in 1982. White and Calnan (1990), who compared historical photographs of the lower Nueces Delta (below the eastern-most MoPac railroad) with those taken in 1959 and 1979, also reported an increase in total delta area. Between 1930 and 1959, the total area of the lower delta (which included both vegetated area and barren flats) increased by 164 hectares (ha) (405 acres), and between 1959 and 1979, increased by 52 ha (133 acres) (White and Calnan 1990). This process of down-basin transport of sediment was also subjectively verified in the 1930's and 1940's, when La Fruta Dam, constructed in 1935 on the lower Nueces River, began to lose a significant amount of its storage capacity due to siltation (Corpus Christi 1990).

However, although in recent years the total area of the lower delta has increased, the total vegetated area has decreased and the total water and barren areas have increased. During the 49-year period between 1930 and 1979, the total area increased by 216 ha (534 acres), but the water/barren areas increased by 345 ha (852 acres), for a net loss of 129 ha (318 acres) of vegetation (White and Calnan 1990). Subsidence (Brown *et al.* 1976) and the loss of fluvial sediments from the Nueces River were identified as possible mechanisms causing the increase in water and barren areas and the loss of marsh vegetation (White and Calnan 1990).

In yet another venture, Peirce and his guide traveled west from Corpus Christi by land, crossed the Nueces River from the south and entered into the upland Nueces floodplain several miles upstream from the delta:

> *"Above the junction of the Nueces River with the bay the river is bordered on each side by a strip of timber several miles in width; the Nueces Bottoms. The bottoms are dark and gloomy, every particle of ground not occupied by the large and magnificent trees being covered with shrubs and tall palmetto leaves; while the direct sunlight is almost completely shut out by the long and flowing Spanish moss which covers every tree, weaving their twigs and leaves together in a tangled and matted web. But for the many roots which form a network beneath the surface, all this land would be too boggy to uphold any living creature, and at the channel's sloping sides, where but few roots are present, it is dangerous to venture away from snags and logs.*
>
> *"Our course through the timber was anything but straight, and it was full two hours before the second river was before us. As was expected, here we met with trouble; for although the stream was narrow, it was not supplied with snags upon which we could cross. My partner predicted, that further down its course we should find the water-way much wider and more snaggy. Beating our way through the deep-tangled wildwood for two or three miles toward the bay, we reached that part of the swamp where the two rivers united at an acute angle. Here there was an entire change of scene. Instead of a narrow channel bordered by steep banks, there was a spread of mire acres in extent, wherein thousands and thousands of snags and water soaked logs were piled in confusion. More than this, hundreds of snakes were to be seen about and upon the driftwood, where they had come to bask in the sunshine and to feed in the shallow pools. Nearly everything supported at least one reptile, and I thought that before attempting to cross we would have to clear our intended path with powder and shot. These serpents were not all of one species, but moccasins were the predominating kind."* (Peirce 1894).

From Peirce's description, the Nueces Delta at the turn of the century began where the heavily forested bottomland of the Nueces River ended. The present floodplain, however, is significantly less wooded than what Peirce observed (Figure 2-13), likely as a result of decades of agriculture and ranching activities. The "second river" encountered in this floodplain was likely Hondo Creek, which at present is only a remnant braid of the lower Nueces that joins the river almost perpendicularly just downstream of Calallen Diversion Dam. The description of "thousands and thousands of snags and water soaked logs" at the upper end of the delta gives testimony to the size and effect of the immense floods that must have undoubtedly ravaged the heavily-wooded lower floodplain of the (reservoir-free) Nueces River watershed.

CHANGES IN HYDROGRAPHY

Water Level

There have been numerous physical changes in Nueces Estuary during the 20th-century that have altered, to some degree or another, the historical response of water level to tides and wind. These modifications

Figure 2-13: Typical view of the Nueces River floodplain upstream of the Nueces Delta. A flooded Hondo Creek is visible in the lower right. The photograph was taken on June 26, 1997, during which a flood in the lower watershed had activated secondary channels in the floodplain. The telephone pole in the center of the photograph provides an approximate scale.

Photo courtesy of U.S. Bureau of Reclamation.

include such activities as the stabilization and jettying of inlets, dredging of deep shipping channels in the bay and through the barrier island system, and installation of additional barrier features. Other factors include commercial shell dredging activity, which has been attributed for removing about 50% of the volume of Nueces Bay during the period of 1950 to 1968 (Ward 1997), and the conversion of tidal marshes to upland, particularly along the south shore of Nueces Bay, which has transformed approximately 15% of the area of Nueces Bay since 1925 (Ward 1997).

Salinity and Freshwater Inflow

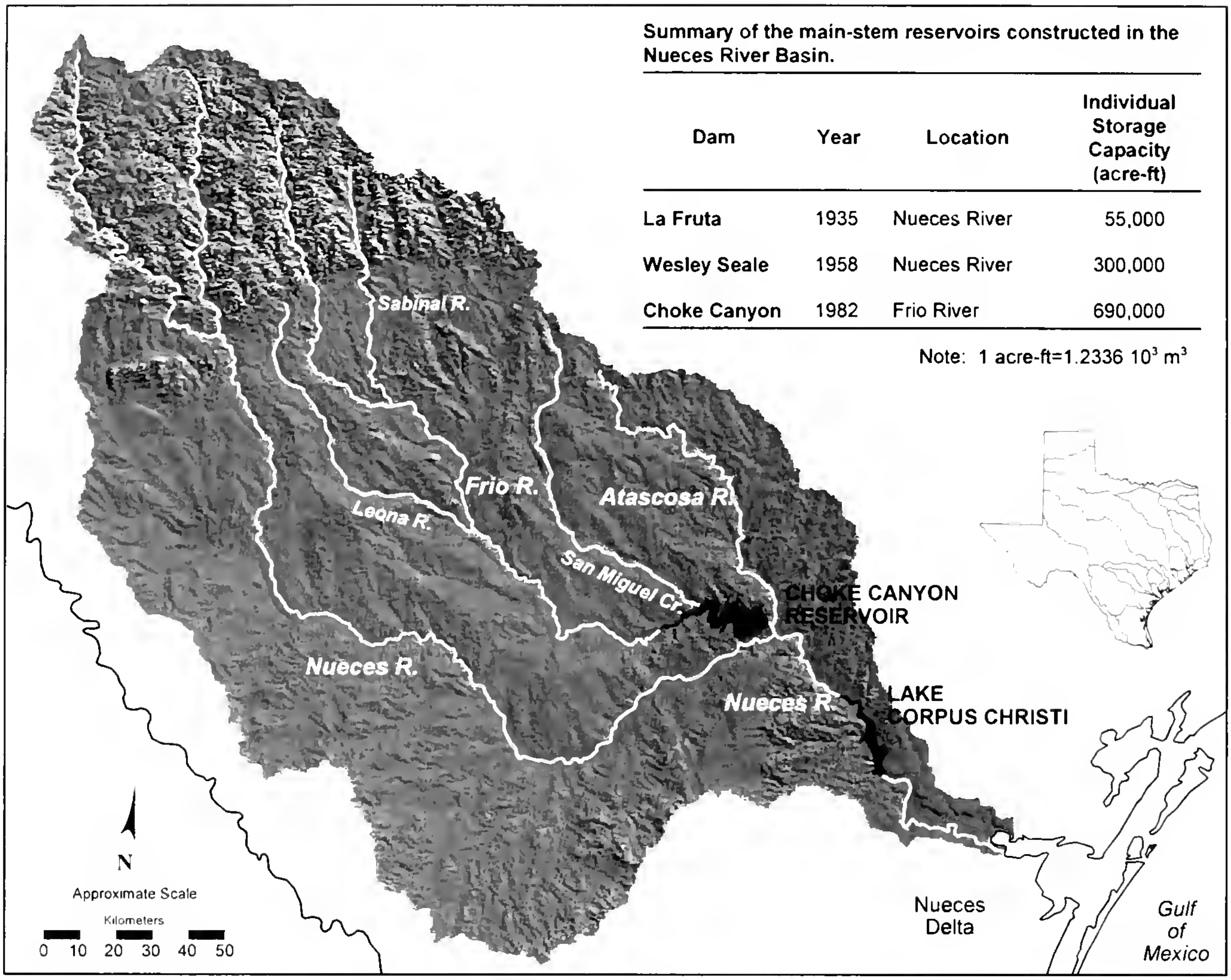
After compiling and analyzing salinity data throughout the Nueces Estuary from the 1950's through the 1990's, Ward and Armstrong (1997) found that the much of the estuary exhibited a well-defined increasing trend in salinity, including Nueces Bay and most of the open areas of Corpus Christi Bay. The average rates of increase were not considered insignificant. For example, over ten years, the average rates of salinity increases would result in an increase of average salinity of Corpus Christi Bay by 0.5 ppt and Nueces Bay by 2.5 ppt (Ward and Armstrong 1997). After inspection of the data, these authors determined that the greatest contributor to the declining trend was the reduced frequency of occurrence of high-flow events in the Nueces River. Several factors have been identified as having possibly contributed to reduced stream flow in the Nueces River, including an increase in water storage and evaporation due to the construction of reservoirs, an increase in the consumption of water withdrawn from streams or shallow aquifers and a possible decrease in rainfall within the greater watershed (Asquith *et al.* 1997).

Since 1935, three main-stem reservoirs have been constructed on the Nueces River and its tributaries. These dams include La Fruta Dam, Wesley Seale Dam (Lake Corpus Christi), which replaced La Fruta Dam, and Choke Canyon Dam (Figure 2-14). A direct result of their construction was that the combined basin storage capacity dramatically increased over a relatively short period from 67,848 10^3 m^3 (55,000 acre-ft) in 1935 to over 1,221,264 10^3 m^3 (990,000 acre-ft) in 1982 (Figure 2-14). Wesley Seale Dam lies on the lower reach of the Nueces River, and Choke Canyon Dam lies on the lower Frio River, the largest tributary to the Nueces.

Developed for the purposes of providing a reliable and municipal water supply and flood protection, these dams have contributed to reduced streamflow in the lower Nueces River by their diminutive influence on larger river hydrographs, and through direct water loss to consumptive uses and evaporation. The present permitted firm yield of the reservoir system is 171,470 10^3 m^3 (139,000 acre-ft) for municipal and industrial use, and a portion of delivered water returns to the estuary through treated return flows. Because of the relative shallow depth of the two reservoirs and the relatively hot climate, evaporation from these two water bodies can remove a significant amount of water from the river system. For example, during 1999 alone, over 217,730 10^3 m^3 (176,500 acre-ft) were lost to evaporation from the combined reservoir system (Hilzinger 2000).

Another factor possibly contributing to decreased stream flow in the lower Nueces River include increased non-reservoir surface water withdrawals in the greater watershed. For example, long-term (1940 to 1990) analysis of reported surface water withdrawals in the basin upstream of the reservoirs indicates an increase of about 60 % from 1965 to 1990 (Green and Slade 1995), which could have reduced the amount of inflow to the reservoirs.

Finally, a decreasing precipitation trend in the Nueces watershed would be expected to reduce streamflow. Howerver, after analyzing rainfall data from four south Texas gauges (Cotulla, Beeville, Sabinal and Corpus Christi) reflecting conditions for the Nueces watershed, Medina (2000) found that annual precipitation (using a base period that consisted of data since 1900) produced no particular trend (Figures 2-15a through 2-15c). Using a baseline that began during the late 1940's (*e.g.*, Figure 2-15d), annual precipitation portrayed an increasing trend (Medina 2000). The most prominent and common feature of the precipitation data at all stations was the drought of the late 1940's and early 1950's. Similarly, Asquith *et al.*



Summary of the main-stem reservoirs constructed in the Nueces River Basin.

Dam	Year	Location	Individual Storage Capacity (acre-ft)
La Fruta	1935	Nueces River	55,000
Wesley Seale	1958	Nueces River	300,000
Choke Canyon	1982	Frio River	690,000

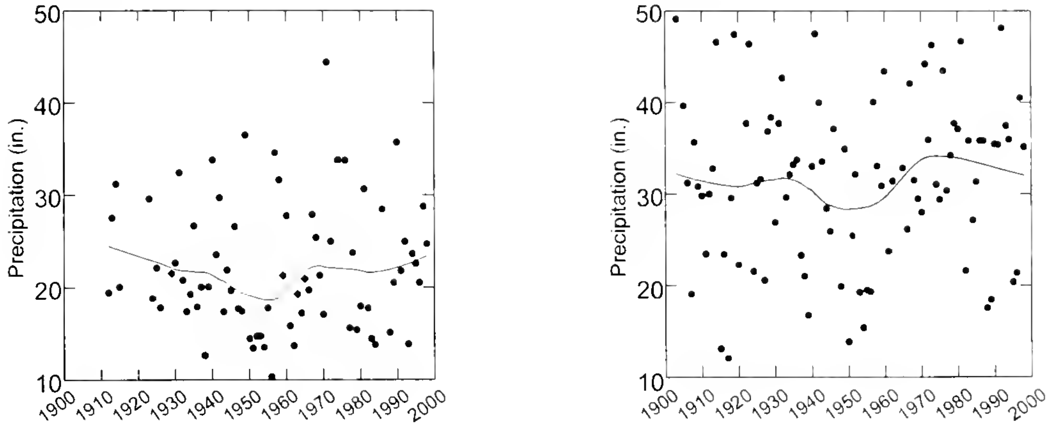
Note: 1 acre-ft=1.2336 10^3 m^3

Figure 2-14: The Nueces River Basin, including major drainages and reservoirs.

Source of topographic base map: U.S. Geological Survey 1997.

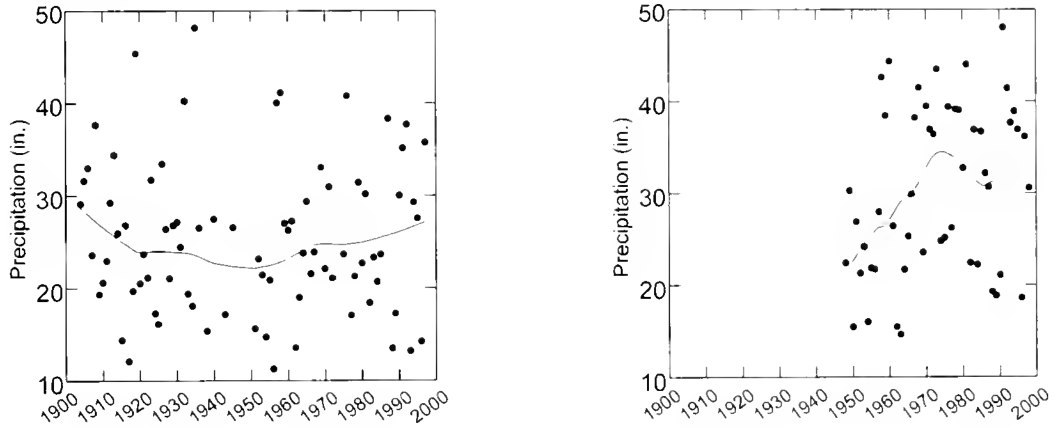
(1997) found little evidence for statistical trends in precipitation along the Coastal Bend from 1968 through 1993.

Recently, two independent investigations were conducted to quantify changes in streamflow of the Nueces River since 1940, one regarding inflow into Nueces Estuary and the other regarding inflow into Nueces Delta. The first study was conducted by Asquith *et al.* (1997), who used streamflow in the Nueces River near Mathis (located immediately below Lake Corpus Christi) to generally represent estuary inflow. After performing a statistical trend test on daily flow values, it was concluded that the data showed strong evidence for a downward trend for the period of 1940 to 1996. When analyzed in the historical context of reservoir construction, it was reported that the change in mean annual streamflow during the period after the construction of Lake Corpus Christi (1958 to 1982) was negligible (a decrease of about 1%), but that the change during the period after construction of Choke Canyon Dam (1982 to 1996) was large (a decrease of about 55%) (Asquith *et al.* 1997). Although their analysis used the construction dates of large reservoirs to delineations of the record, it was explained that the effects of reservoirs were only partially responsible for the observed differences between the time periods.



(a) Cotulla

(b) Beeville



(c) Sabinal

(d) Corpus Christi

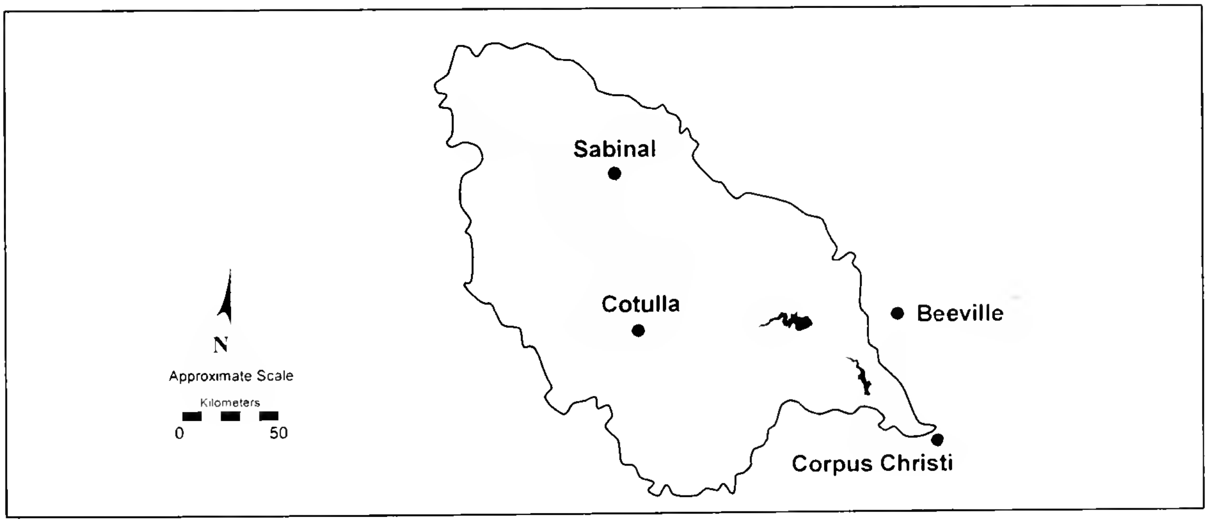


Figure 2-15: Annual precipitation trends at four gauges about the greater Nueces River watershed since about 1900.

Source: Medina 2000.

Note: 1 inch = 2.54 cm

The second study was conducted by Irlbeck and Ward (2000), who used river over-banking events into the upper Nueces Delta (*i.e.*, Rincon Bayou) to generally represent delta inflow. After analyzing the flow regime characteristics of deltaic inundation events, it was concluded that the magnitude of such events has also decreased during the period of 1940 to 1999. Again, in the context of reservoir construction, it was reported that change in the annual mean flow into the delta from the river during the period after the construction of Lake Corpus Christi (1958 to 1982) was large (a decrease of about 39%), and that the change during the period after construction of Choke Canyon Dam (1982 to 1999) was very dramatic (a decrease of over 99%) (Irlbeck and Ward 2000).

The comparative results of these two investigations (Table 2-1) show a marked difference in the response of the Nueces Delta to reductions in stream flow over the past sixty years when compared to that of the other two periods (1958 through 1981, and 1982 through 1999) (Figure 2-16). The distribution of large precipitation events were also found to be less frequent during the drought years of the late 1940's and early 1950's than in the latter two periods, which were not significantly different from each other (Medina 2000).

This information is relevant because this first period, which was used as the baseline for calculating percent changes in estuary and delta inflow by Asquith *et al.* (1997) and Irlbeck and Ward (2000), respectively, likely under-represents to some degree the actual baseline conditions for freshwater inflow to the Nueces Estuary and Delta. In addition, the second period, which showed the smallest percent change in both analyses, also experienced the largest mean watershed precipitation (Figure 2-16).

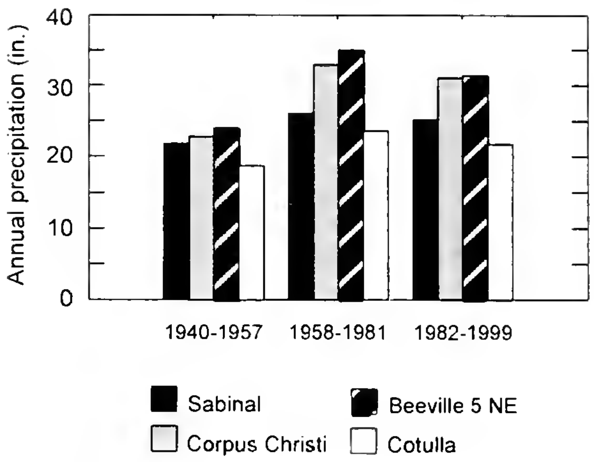


Figure 2-16: Mean annual precipitation of available data at four gauges about the greater Nueces River watershed. Source: Medina 2000.

Note: 1 inch = 2.54 cm

CHANGES IN ECOLOGY

The history of the Nueces Estuary is not dissimilar from that of many other estuaries, in that it includes man-made alterations such as diverting or removing freshwater sources, creating channels, extracting sediments, disposal site of waste materials and harvesting plants and animals. These changes have

Table 2-1: Summary of mean annual flow of the Nueces River into the Nueces Estuary (1940 to 1996)[1] and upper Nueces Delta (1940 to 1999)[2]. Time periods in both studies were based upon the construction dates of large reservoirs in the watershed.

Time Period	Mean annual river flow into Nueces Estuary (acre-ft)	Percent change from Period I	Mean annual river flow into upper Nueces Delta (acre-ft)	Percent change from Period I
1940-1957	619,000	—	127,997	—
1958-1982	614,000	-0.8%	77,989	-39.1%
1983-1996(9)	279,000	-54.9%	537	-99.6%

[1] Source: Asquith *et al.* 1997.

[2] Source: Irlbeck and Ward 2000.

Note: 1 acre-ft = 1.2336 10^3 m^3

often greatly affected the general ability of the estuary to offer the diverse range of habitats that allow a wide range of organisms to thrive. Major alterations affecting water-mass exchanges between the estuary and the Gulf (and therefore the response of water levels in the Nueces Estuary and Delta) include alterations of the Nueces River channel, oyster shell mining and the excavation of shipping channels, barrier structures and artificial passes. The primary alteration affecting salinity concentrations in the estuary and delta is reduced freshwater inflows from to a combination of dam construction and water extraction for agriculture, industry and municipal uses.

Data records do not exist to accurately document all of the resulting alterations to the ecology of the Nueces Estuary and Delta over the past century. However, it is generally agreed that the combined effect of these activities has resulted in an estuary and delta with higher salt concentrations in the soils and water, channelized flow that reduced flooding by freshwater overflow and tides, species shifts to more salt tolerant forms and probably reductions in the total number and biomass of plants and animals. The most notable and evident changes have been reductions in oyster and shrimp harvests (Montagna *et al.* 1998), each of which requires a low salinity regime at some point in their life cycle (Moffet 1970). With few exceptions (*e.g.*, the monitoring work conducted by the Texas Parks and Wildlife Department in Nueces Bay), available data has been primarily derived from subjective comparisons of historical sources with present conditions, inferences drawn from similar ecosystems, which have endured comparable change processes, and direct observations from recent monitoring activities.

CHAPTER THREE

Hydrography

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> ***"Water is the blood of the earth,***
> ***and it flows through its muscles and veins."***
>
> ❖ Kuantzu (late 4th Century)

INTRODUCTION

The Nueces Estuary and Delta are subject to numerous hydro-meteorological forces, including a combination of river flow, precipitation, peripheral runoff and forcing from wind and tide. Each of these influences, in isolation or in combination, may greatly affect the quality and quantity of estuarine habitat available. Such hydrographic events can alter water chemistry (*e.g.*, salinity and nutrients); transport detrital material; cause large volume exchanges between the bay, delta and river; and make accessible or restrict habitats available for estuarine aquatic organisms. Therefore, interpretation and analysis of the effects of the demonstration project and resulting biological responses required a comprehensive understanding of the hydrography of the area during the study period.

OBJECTIVES

1) To quantify (by direct measurement and data analysis) the hydrographic interactions of the upper Nueces Delta with the Nueces River and Nueces Bay during the study period (October 1, 1994, through December 31, 1999);

2) To identify and describe significant hydrographic events during this period; and

3) To describe the observed changes in the hydraulic characteristics of Rincon Bayou resulting from the demonstration project features.

METHODS AND APPROACH

DATA SOURCES

Hydrographic data for this analysis were obtained from a variety of sources, including the Texas Coastal Ocean Observing Network (TCOON) marine monitoring system of Texas A&M University-Corpus Christi Conrad Blucher Institute (CBI), the weather station network administered by the National Weather Service (NWS) and the national stream flow gauging program conducted by the U.S. Geological Survey (USGS) (Table 3-1).

Table 3-1: Summary of hydrographic data sources.

Data Source	Parameter	Measurement Location	Data Type
Nueces River at Calallen, USGS	Estimated daily flow	Nueces River	Data recorded at 15-minute intervals
TCOON system, CBI	Water level Wind direction and velocity Salinity	Nueces and Corpus Christi bays	Data recorded as 6-minute averaged values
Corpus Christi Bay NWS	Daily precipitation	Corpus Christi International Airport	Data archived as daily values
Rincon Bayou near Calallen, USGS	Water level Current velocity Calculated flow	upper Rincon Bayou	Data recorded at 15-minute intervals
	Daily precipitation		Data archived as daily values

Data obtained from the TCOON system included salinity and water level. For each of these parameters, hourly measurements were obtained from the CBI data archive, and, for the analysis reported here, subjected to 24-hour averaging to obtain daily mean values. The salinity data used were from the CBI SALT03 gauge, which is situated due south of White Point in the center of the bay about equidistant from the mouth of Rincon Bayou and the mouth of the Nueces River (Figure 3-1). This gauge responds to flow from both conveyances. Salinity concentrations are measured by robot conductivity sensor and converted to salinity, reported in parts per thousand (ppt).

Water level in Nueces Bay was that measured at CBI's White Point gauge, nearer the mouth of Rincon Bayou. While there is no doubt some slope to the water surface in Nueces Bay is in response to meteorology, tides and river hydrographs, this is negligible in comparison to the temporal excursions in water level in the river and marsh. Therefore, stage data from the White Point gauge was regarded as an acceptable indication of the general coincident elevation of Nueces Bay.

The USGS gauges from which data were obtained included the Nueces River at Calallen (Station 08211500) (Calallen gauge) and Rincon Bayou near Calallen (Station 08211503) (Rincon gauge). The Calallen gauge was located on the Nueces River, about 0.64 km upstream from Calallen Diversion Dam (Figure 3-2) and about 3.05 km upstream from the entrance of the Nueces Overflow Channel. Flow data were obtained from both gauges, and stage and precipitation data were also obtained from the Rincon gauge. There are significant limitations to the accuracy of the flow data from the Calallen gauge at higher values for two primary reasons. First of all, the gauge ceases to represent the total flow of the Nueces River above about 56.63 cubic meters per second (m^3/s) (2,000 cubic feet per second (cfs)) due to activation of additional flow channels in the floodplain. Second, no reliable field observations of discharge values are available above 77.87 m^3/s (2,750 cfs), so all daily flow values in excess of 77.87 m^3/s (of which there were 3 in the record under review) were estimated by extrapolation.

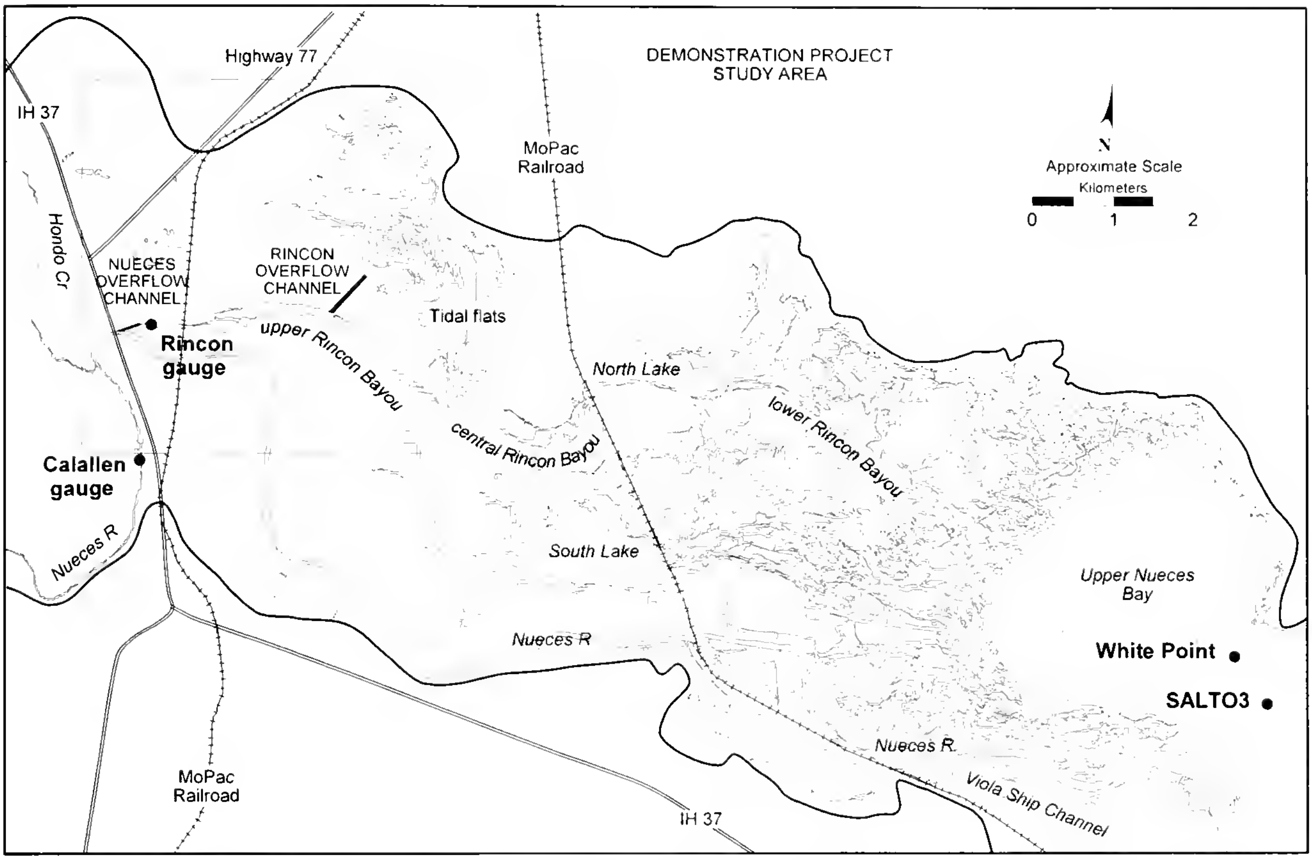

Figure 3-1: Location of hydrographic gauging stations in the Nueces Delta and upper Nueces Bay. The location of the Corpus Christi Airport station is not shown, but is located approximately 14 km to the southeast of the study area.

The Rincon gauge was located in the head-water channel of Rincon Bayou, approximately 274 m downstream (Figure 3-3). There was a gap in the data record from the Rincon gauge from October 26, 1995, when the Nueces Overflow Channel was opened, through May 15, 1996, when the Rincon gauge was activated. The absence of data limited the analysis of the demonstration project during this seven-month period when no measurements of flow, water level or precipitation at the station were available. However, because this period proved to be relatively dry with few hydrographic events, the missing data were not deemed critical. Additional technical information on the Rincon gauge instrumentation, data and observed relations with the Calallen gauge was developed separately by Irlbeck and Ockerman (2000) and has been included as Appendix A of this Concluding Report. Precipitation data were also obtained from the National Climatic Data Center records for Corpus Christi Airport, which is located approximately 14 kilometers southeast of the study area. This gauge supplied precipitation data for the region before the Rincon gauge was installed.

QUANTIFICATION OF HYDROGRAPHIC INTERACTIONS IN THE STUDY AREA

Once the hydrographic parameters of interest were thus identified, raw data for the period of 1992 through 1999 were obtained from these sources and compiled by Ward (2000). Prior to late-1993, virtually the only extant data for the study area was salinity in Nueces Bay and inflow measured at Calallen. In 1993, reliable records from CBI tide gauges and anemometers became available. By the date of the breaching of the Nueces Overflow Channel on October 26, 1995, fairly continuous data from the region was available, with only the USGS gauge in Rincon Bayou itself lacking. It did not become operational until May 16, 1996.

Figure 3-2: View of the Nueces River at Calallen Diversion Dam. The photo was taken on June 26, 1997, for which the mean daily flow rate in the river was 63.7 m^3/s (2,250 cfs).

Photo courtesy of the Bureau of Reclamation.

Three time scales were considered of pertinence to the evaluation of the compiled hydrographic data for the Nueces Estuary: intratidal, intertidal and event-duration. The intratidal (or intradiurnal) time scale represented short-term behavior at an hourly resolution; the intertidal (or interdiurnal) time scale represented day-to-day variations of hydrographic parameters averaged over 24 hours; and the event-duration scale extended over the time period encompassing all responses to a specific hydrographic event, and could range from several days to many weeks. Therefore, to facilitate detailed analysis at varying degrees of detail, all available data was compiled in hourly, daily and event-specific formats (Ward 2000). Further discussion of the approach and results of the intratidal, intertidal and event-duration analyses conducted by Ward (2000) has been included as Appendix B of this Concluding Report.

IDENTIFICATION OF HYDROGRAPHIC EVENTS DURING THE DEMONSTRATION PERIOD

In an effort to develop a common summary of hydrographic events useable in the analyses of changes in water column productivity (Chapter 4), benthic communities (Chapter 5) and vegetation communities (Chapter 6), the compiled hydrographic data record was divided into separate "events" (or event-duration analysis) (Ward 2000). A hydrographic "event" was considered to include one or more of the following response mechanisms: 1) a substantial volume of freshwater flow, 2) an increase in water level (stage) or 3) a decrease in salinity. Where and how each of these three broad response mechanisms were characterized depended largely upon the availability of data. In general, the responses of freshwater inflow and water level were each divided into two components; one for the upper Nueces Bay (and lower delta), and one for Rincon Bayou (and upper delta). The response of salinity was considered for the hydrographic analysis only in upper Nueces Bay, but was examined in each of the subsequent chapters at the various monitoring stations. The initial conceptual model for such an event was a flood hydrograph translating down the

Figure 3-3: View of the Rincon gauge (Station 08211503).

Photo courtesy of the Bureau of Reclamation.

Nueces River into the vicinity of the upper delta. However, as became evident, other hydro-meteorological processes would also effect similar responses in these variables.

Criteria for Event Delineation

After inspection of the entire period of record on both intertidal and intratidal scales, Ward (2000) formulated criteria to identify an event based upon the separate hydrographic behaviors of each of the key response parameters. These response variables included stage (in Nueces Bay, in Rincon Bayou and the super-elevation of Rincon over Nueces Bay), flow (in the Nueces River and in Rincon Bayou) and salinity (in Nueces Bay) (Table 3-2). It should be emphasized that these criteria were ultimately arbitrary but were utilized to ensure an objective selection of candidate events for analysis. Precipitation was not treated as a separate hydrographic variable, though it was certainly an important hydrographic element in understanding the response of the delta ecology. The reason for its exclusion as a defining parameter was that it provided no information *per se* on the response of the Nueces Estuary or Delta. A similar argument was made for the exclusion of wind as a defining criterion.

Once these criteria were established, the daily data for the period of study was manually inspected (Ward 2000). Individual occurrences within the record which met at least one of the six criteria were identified as hydrographic events. Then, for each event, the 24-hour mean data for all hydrographic variables during the event were separated and transferred for individual analysis. The duration period for each event was at least that for which the defining criterion was satisfied, though often a longer event period was chosen to be sure that the complete response of the bay or delta was included in the analysis. When several hydrographic events overlapped (*i.e.*, when several variables each satisfied criteria separately and simultaneously), the event duration was at least the period from the first occurrence of the criterion threshold for the earliest parameter to at least the last such threshold for the latest parameter.

The greatest difficulty reported in separating such events was met when a time series of events occurred in which the response of one parameter overlapped that of the next. For example, a series of river hydrographs might occur, each of which raised the Rincon stage or Calallen flow above the threshold defining an event, and a new surge of inflow occurred

Table 3-2: Criteria used to define hydrographic events in the data record by response variables.
Source: Ward 2000.

Response Parameter	Location	Defining Criteria of a Hydrographic Event
Flow	Nueces River	A 24-hour mean (daily) flow in the Nueces River at Calallen exceeding 14.2 m^3/s (500 cfs).
	Rincon Bayou	A 24-hour mean (daily) flow in Rincon Bayou, either positive or negative, exceeding 0.28 m^3/s (10 cfs).
Stage	Nueces Bay	A 24-hour mean (daily) stage in the water elevation of Nueces Bay exceeding 0.30 m (1.0 ft), referenced to the consistent CBI datum from Ward (1997), established by "empirical leveling".
	Rincon Bayou	A 24-hour mean (daily) stage in the water elevation of Rincon Bayou exceeding 0.61 m (2.0 ft), relative to Rincon gauge datum, which is 422 cm above the consistent datum for CBI gauges.
	Super-elevation	The difference of Rincon Bayou minus Nueces Bay daily stage values exceeding 0.15 m (0.5 ft), referenced to common datum.
Salinity	Nueces Bay	Change in salinity concentrations of Nueces Bay exceeding 5 ppt over a five day period.

before the recession of the preceding event has subsided. Separating these into individual events was therefore rather arbitrary, and, from the estuarine response point of view, this division may or may not have been differentiated in the actual environment, which may have responded as if adjacent events in the record were a single "merged" event.

Characterization of Individual Events

Once individual events were thus delineated in the record, integrated values for each response parameter in each event were computed. The term "integrated" means either averaged or accumulated, whichever was more meaningful for the parameter under consideration. The parameters compiled for each event include the following: event number, date, duration, rainfall, flow, stage and salinity.

Event Number – For purposes of tracking and reference, each identified event occurring from October 1, 1994, through December 31, 1999 (the duration of the monitoring program), was numbered sequentially in time.

Date and Duration – The span of each event was specified by its starting date and its duration in days. In some cases, the ending date of one event was immediately before the starting day of the next, which indicates that a subjective separation had been assumed in the record for purposes of analysis.

Rainfall – Local precipitation for each event was determined by summation of daily totals during the event. For the period of October 1, 1994, through May 15, 1996 (*i.e.*, prior to the activation of the Rincon gauge), precipitation was that reported at Corpus Christi Airport, which evidenced a correlation with the Rincon gauge of 0.81 for the 3.7 years of coincident data. After May 15, precipitation was that reported by the Rincon gauge.

Flow – Daily values for both flow variables (Nueces River and Rincon Bayou) were converted to daily volume and then summed to determine the cumulative event volume. For flow in the Nueces River, daily average flow was also computed for each event by dividing the total flow volume by the event duration in days. Because flow in Rincon Bayou was frequently bi-directional, these data were analyzed somewhat differently. Total positive volume (pos) was determined by considering only that flow directed from the river into the delta. Total negative volume (neg) was similarly determined but considering only that flow directed from the delta into the river. Total exchange (gross) was defined to be the sum of the absolute values (*i.e.*, ignoring signs) of the positive and negative volumes. Finally, total net exchange (net) was defined to be the algebraic sum (*i.e.*, observing signs) of the positive and negative volumes.

It is important to note that, during the demonstration period, the Nueces River did not exceed the natural flooding threshold for the delta, which was 1.64 m (5.40 ft) (Bureau of Reclamation 2000), except on four occasions. This means that, except for these events (Events 16, 18, 25 and 36), the only water exchanged between the Nueces River and Rincon Bayou during the study period passed through the Nueces Overflow Channel. During the excepted events, an additional amount of water also entered Rincon Bayou naturally via the low depressions along the bank of the river. Therefore, for all other events, the Rincon Bayou flow volumes reported were those measured through the Nueces Overflow Channel at the Rincon gauge. For Events 16, 18, 25 and 36, an additional volume was added to that gauged through the overflow channel. This additional amount depended upon the daily stage level attained by the river during the event and was estimated using the hydraulic model developed by Reclamation (2000). Accordingly, for Event 16, which attained a peak daily stage of 1.70 m (5.57 ft) msl, an additional 4 10^3 m^3 (3 acre-ft) were added; for Event 18, which attained a peak daily stage of 1.72 m (5.65 ft) msl, an additional 5 10^3 m^3 (4 acre-ft) were added; for Event 25, which attained a peak daily stage of 2.22 m (7.28 ft) msl, an additional 1,189 10^3 m^3 (964 acre-ft) were added; and for Event 36, which attained a peak daily stage of 1.74 m (5.72 ft) msl, an additional 6 10^3 m^3 (5 acre-ft) were added. The remark "natural flow event" identifies these events in Table 3-3.

Stage – For the water level in Nueces Bay and Rincon Bayou, both the daily average and peak daily stages were utilized, the latter since the average alone might not have fairly depicted the range of water level excursion during an event. Raw daily stage data from the Rincon gauge, which is reported in local time, was corrected for GMT (*i.e.*, the 15-minute data were re-averaged) to allow temporal consistency with the other data variables. The super-elevation of water levels, determined by subtracting the Nueces Bay stage from the Rincon Bayou value, was used to determine the predominant influence on stage in upper Rincon Bayou. On an instantaneous basis, the super-elevation is the direct force for discharge through the Nueces Overflow Channel.

Salinity – The salinity response of upper Nueces Bay to an inflow event would be expected to be an initial drop in concentration, followed by a slow increase with time, or "recovery". However, this approach of integrating the salinity parameter could possibly understate the response of salinity to lower magnitude hydrographic events, because the entire response could be occur within the event's duration and therefore elude detection. Four separate indicators were thus computed from the salinity data for each hydrographic event: 1) the salinity value at the beginning of the event (start), 2) its net incremental change at the close of the event (chg), 3) the percent of the beginning value that the increment represented (% chg), and 4) the minimum value attained during the event (min). As so defined, the sign of the incremental (percent) change indicates whether salinity increased or decreased over the duration of the event (negative for a decrease and positive for an increase).

RESULTS

In this analysis, hydrographic events were delineated according to the mechanism or feature exhibiting a response: namely, the response of flow in the Nueces River or in Rincon Bayou; water level in Nueces Bay or in Rincon Bayou; and salinity in upper Nueces Bay. A cursory inspection of the hydrographic events presented in Table 3-3 reveals the fact that each of these response mechanisms can occur in isolation, without the involvement of the others. This indicates that a certain degree of care must be used in determining how a hydrographic event has influenced the chemistry and ecology of the project area. For example, if inundation and de-watering were of concern, then the extent to which events accomplished a response of water level would be of central interest, and the most important of these was the response of water level in Nueces Bay for the lower delta and in Rincon Bayou for the upper delta. If freshwater inflow to Nueces Bay from the river were the major determinant, perhaps through a sediment or chemical load, then the flow events in the Nueces River would be regarded as most important. If it were freshwater flow into the upper delta, then flow in Rincon Bayou would be critical. Finally, if the depression of salinity were a key interest, then the salinity events in Nueces Bay would be of primary concern.

OVERVIEW OF HYDROGRAPHIC EVENTS THAT OCCURRED DURING THE DEMONSTRATION PERIOD

For the period investigated (*i.e.*, October 1994 through December 1999), a total of 37 hydrographic events were identified (Table 3-3). Five of these events occurred prior to the opening of the Nueces Overflow Channel, and thirty-two afterward. These events were highly variable in the magnitude of their responses, durations and in the subset of hydrographic variables in which a response occurred. Some were associated with seasonal high waters in Nueces Bay, some were salinity responses elicited only by internal circulations of the bay, some were responses to intense rainfall and, of course, some were in fact inflow hydrographs in the Nueces River. Most (28) of these events occurred after operation of the USGS Rincon gauge in the Nueces Overflow Channel, allowing the direct measurement of flow diverted by the demonstration project, the associated water level rise and *in situ* precipitation.

Of the total 37 events observed, 15 met the flow criteria for a flow event in the Nueces River, 16 met the criteria for a stage event in Nueces Bay and 21 met the criteria for a salinity event. Of the 28 events occurring after the installation of the Rincon gauge, 20 met the criteria for a flow event in Rincon Bayou, 27 met the criteria for a stage event in Rincon Bayou and 14 met the criteria for a super-elevation event.

Table 3-3: **Summary of hydrographic events which occurred during the demonstration period: October 1, 1994, through December 31, 1999.** Response variables which met event criteria are indicated by shading.

Event No.	Starting Date			Duration (days)	Rainfall (inches)	Flow (acre-ft)						Stage (ft MSL)						Salinity (ppt)				Remarks
						Nueces River		Rincon Bayou				Nueces Bay		Rincon Bayou		Super-elev.		White Point				
						total	ave.	pos.	neg.	gross	net	mean	peak	mean	peak	mean	peak	start	chg.	%chg	min.	
1	1994	12	20	14	3.19	4,013	287	0	0	0	0	1.15	1.53	-	-	-	-	26.6	-6.6	-24.8	20.1	
2	1995	5	29	6	2.01	649	108	0	0	0	0	1.79	1.92	-	-	-	-	28.8	-3.2	-11.1	24.6	
3		6	18	13	1.14	6,071	467	0	0	0	0	1.38	2.10	-	-	-	-	27.1	-8.8	-32.4	14.9	
4		8	5	10	3.70	155	16	0	0	0	0	2.08	2.49	-	-	-	-	25.1	-0.7	-2.8	24.4	
5		9	22	19	2.99	8,899	468	0	0	0	0	2.26	2.83	-	-	-	-	30.4	-3.7	-12.2	26.7	
6		10	26	10	9.76	1,444	144	-	-	-	-	2.28	3.39	-	-	-	-	23.8	-0.9	-3.8	18.4	
7		12	1	12	0.04	1,311	109	-	-	-	-	1.04	1.21	-	-	-	-	25.1	-2.4	-9.6	15.8	
8		12	17	6	0.51	224	37	-	-	-	-	1.08	1.44	-	-	-	-	24.2	1.5	6.0	8.7	
9		12	25	5	0	195	39	-	-	-	-	0.86	1.09	-	-	-	-	23.2	4.9	21.1	6.4	
10	1996	1	1	4	0	990	247	-	-	-	-	0.90	1.22	-	-	-	-	23.7	-0.1	-3.7	0.9	
11		8	21	15	6.72	488	33	27	-1	28	26	1.50	2.09	1.66	2.21	0.17	0.26	43.8	-0.9	-20.5	35.2	
12		10	1	18	0.57	1,012	56	283	-97	380	186	2.36	3.47	2.44	3.42	0.07	0.30	40.9	-2.6	-6.4	38.3	Fall-maxima high water
13		10	19	5	0.19	33	7	37	-23	61	14	1.95	2.38	2.18	2.47	0.23	0.46	44.4	0.4	0.9	39.0	Fall-maxima high water
14		10	24	10	0.15	479	48	58	-23	81	34	2.10	2.51	2.22	2.74	0.12	0.23	39.6	0.2	0.5	38.8	Fall-maxima high water
15	1997	4	1	13	4.25	227	17	39	-51	90	-12	2.16	2.70	2.38	2.99	0.21	0.34	31.4	-5.6	-17.8	25.3	
16		6	21	13	1.95	36,778	2,829	780	-2	792	789	1.38	1.62	3.79	5.57	2.41	4.34	26.8	-23.0	-85.8	2.9	Natural flow event
17		7	4	23	0.05	53,704	2,335	1,116	-354	1,470	762	1.25	1.52	3.33	5.33	2.08	4.15	3.7	0.3	8.1	1.7	
18		10	6	20	9.53	23,421	1,171	732	-465	1,197	267	2.23	3.58	3.09	5.65	0.86	3.14	26.5	-17.2	-64.9	5.1	Natural flow event
19	1998	3	25	9	0	1,209	134	46	-25	71	-25	1.80	2.15	2.00	2.42	0.20	0.28	24.0	2.8	11.7	24.0	
20		6	6	9	0	0	0	28	-16	44	11	1.79	2.21	2.03	2.51	0.24	0.31	31.8	2.2	6.9	30.2	
21		8	12	11	4.67	735	67	20	-3	23	17	1.31	1.86	1.43	1.76	0.12	0.25	38.5	-7.2	-18.7	31.3	
22		8	23	8	0.07	3,967	496	14	-20	35	-6	1.74	2.34	1.97	2.44	0.23	0.42	31.6	-3.0	-9.5	25.9	TS Charley LF on 8/21
23		9	1	28	4.16	52,921	1,890	765	-140	904	625	2.41	3.38	3.08	4.27	0.67	1.73	30.8	-19.9	-64.6	9.9	TS Frances LF on 9/10
24		9	29	17	3.06	29,798	1,753	215	-38	254	177	1.93	2.20	2.62	3.06	0.69	1.00	12.3	-7.9	-64.2	4.3	
25		10	16	14	6.61	39,796	2,843	3,225	-174	3,399	3,051	2.48	2.88	4.55	7.28	2.07	5.12	5.4	-3.2	-59.3	1.5	Natural flow event
26		10	30	13	0.96	24,321	1,871	229	-75	304	153	2.09	2.41	2.94	3.51	0.86	1.40	2.1	3.1	147.6	1.8	Fall-maxima high water
27		11	12	16	2.49	26,656	1,666	123	-58	181	65	1.56	1.95	2.47	3.18	0.91	1.64	5.7	-2.5	-43.9	3.1	
28	1999	3	5	12	0.03	261	22	32	-25	57	8	1.58	2.28	1.92	2.56	0.34	0.52	23.2	2.7	11.6	23.2	
29		3	24	23	2.15	19,630	853	247	-113	360	134	1.72	2.39	2.32	3.37	0.60	1.44	25.0	-9.1	-36.4	9.5	
30		4	27	10	0.01	482	48	81	-102	183	-22	2.07	2.77	2.27	3.01	0.20	0.27	19.7	2.5	12.7	19.4	
31		5	7	17	1.36	179	11	35	-132	167	-98	2.08	2.64	2.27	2.82	0.19	0.23	22.7	2.4	10.6	22.7	
32		6	2	6	0	3,729	621	26	-16	42	10	1.63	1.82	2.04	2.28	0.41	0.51	23.2	-1.4	-6.0	19.7	
33		6	19	8	1.90	2,390	299	4	-96	100	-92	1.83	2.07	2.08	2.47	0.24	0.40	27.3	-8.0	-29.3	18.4	
34		6	28	15	1.23	22,350	1,490	173	-43	216	131	1.40	2.01	2.36	3.23	0.96	1.66	18.9	-9.1	-48.1	6.2	
35		8	19	16	6.22	8,504	532	206	-255	461	-49	1.46	3.70	2.13	4.40	0.67	2.30	22.7	-6.2	-27.3	9.7	H Bret LF on 8/23
36		9	4	17	1.03	30,960	1,821	1,159	-307	1,466	853	1.56	1.82	3.11	5.72	1.55	4.37	16.3	-9.5	-58.3	2.7	Natural flow event
37		9	27	21	2.27	2,352	112	23	-61	83	-38	2.03	2.36	2.14	2.43	0.11	0.34	10.0	8.6	86.0	11.3	

Water level in Rincon Bayou (at least since the Nueces Overflow Channel was opened) was the most responsive parameter to hydro-meteorological forces in the upper delta during the demonstration period (Table 3-3).

SUMMARY OF SELECTED INDIVIDUAL EVENTS

As can be observed from Figures 3-4 through 3-9, most of the observed hydrographic events involving large flows in the Nueces River occurred during the latter portion of the demonstration period, particularly during 1997, 1998 and 1999. This absence of such events in the early part of the demonstration period was attributable to the fact that, during the first few years, south Texas experienced a moderate to severe drought. However, although large freshwater diversion events were absent during this period, modest flow events into Rincon Bayou from the Nueces River did occur (*e.g.*, Events 12, 13 and 14, and probably a few of Events 6 through 10). The driving mechanism for these events was not flow in the river but other hydro-meteorological forces affecting water level in the Nueces Estuary (Table 3-3). Several other similar exchange events occurred throughout the demonstration period.

Fall 1996: Events 12 through 14

One example of these kinds of small exchange events were Events 12, 13 and 14, which resulted from a fall *maxima* high water event in the Gulf of Mexico (Table 3-3). From October 3 through 8, as the water levels in Nueces Bay and Rincon Bayou increased, a sustained positive flow occurred through the overflow channel, which peaked on October 6 at 1.04 m^3/s (36.9 cfs) (Figure 3-10). During same period, only a minimal amount of river flow (no more than 0.10 m^3/s, or 3.5 cfs) passed over Calallen Diversion Dam. However, during October 9 through 14, flow in the river rose to about 4.67 m^3/s (165 cfs) on October 12, while water levels in the upper delta and bay began to decrease. The surprising result was that water diversion through the channel reversed direction and flowed from the upper delta into the Nueces River until October 15, when the water level in the bay again began to increase. This behavior, which continued through Events 13 and 14, demonstrated that, at low flow volumes in the Nueces River, diversions through the overflow channel were driven primarily by water level variations in Nueces Bay and the upper delta.

The USGS made several salinity measurements at the Rincon gauge during Event 12. Salinity was measured on October 4, 5 and 6, which was the period of sustained positive flow through the overflow channel. The salinity values for each day were 2.0, 3.9 and 7.2 practical salinity units (psu) (which are approximately equivalent to parts per thousand), respectively. During this period, no flow occurred in the Nueces River on October 4 and 6, and only 0.10 m^3/s (3.5 cfs) occurred on October 5. The increasing salinity values over this 3-day period indicates that flow was moving up the Nueces River channel and into Rincon Bayou as a result of the rising water level in Nueces Bay. Therefore, the total net diversion into Rincon Bayou during these three events (289 10^3 m^3, or 234 acre-ft) was relatively fresh water.

Summer 1997: Events 16 and 17

The first significant occurrence of freshwater flow during the demonstration period occurred from June 21 through July 27, 1997 (Events 16 and 17). These two events occurred one immediately after the other, and were derived from the same basin-wide precipitation event. This storm was one of the many tropical/middle latitude heavy rain events common to south Texas. On June 21, a near-stationary low pressure system over south-central Texas began to move east and north, causing scattered showers and thundershowers over a large part of north Texas, the Texas Hill Country and central Texas. This movement allowed tropical moisture to move in from the south and feed into the area of instability, lift and daytime heating in the afternoon, which resulted in a second round of locally heavy rain in the greater Nueces watershed.

Rainfall amounts with this second rain event varied from 23 to 58 centimeters (cm) (9 to 23 inches) over the Texas Hill Country, and between 13 and 25 cm

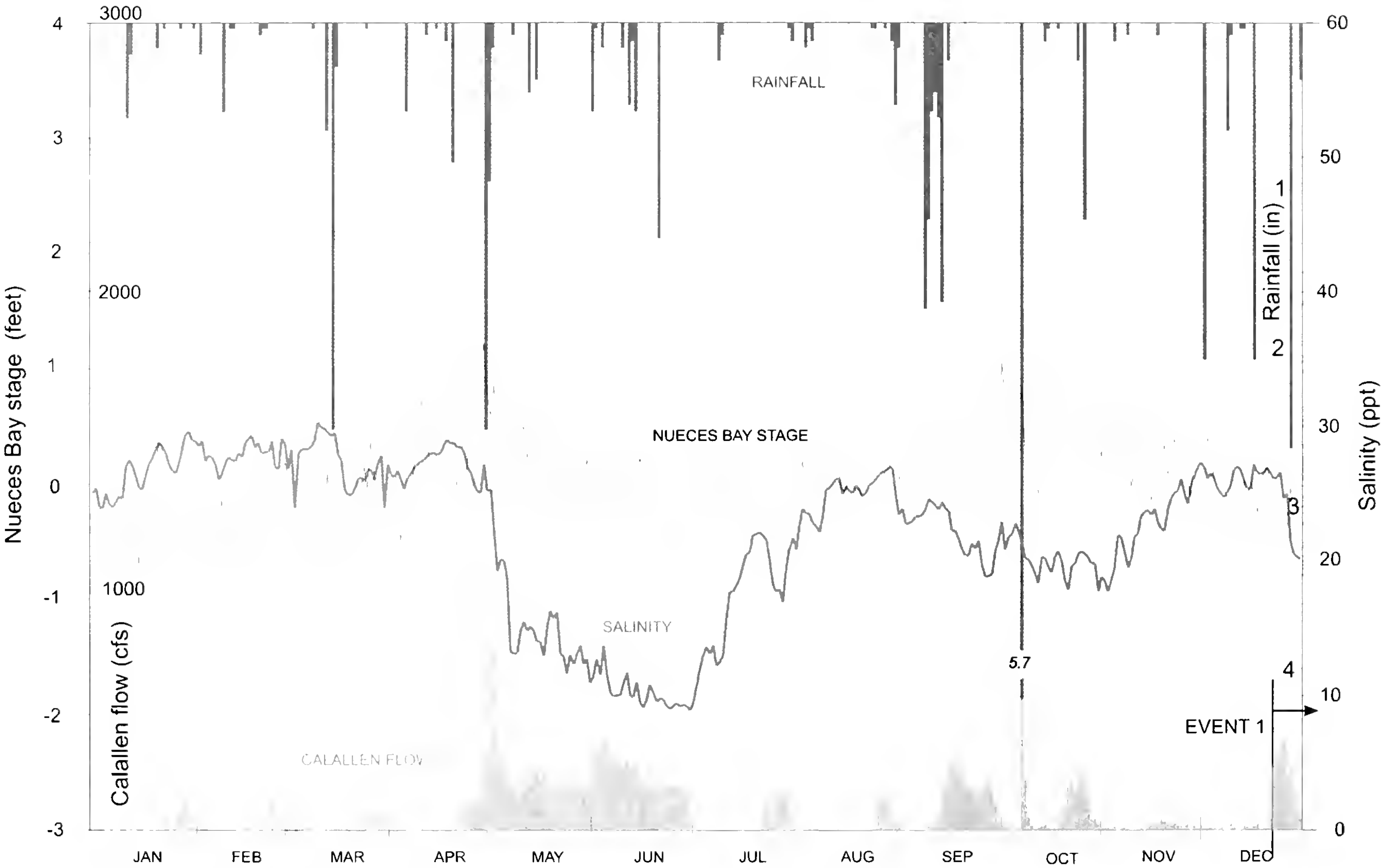

Figure 3-4: Hydrographic data for 1994. The demonstration (*i.e.*, monitoring) period began October 1, 1994.

Note: 1 inch = 2.54 cm; 1 ft = 0.3-46 m; 1 cfs = 0.0283 m^3/s.

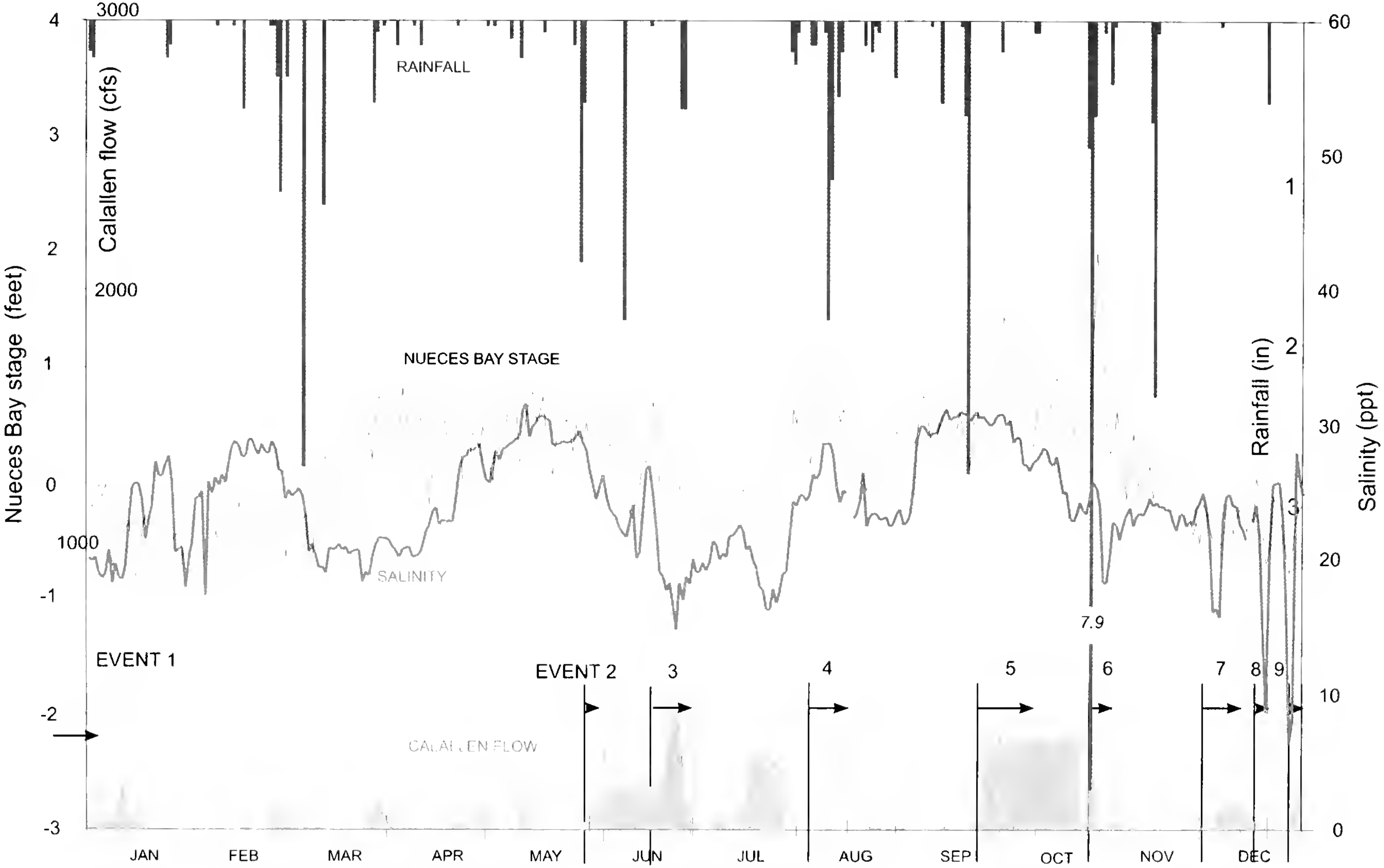

Figure 3-5: Hydrographic data for 1995. The Nueces Overflow Channel was completed on October 26, 1995.

Note: 1 inch = 2.54 cm; 1 ft = 0.3046 m; 1 cfs = 0.0283 m^3/s.

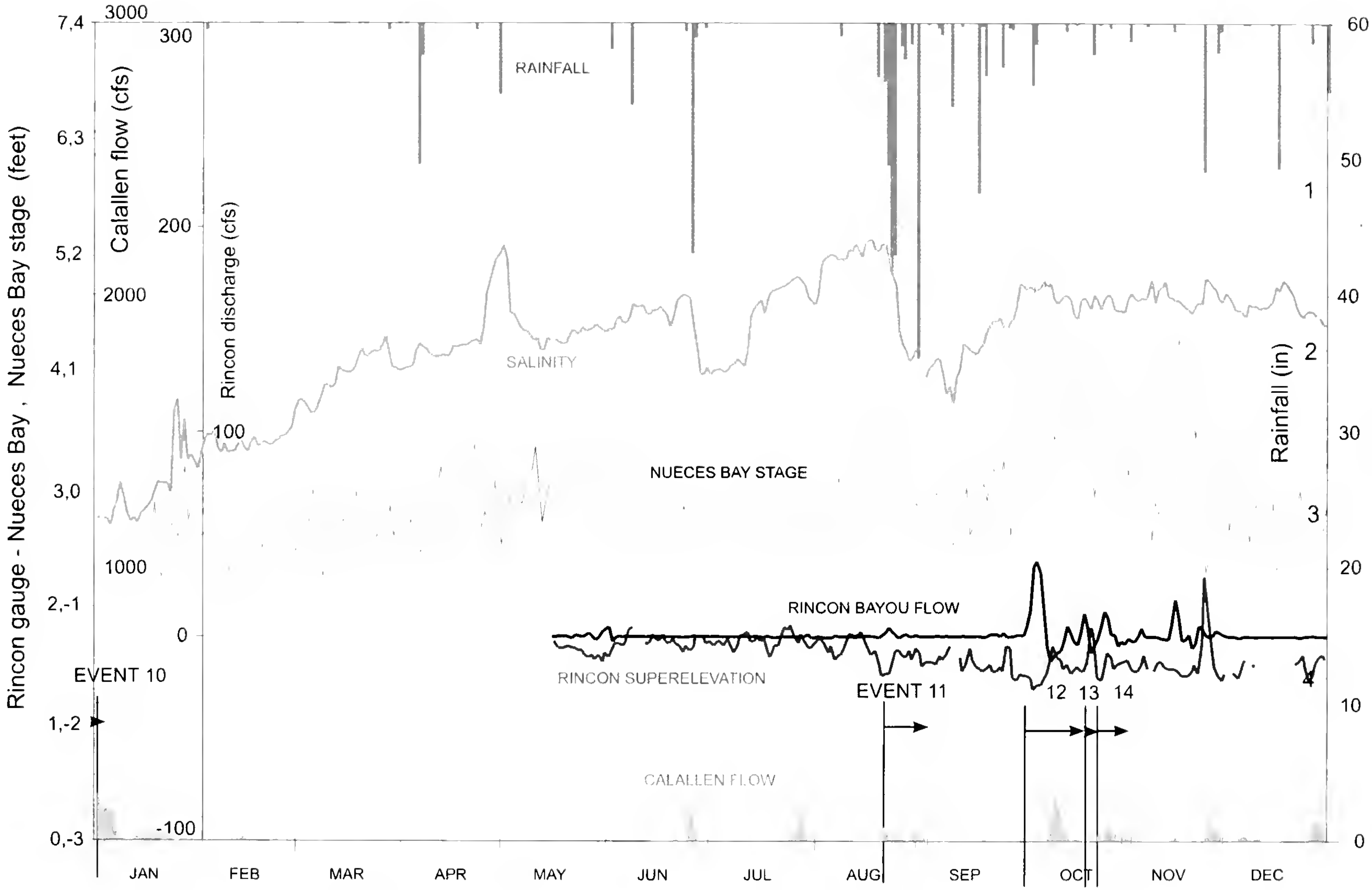

Figure 3-6: Hydrographic data for 1996. The Rincon gauge was installed on May 16, 1996.

Note: 1 inch = 2.54 cm; 1 ft = 0.3046 m; 1 cfs = 0.0283 m^3/s.

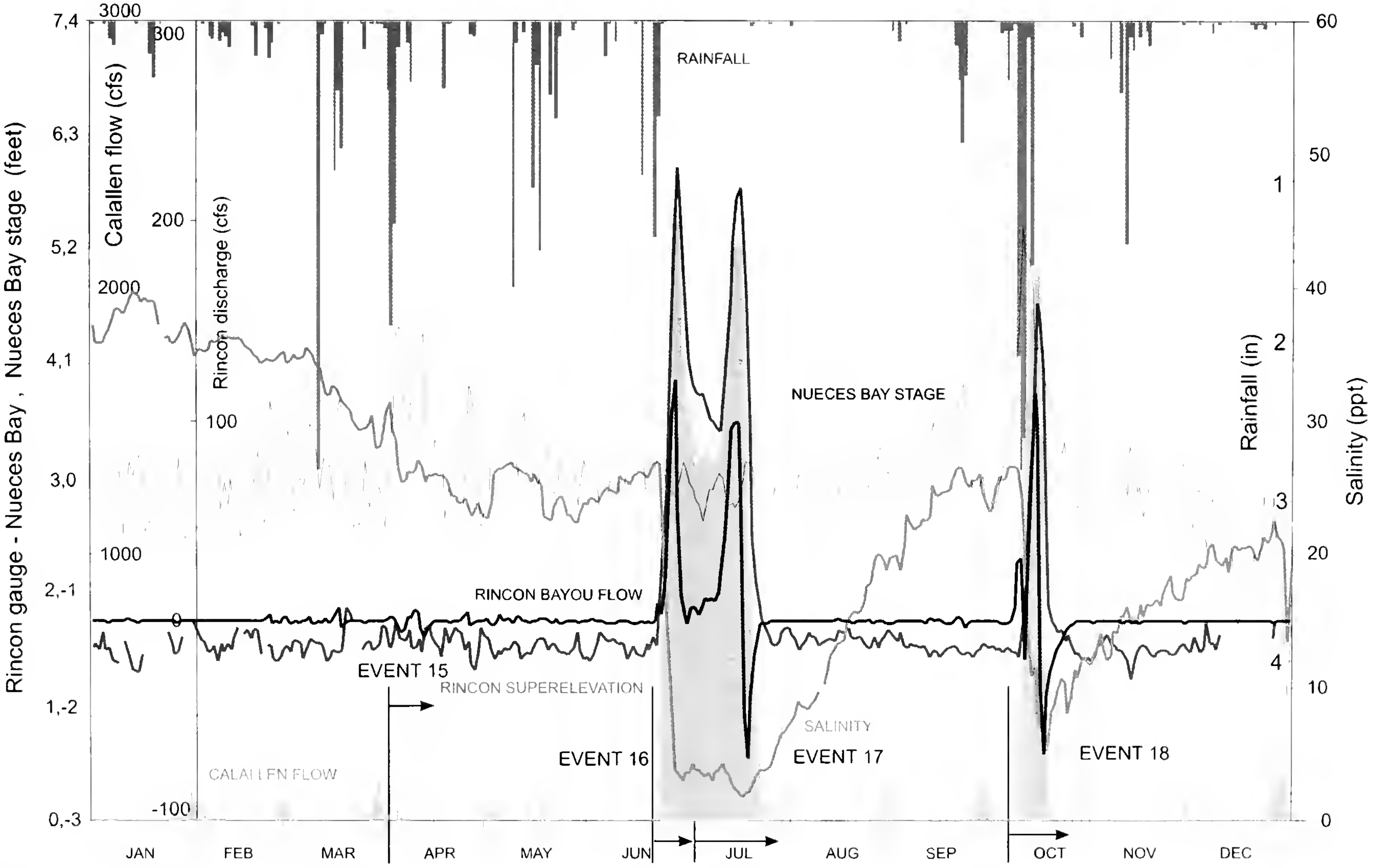

Figure 3-7: Hydrographic data for 1997.

Note: 1 inch = 2.54 cm; 1 ft = 0.3046 m; 1 cfs = 0.0283 m^3/s.

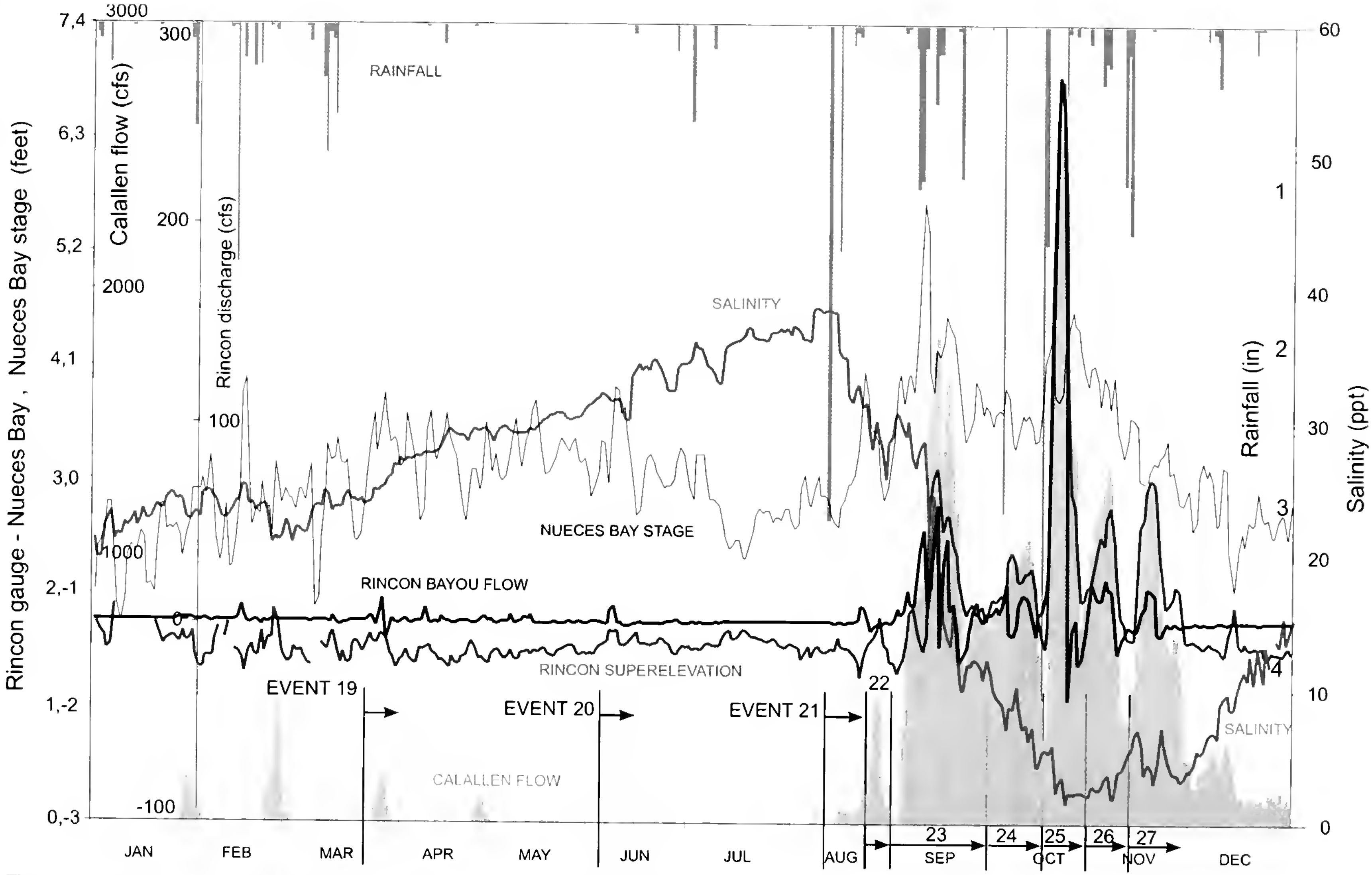

Figure 3-8: Hydrographic data for 1998. Rincon Bayou flow only indicates that gauged through the Nueces Overflow Channel. During Event 25, it was estimated that an additional 1,204 10^3 m^3 (976 acre-ft) (not graphed) was also naturally discharged into the upper delta over several low points along the river bank.

Note: 1 inch = 2.54 cm; 1 ft = 0.3046 m; 1 cfs = 0.0283 m^3/s.

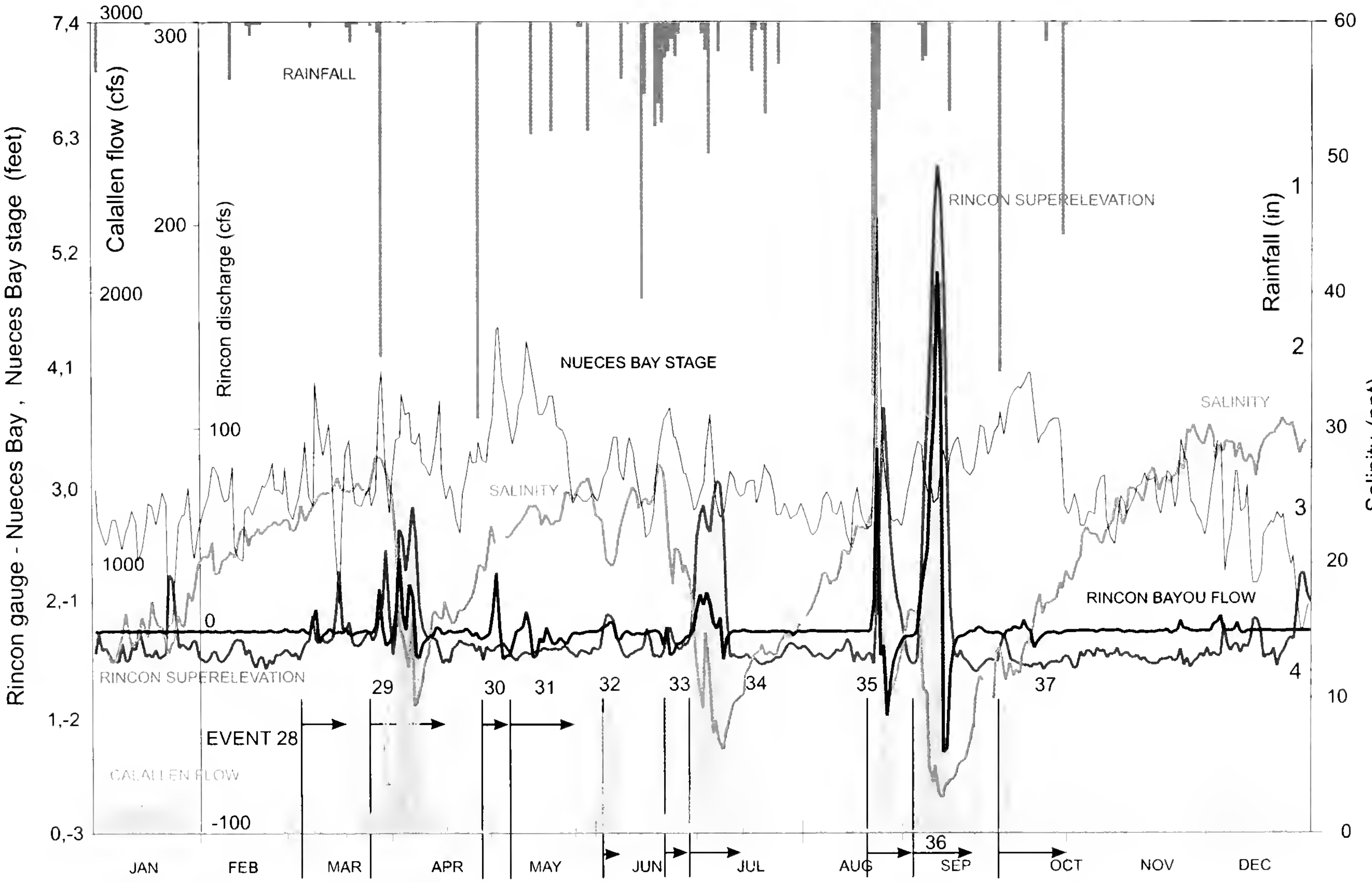

Figure 3-9: Hydrographic data for 1999.

Note: 1 inch = 2.54 cm; 1 ft = 0.3046 m; 1 cfs = 0.0283 m^3/s.

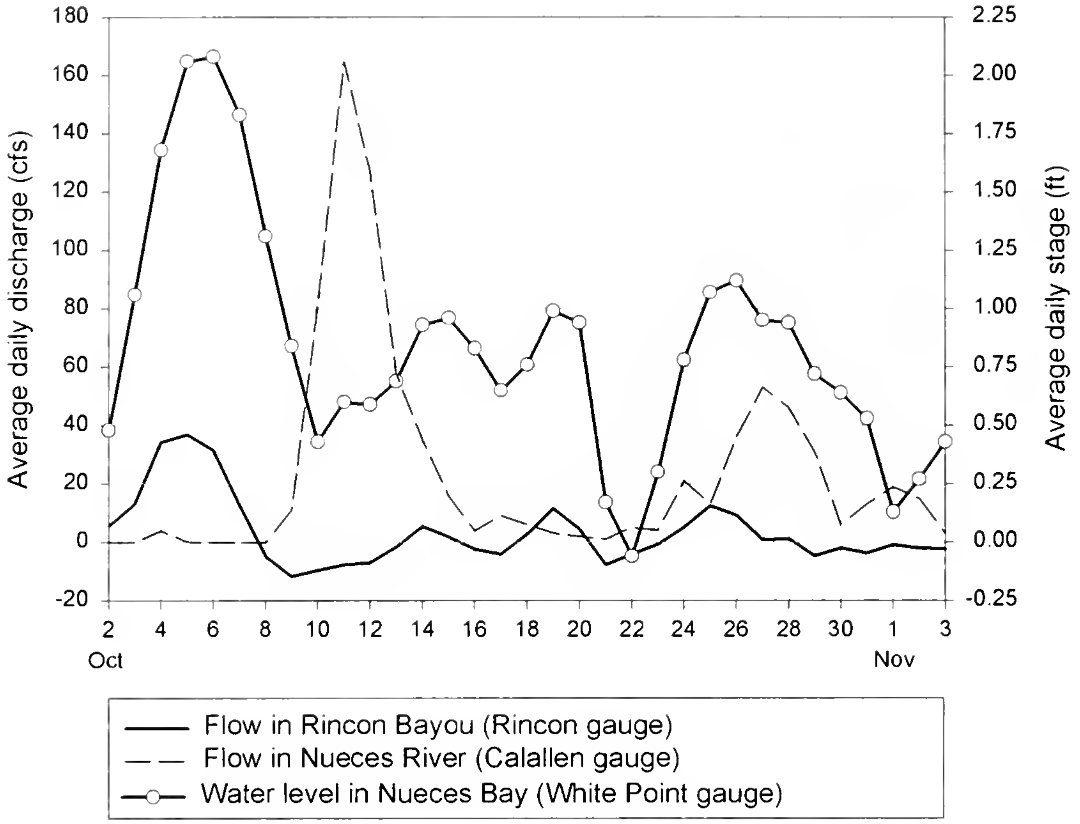

Figure 3-10: Selected hydrographic data for Events 12, 13 and 14 (October 2 through November 3, 1996). During this period of low flow in the Nueces River, water level in Nueces Bay (not flow in the Nueces River) was the predominant factor in determining the rate and direction of flow through the Nueces Overflow Channel and Rincon Bayou.

(5 to 10 inches) over central and south-central Texas, including the headwaters of the Nueces and the Frio drainages. A similar pattern, on a larger scale, affected central and south central Texas in December of 1991, causing 30 to 51 cm (12 to 20 inches) of precipitation over much of south Texas. Direct precipitation in the upper delta from the 1997 storm totaled only 4.9 cm (1.94 inches) through June 21-23, with the only other measurable precipitation being 0.1 cm (0.04 inches) from July 20 to 21.

These two hydrographic events (16 and 17) exemplified a common resulting flow pattern in the lower Nueces River from precipitation events in the greater watershed: namely, a duel-peak hydrograph in the river at the point of diversion into the delta (Figure 3-7). The first principal peak (Event 16) arrived at the upper delta on June 26, and represented runoff primarily in the lower (eastern) watershed. Approximately 20 days later, during which time the Nueces River at Calallen experienced a sustained flow of about 39.6 m^3/s (1,400 cfs), the second principal peak (Event 17) arrived on July 15. This peak represented runoff from the same storm but from the upper (western) watershed. As a result of the total river inflow into the bay system, the salinity of Nueces Bay was reduced from 26.8 ppt at the beginning of Event 16, to 3.4 ppt at the end of Event 17.

Because the average ambient water level in Nueces Bay was so low and the average stage in the river at the point of diversion was so high, the hydraulic head imposed by the river (as represented by mean super-elevation) was considerable (greater than 1.21 m, or 4.0 ft) (Table 3-3). This indicates, unlike during Events 12 through 14, the diversion rate into Rincon Bayou during Events 16 and 17 was predominantly a function of the elevated stage in the Nueces River. As each principal peak receded, discharge through the overflow channel dropped sharply (Figure 3-7). At the event's conclusion, the loss of stage in the river immediately resulted in a sharp decrease in the rate of discharge, and the upper delta discharged a significant amount of water back into the river. This pattern, the reversal of diverted flow at the end of large river flow events, would become common in subsequent events. During both events, the Rincon Overflow Channel was activated, diverting water into the extensive tidal flat area of the upper delta.

Fall 1997: Event 18

The fall event of 1997 (Event 18) resulted from very heavy precipitation in the lower Nueces Watershed. This event, although comparable to Event 16 in regards to positive flow and maximum stage in Rincon Bayou, was different from the previous two events in one significant way. Unlike Events 16 and 17, which were events responding to precipitation higher in the basin, Event 18 was a hydrographic response to intense local precipitation directly on the study area and lower watershed. Approximately 23 cm (9.17 inches) fell within the area during the first 6 days of the event, contributing to heavy local runoff and artificially elevated water levels in the upper delta and Nueces Bay (as reflected in mean and peak stage). As a result, discharge into the delta from the river actually began before the river (gauged at Calallen) began to respond to the event (Figure 3-7).

As with the two previous events, the rate of diversion into the delta fell off sharply as soon as stage in the river began to drop, and, like Event 17, remained negative for the concluding days of the event. Although the total positive flow diverted into Rincon Bayou during this event was about the same as that for Event 16, over 60% of this volume flowed back into the river at the end of the event. This difference was attributable to the fact that water levels in the Nueces River at the point of diversion (and therefore, the hydraulic head) were not maintained after the river crested, as was the case with Event 16.

Fall 1998: Events 21 through 27

For purposes of event analysis, the fall of 1998 was a very complicated period. The careful observer of Table 3-3 and Figure 3-8 will recognize that, as with Events 12 through 14, Events 21 through 27 were essentially contiguous, or that the ending day of each event immediately preceded the beginning day of the next. The challenge in interpretation was separating the effects of a bewildering number of influencing factors. For example, during this 96-day period, two tropical storms made landfall in the region, a fall-maxima high water event occurred in the Gulf of Mexico, over 56 cm (22 inches) of local rainfall was recorded in the study area, over 219,820 10^3 m^3 (178,194 acre-ft) flowed from Nueces River into the bay and over 5,092 10^3 m^3 (4,128 acre-ft) was diverted into the upper delta. For purposes of interpreting biological responses in the delta, one may justifiably consider each numbered event as a mere temporal component of the greater autumn occurrence of 1998.

Beginning on August 17, heavy rain episodes caused by a cool air mass sagging into central Texas began to occur over much of south Texas. Because the rainfall followed record drought conditions between April and July, very little runoff resulted. In fact, over 15 cm (6 inches) of precipitation fell over a 2,000-km^2 area in the Frio River watershed and produced absolutely no flooding (Patton 1998). The rainfall continued throughthe day on August 18, with a wide-spread area in the greater Nueces watershed receiving 20 to 33 cm (8 to 13 inches).

Tropical Storm Charley made landfall near Port Aransas the night of August 21 (Events 21 and 22). As the storm center moved slowly inland toward the Hill Country west of San Antonio, it produced 5 to 8 cm (2 to 3 inches) of rain in a three-hour period, with the heaviest rainfall resulting from "feeder" bands that wrapped around the center. These bands were moving very slowly and dropped several inches of rain before they departed an area. Primarily because the region had received large rainfall totals for several days prior, significant and fatal flooding on the upper Frio and Nueces rivers resulted. Direct precipitation in the delta from the storm's landfall totaled only about 0.6 cm (0.24 inches) (August 21 to 23). Nevertheless, a modest peak in stage and discharge in Rincon Bayou occurred on August 23 and 24, primarily due to the storm surge (Figure 3-8). Because a relatively small amount of precipitation fell in the lower Nueces watershed associated with the landfall of Charley, the Nueces River at Calallen recorded only a modest peak on August 8.

However, as previously mentioned, Charley did result in a broad flooding event in the western basin. The Nueces River at Calallen began to respond to this flooding on September 4, and crested on September 14 (Event 23). Flow through the Nueces Overflow Channel generally followed that of the river, but fluctuated on a hourly and daily basis. This oscillation was primarily due to the complicating effect of a second storm surge associated with Tropical Storm Frances, which made landfall near San Antonio Bay on September 10. The arrival of Frances may be observed in Figure 3-11, when, during September 7 through 10, stage and flow in Rincon Bayou increased dramatically, while stage in the Nueces River remained essentially constant. Similarly, when the surge subsided after September 10, discharge through the overflow channel dropped sharply, even though flow in the Nueces River at Calallen increased significantly. Direct precipitation in the delta from Tropical Storm Frances totaled 5.7 cm (2.26 inches) from September 9 to 12.

Flow in the Nueces River continued to remain above 19.8 m^3/s (700 cfs) (Events 23 and 24) for several weeks after the landfall of Frances as a result of the storm's heavy rain in the upper watershed. Flow in Rincon Bayou was also generally positive during this period but not substantial (less than 0.28 m^3/s, or 10 cfs). As with the previous events, flow in Rincon

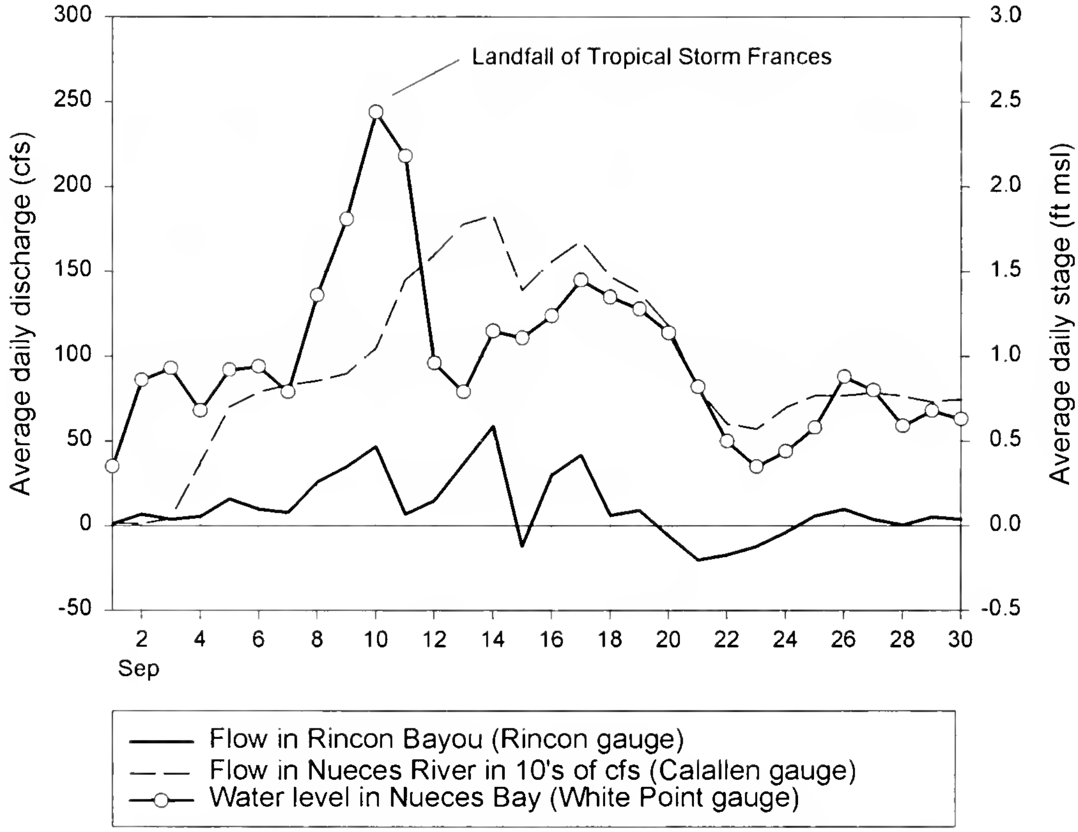

Figure 3-11: Selected hydrographic data for Event 23 (September 1 through 31, 1998).

Bayou became negative immediately after stage in the river began to receded beginning October 13 (Figure 3-8).

Due to significant runoff from the large amounts of tropical moisture and associated precipitation in the upper Nueces Basin during this period, the Nueces River again began to rise, cresting on October 21 (Event 25). This crest resulted in an estimated daily flow rate of 73.6 m^3/s (2,600 cfs) in the Nueces River at Calallen, the highest flow rate attained during the demonstration period. The corresponding water elevation in Rincon Bayou was also the highest daily stage recorded during the study, 2.22 m (7.28 ft msl), which was 0.48 m (1.56 ft) higher than the next highest event daily peak (Event 36). Because of this, Event 25 was the only event to witness the Nueces River meaningfully exceed the natural (*i.e.*, without-project) diversion threshold of the upper Nueces Delta, which was 1.64 m (5.40 ft) msl. As a result, the estimated amount of delta inflow over the natural river bank (1,204 10^3 m^3, or 976 acre-ft) was about 50% as much as that which was gauged through the overflow channel (2,560 10^3 m^3, or 2,075 acre-ft). It was during this event that the road crossing at the lower end of the Rincon Overflow Channel washed out (Figure 3-12).

Events 26 and 27 concluded the fall occurrence of 1998, resulting in two more smaller peaks in river and diversion flows as the greater watershed finally drained the accumulated runoff of the preceding months.

Fall 1999: Events 35 and 36

Hurricane Bret was the first major hurricane of the Atlantic 1999 season (Figure 3-13). The storm formed in the southern Gulf of Mexico and moved slowly northward along the Mexican Coast. As it approached south Texas, it rapidly intensified into a Category 4 hurricane. Landfall was made as a Category 3 storm on August 23, in a remote area between Brownsville and Corpus Christi (Event 35). The storm surge from Bret was substantial, and combined with the 14.43 cm (5.68 inches) of local precipitation that fell on August 22 and 23, the Rincon gauge recorded a maximum elevation of 1.76 m (5.79 ft) msl (August 23). This value was the highest value recorded during the study period without a corresponding flow event in the Nueces River. Once the low pressure system had moved on-shore, the surge tide and local runoff in the upper delta began to drain out, resulting in a net negative flow through the overflow channel for Event 35 (Figure 3-9).

Figure 3-12: Discharge into the tidal flats area through the road crossing at the north end of the Rincon Overflow Channel during Event 16 (June 27, 1997). Each of the 10 corrugated HDPE culverts shown were 24"-diameter. This structure was subsequently washed out during Event 25 (October 1998).

Photo courtesy of the Bureau of Reclamation.

As a result of heavy rainfall in the watershed associated with Hurricane Bret, particularly in the southwestern portion, the Nueces River again responded with a large hydrograph beginning on September 5 (Event 36). The amount of diverted flow through the overflow channel was the second largest recorded for any event, with a net flow of 1,052 10^3 m^3 (853 acre-ft) over 17 days. The salinity of Nueces Bay, which had already been lowered by the landfall of Hurricane Bret some three weeks before, continued to decrease as a result of the event.

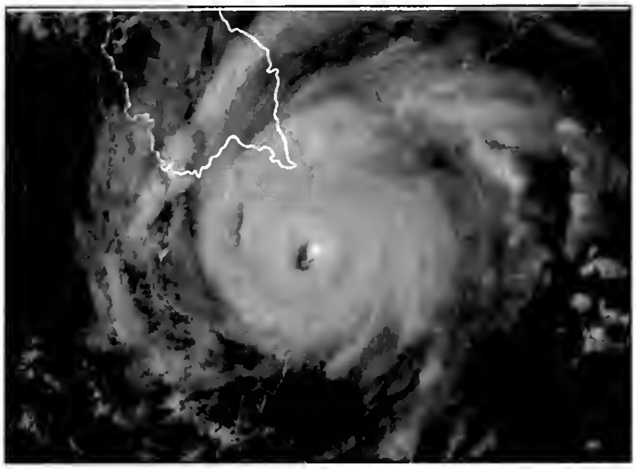

Figure 3-13: Visual satellite image showing the location of Hurricane Bret in relation to the Nueces Watershed just before landfall (August 22, 1999). Having threatened to lay waste to much of south Texas, the storm made landfall as a Category 3 Hurricane. Meteorologists were surprised, however, by Bret's lackluster performance inland. "We ain't surprised," said one Texas native. "You think something named 'Bret' is gonna do much here? I have breakfast cereal with more hair on its chest."

Source of image: National Environmental Satellite, Data and Information Service of the National Oceanic and Atmospheric Administration.

DISCUSSION

FLOODING THRESHOLDS FOR THE UPPER NUECES DELTA

For over 13 years prior to the opening of the Nueces Overflow Channel (*i.e.*, October 26, 1995), the minimum flooding threshold required for the Nueces River to spill freshwater into the upper Nueces Delta was rarely attained (Irlbeck and Ward 2000). Based upon recent estimates, a flow in the Nueces River at Calallen greater than about 59.5 m^3/s (2,100 cfs) was required to breach the lowest portion of the northern river bank (Irlbeck and Ockerman 2000). However, excavation of the overflow channel fundamentally changed this condition. The minimum flooding threshold was thus lowered from 1.64 m (5.4 ft msl) to about 0.0 m msl. As can be observed from the summary of hydrographic events in Table 3-3, this change not only allowed more frequent diversions of fresh water into Rincon Bayou and the upper delta, but also provided the opportunity for other non-riverine elements like wind and tide to force water exchanges between the upper delta and the Nueces River. As a result, near continual (*i.e.,* daily) exchange between the Nueces River and the upper delta was observed during the demonstration period, whereas before the interaction was limited to only extremely rare river inflow events.

During the 50-month period when the overflow channels were open, over 8,810 10^3 m^3 (7,142 acre-ft) was diverted from the Nueces River into Rincon Bayou and the upper delta. Using the hydraulic model developed by the Bureau of Reclamation (2000), it was estimated that, of this total amount, only about 1,204 10^3 m^3 (976 acre-ft) would have been diverted without the demonstration project features. Therefore, during the demonstration period, the total volume of freshwater inflow into the upper Nueces Delta was increased by about 732% from what would have occurred without the project. In a longer-term examination, Irlbeck and Ward (2000) analyzed the inflow patterns of the upper delta assuming that demonstration project features had been in place since the completion of Choke Canyon Dam in 1982 through 1999. These authors concluded that the average annual inflow amount to the upper delta during this 17.6-year period would have been increased from about 666 10^3 m^3 (540 acre-ft) to approximately 4,219 10^3 m^3 (3,420 acre-ft), or by over 633% from that which would have occurred without the project (Irlbeck and Ward 2000). This long-term analysis has been included as Appendix C of this Concluding Report.

ACTIVATION AND BEHAVIOR OF DEMONSTRATION PROJECT FEATURES

Nueces Overflow Channel

Because the controlling (bottom) elevation of the Nueces Overflow Channel was at or near mean sea level, it was activated (or it allowed the exchange of water) when there was a change in water level in either bay or the river. Throughout most of the demonstration period, bi-directional flow occurred almost daily. Changes in the physical condition of the Nueces Overflow Channel included the encroachment of vegetation along the water's edge, and a slight narrowing of the bottom of the channel due to erosion from its banks (Figure 3-14).

Since the primary purpose of the demonstration project was to divert a portion of the flow in the Nueces River through the diversion channel, a logical inquiry was the proportion of such a flood so diverted. Upon examination of the relation between the total event flow volume in the Nueces River and in the Nueces Overflow Channel, it was determined that the volume diverted into Rincon Bayou increased generally with the flow in the river, and the actual proportion of the flow amount diverted was on the order of 2% of that in the river (Ward 2000). The actual rate of discharge, however, varied considerably between events depending upon the water level in Nueces Bay and Rincon Bayou.

Figure 3-14: The Nueces Overflow Channel looking southwest. Note the changes in vegetation and channel characteristics from October 1995, immediately after construction (above), to June 1999, towards the end of the demonstration period (below).

Photos courtesy of the Bureau of Reclamation.

That the relation between Nueces River event volume and the volume transported through Rincon Bayou should depend upon water level was not unexpected, based upon hydraulic considerations. Unlike a river channel system in which the head gradient and the water level (stage) are closely related, there is no direct relation between water level and flow in the Nueces River below Calallen Diversion Dam because of the corrupting effect of tidal and meteorological water-level variations. For the events observed, the Nueces River hydraulic head was superposed on whatever water level was present in Nueces Bay, which affected how the river head could drive flow through the overflow channel. Deeper water made available a greater cross-section area of the channel and lowered the frictional resistance. Therefore, a given hydraulic head in the Nueces River drove a greater flow through the diversion channel when the Nueces Bay water level was higher.

Rincon Overflow Channel

In addition to increased inflow, the demonstration project features also increased the distribution of diverted fresh water within the tidal flats of the upper delta. The controlling elevation of the Rincon Overflow Channel was about 1.14 m (3.75 ft) msl. When water levels in Rincon Bayou exceeded this threshold, flow would pass through the channel and across the tidal flats to the northeast. Without this overflow channel, total diversions through the demonstration project would have been lower, and most of the freshwater diverted would have remained channelized in the upper delta.

Although no direct gauging data were available to determine exactly when and to what degree the Rincon Overflow Channel was activated during the demonstration period, it is certain that, on at least two occasions, the channel passed a significant amount of freshwater into the tidal flats. The first occurrence was during Event 16, when such discharge was observed in the field, and the second was during Event 25, when the road structure at the north end of the channel was washed out into the tidal flats (Figure 3-15). Based upon comparable event stages, super-elevations and flow volumes, it was strongly suspected that the Rincon Overflow Channel also passed some amount of diverted fresh water during Events 17, 18 and 36, although this was not visually verified.

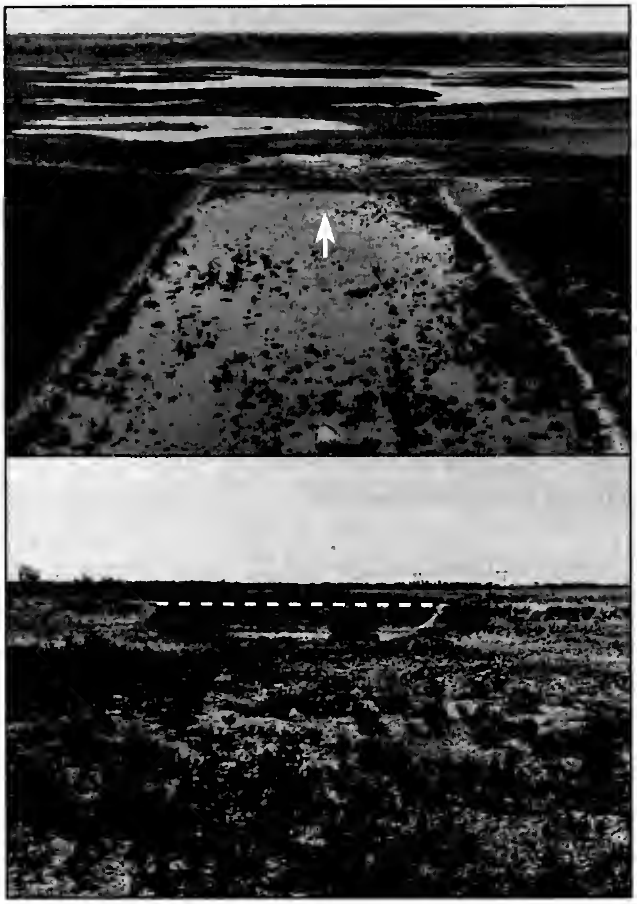

Figure 3-15: The Rincon Overflow Channel. The road crossing structure, as shown from the air during Event 16 in June 1997 (above), was washed out during Event 25 in October 1998, as shown in June 1999 (below). The HDPE culverts (foreground of the lower photo) were 24"-diameter, and the livestock (background of the lower photo) were Red Brangus.

Photos courtesy of the Bureau of Reclamation.

Figure 3-16: The low water crossing at the head of the upper Rincon Bayou channel. The integrity of this structure, although significantly over-topped during Event 25 (October 1998), remained unchanged throughout the demonstration period. Each HDPE culvert was 36"-diameter. The photo was taken on June 1999.

Photos courtesy of the Bureau of Reclamation.

Low Water Crossing

The low water crossing at the head of Rincon Bayou performed exceptionally well. All flows diverted from the river (either naturally or through the Nueces Overflow Channel) passed through this structure (Figure 3-16). On at least one occasion (Event 25), a significant amount of water passed over the top of the crossing, with no damage visible. At the end of the demonstration period, the structure was essentially the same as at the beginning.

SUMMARY

The demonstration project features significantly lowered the minimum flooding threshold of the upper Nueces Delta, and thereby increased the opportunity for larger, more frequent hydrographic events. Based on observations and data analysis during the demonstration project, such events were categorized into three general types: small "exchange" events, "positive-flow" events and "tidal flat inundation" events.

EXCHANGE EVENTS

Exchange events were considered to be frequent, low-volume interactions between the channels and pools of Rincon Bayou and either adjacent water body (Nueces Bay or Nueces River) (Figure 3-17). Exchange events were primarily caused by daily differences in water level elevations, although these differences were in turn the result of a variety of other factors like tide, wind, river inflow, *etc.* The net flow volume for these types of events was generally low (less than 123 10^3 m^3, or 100 acre-ft), and could be either positive or negative through the Nueces Overflow Channel. Although the effects of exchange events were confined to the channels of Rincon Bayou, they provided considerable dilution and mixing of ambient waters, especially in the upper delta. Events 11, 15, 22 and 31 were typical examples of exchange events (Table 3-3). Prior to the demonstration project, the Rincon Bayou and the upper delta were completely isolated from such daily interactions with the river.

POSITIVE-FLOW EVENTS

The second event type, positive-flow events, were considered to be infrequent, large-volume events which resulted in a positive flow of water from the Nueces River into Rincon Bayou (Figure 3-18). Because these events were primarily driven by flow events in the Nueces River, they typically occurred during the spring or fall. Unlike exchange events, the volumes associated with positive-flow events (usually greater than 123 10^3 m^3, or 100 acre-ft) did not simply dilute water in Rincon Bayou but also displaced it to a considerable extent. Because of their magnitude, positive-flow events were not confined to Rincon Bayou but frequently affected the lower adjacent flats, channels and pools. Depending upon their magnitude, such events might or might not have also inundated the higher marshes and tidal flats of the delta. As previously discussed, the actual diverted volume and effectual extent of any one such event was greatly dependant upon the ambient water level in Nueces Bay. Events 26, 27, 29 and 34 were typical examples of positive-flow events that did not inundate higher adjacent marshes and flats (Table 3-3). During the demonstration period, the amount of fresh water diverted into the upper Nueces Delta was increased by about 732%, and most of this increase was attributable to positive-flow events.

Figure 3-17: Typical view of the Nueces Overflow Channel during tidal exchange. The view is looking downstream (east) from the Nueces River.

Photos courtesy of the Bureau of Reclamation.

Figure 3-18: View of the upper Rincon Bayou (background) during a typical positive-flow event (Event 16). The head-water channel of Rincon Bayou (about 300 m downstream of the Nueces Overflow Channel) is in the foreground, and the western-most MoPac Railroad bridge is center. Upper Rincon Bayou is in the background. The photograph was taken on June 26, 1997.

Photo courtesy of the Bureau of Reclamation.

TIDAL FLAT INUNDATION EVENTS

Tidal flat inundation events were considered to be large, positive-flow events during which the Rincon Overflow Channel was activated, diverting fresh water into the tidal flats of the upper delta and immersing, to some degree, those higher marshes (Figure 3-19). These events (Events 16 and 25 confirmed, and Events 17, 18 and 36 strongly suspected) were relatively rare during the demonstration period. Although these tidal flats were also periodically inundated by other hydro-meteorological forces (*e.g.*, the storm surge of Hurricane Bret during Event 35), such non-riverine events were not considered to be tidal flat inundation events because fresh water was not significantly involved in the mechanism. Without the demonstration project, these tidal flats would not have been directly freshened, as the largest of the natural diversions that would have occurred (Event 25) would not have exceeded the confines of the Rincon Bayou channel in the upper delta.

Figure 3-19: View of diverted fresh water in the tidal flats area in the upper Nueces Delta during activation of the Rincon Overflow Channel (Event 16). The view is looking east from the outfall of the overflow channel. The photograph was taken on June 27, 1997.

Photo courtesy of the Bureau of Reclamation.

CHAPTER FOUR

Water Column Productivity

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> ***"In water all hath had its primal source; and water still keeps all things in their course."***
>
> ❖ Johann Wolfgang von Goethe (1749-1832)

INTRODUCTION

Observations of nutrient and primary productivity changes in aquatic environments have been used to assess many aquatic ecosystems for changes of primary inputs or suspected ecosystem alterations (Boynton *et al.* 1982; Pennock *et al.* 1999). Estuarine areas, such as the Nueces Delta, depend upon the mixing of fresh water with sea water to maintain biological productivity. Specifically, fresh water imports nutrients and dilutes salinity of the receiving sea water. Therefore, increased freshwater inflow from the demonstration project should have a large impact on the water column and its biological processes. The re-introduction of fresh water from the Nueces River into the upper Nueces Delta offered an opportunity to monitor nutrient and primary productivity responses in a historic river delta that had been altered by lack of freshwater inflows from small and medium runoff events. In the recent past, fresh water flow has been limited to only large events that have flooded the delta every several years.

OBJECTIVES

1) To assess the effect of the demonstration project on salinity and nutrient availability to the water column of the study area;

2) To assess the response of water column phytoplankton populations to changes in salinity and nutrient availability; and

3) To assess the response of the sedimented phytoplankton (microphytobenthos) populations to changes in salinity and nutrient availability.

METHODS AND APPROACH

STUDY DESIGN

Water column processes were examined at eight sampling sites located throughout the upper Nueces Delta (Figure 4-1). At each sampling station, hydrographic data, water samples and mud samples were collected to measure temperature, salinity, inorganic nutrient concentrations, phytoplankton pigments and plankton growth (productivity) rates. Samples were collected monthly at most sites during the demonstration period unless extreme flooding prevented access to the stations or they were dry. A total of 493 samples were taken for most of the measurements. The eight sampling stations were chosen to represent the various segments within the project area, including one reference site and three treatment sites (upper Rincon Bayou, central Rincon Bayou and Tidal Flats). One other station (68) in the Nueces River near the Nueces Overflow Channel was used to provide a characterization of the riverine source.

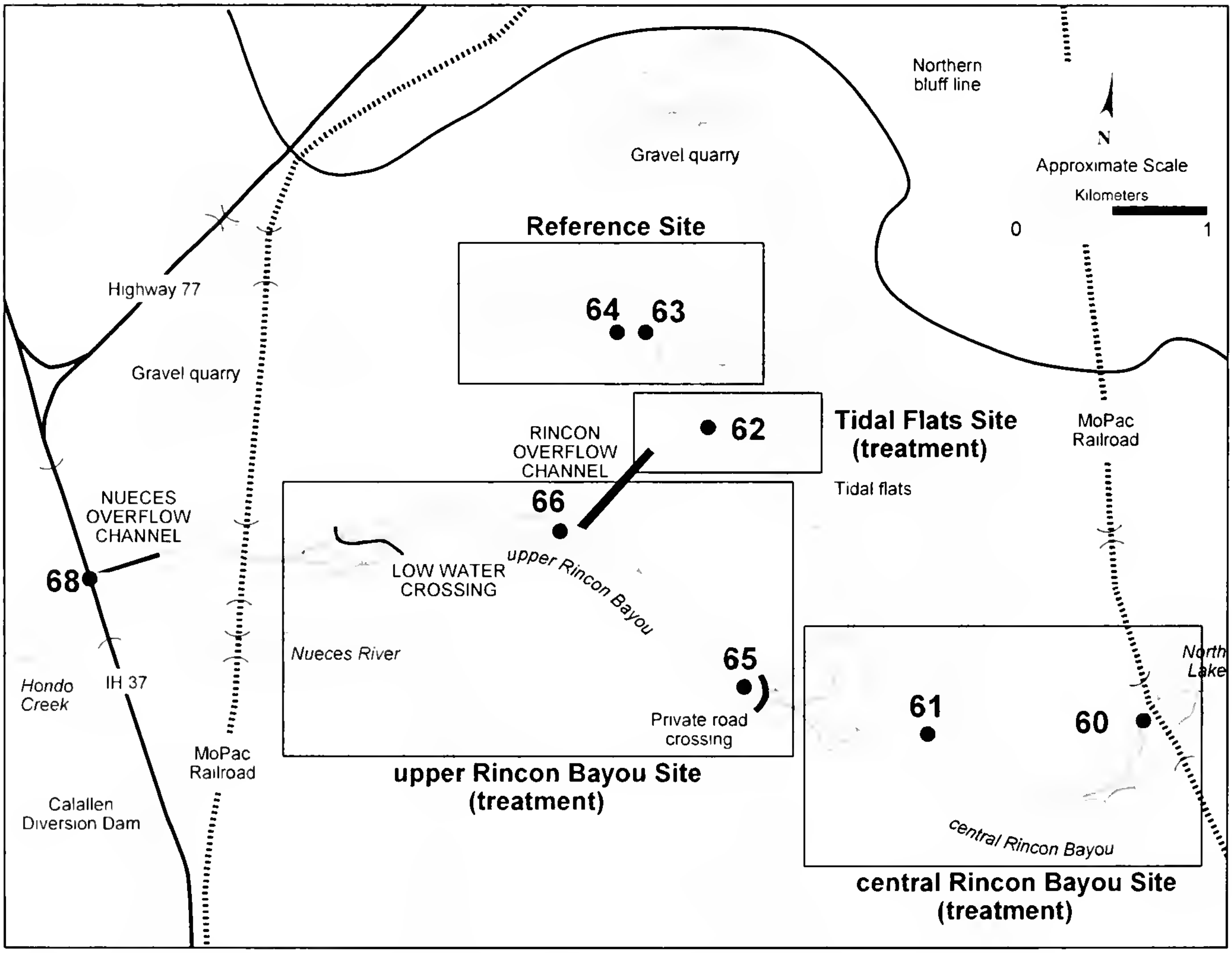


Figure 4-1: Location of water column sampling stations in the upper Nueces Delta. The four sites included one reference site (Stations 62 and 63) and three treatment sites: upper Rincon Bayou (Stations 65 and 66), central Rincon Bayou (Stations 60 and 61) and Tidal Flats (Station 62). In addition to these, one sampling station (Station 68) was occupied in the Nueces River near the Nueces Overflow Channel.

Because phytoplankton are relatively short-lived and are mobile within the water column, they integrate the effects of changes in their environment over very small temporal scales. Therefore, nutrient and primary production responses in the water column (*e.g.*, by phytoplankton) and on the surface sediments (*e.g.*, by microphytobenthos) often occur within the time period of a few hours to several days. This relatively short response time creates a challenge to collect measurements in appropriate time scales. A water column monitoring approach sensitive enough to record bi-weekly or even weekly changes in water column productivity could result in a major imposition on project budgets and collection logistics. After consideration of available resources and funding for monitoring activities, sampling of water column productivity during the demonstration project was scheduled on a monthly basis. This schedule, although possibly limiting the ability to assess the immediate effects of project diversions on phytoplankton and microphytobenthos, provided an opportunity to assess changes in broader column productivity characteristics.

MEASUREMENTS

Hydrography

Physical hydrographic measurements were made at the surface at each sampling site. Parameters recorded were sampling location, date, time, latitude, longitude, sample depth(s), temperature, salinity, dissolved oxygen, per cent oxygen saturation, pH, Secchi depth, water depth and weather conditions. A multi-parameter YSI model 610 profiler instrument was used for *in situ* measurements of salinity and depth parameters. The units of measure (and their nominal accuracy) were: salinity, after conversion from *in situ* conductivity and temperature (0.2 practical salinity units (psu)) and depth (1 cm). Salinity was also measured by field refractometer in many samples and reported as parts per thousand (ppt) for comparison purposes. Differences as large as 4 ppt are often observed due to the high variability of salinity in estuarine waters, the difficulty of maintaining calibration in the electronic instrument and keeping the field refractometer clean and dry. Dissolved oxygen, pH and Secchi depth were not analyzed, but the data were logged for the sake of completeness.

Nutrients

Ambient Nutrient Concentrations – The concentrations of nitrate, nitrite, ammonium, orthophosphate and silicate were determined in all water samples according to published methods of Environmental Protection Agency (1983) and Whitledge *et al.* (1981) using automated continuous flow analyzers. All nutrient samples were analyzed with a Technician AutoAnalyzer II. The water samples were collected in pre-numbered polyethylene bottles and immediately placed in the dark and on ice. Chemical analysis of the samples occurred within 24 hours of collection and was often completed within 5 to 6 hours. Calibration of the automated nutrient channels were performed with each set of samples. A series of five concentrations for each analyte was analyzed prior to analysis of field samples in order to ascertain proper operation. A detailed protocol of standards and their preparation are described by Whitledge *et al.* (1981) and have been used for estuarine/marine samples from 1975 through the present. All standards were prepared in the laboratory using either ultra-pure grade deionized distilled water or, as a standard addition, low nutrient sea water.

Nutrient Amendment Bioassay Studies – Bioassay techniques were employed in the field to evaluate the relative influence of nitrogen, phosphorus, or trace metal additions to changes in phytoplankton biomass (*i.e.*, Chlorophyll A). These bottle assays were enrichment modifications of the productivity estimates and are useful to determine possible nutrient limitations. The bioassay amendment studies were accomplished in screw cap test tubes that contained 50 milliliters (ml) of sample. Initial samples were analyzed for extracted chlorophyll content. Four replicates of each sample were amended with 10 micro-moles per liter (µmole/l) of ammonium, 10 µmole/l of phosphate, 10 µmole/l of ammonium plus 10 µmole/l of phosphate or 100 micro-liters (µl) of "f/2" trace metal stock solution. Four replicates of a control sample with no additions were also utilized. After the additions, the caps were tightened and *in vivo* fluorescence readings were taken on samples. The amended samples were placed in diffuse lighted incubators at 25 °C and additional fluorescence measurements were taken daily for 3 to 4 days. The mean of the four *in vivo* fluorescence samples was used to represent the effect of the amendment additions. No readings were discarded. When the incubations were terminated, the samples were analyzed for extracted (*in vitro*) chlorophyll content.

Phytoplankton Pigments

Changes in phytoplankton biomass were determined using Chlorophyll A as the index of biomass. The chlorophyll and pigment samples were analyzed with a model 10-005RU Turner Designs fluorometer which was specifically designed for pigment analyses using the methodology of Holm-Hansen *et al.* (1965). Calibration of the *in vitro* chlorophyll analysis was accomplished with pure chlorophyll obtained commercially and standardized with a spectrophotometer. Phaeopigment concentrations were also determined in the same samples after addition of a small amount of hydrochloric acid.

Primary Production

Rates of phytoplankton primary production were monitored using replicate ^{14}C incubations and natural sunlight using the method of O'Reilly and Thomas (1983). This method has been used for all measurements in South Texas bays over the previous 8 years. The procedure consists of collection of duplicate water samples that were inoculated with ^{14}C isotope and incubated in a water bath for 2-3 hours in full sunlight. Dark bottle uptake was measured for corrections and ^{14}C inoculation volumes were checked with replicate initial blanks. Primary production ^{14}C measurements were analyzed with a Beckman model LS5801 liquid scintillation counter that employed self-calibration with known sources and calculates counting efficiency. Initial carbonate alkalinity was analyzed by standardized methodology of 25 ml of 0.01 M hydrochloric acid additions to 100 ml of sample. The extremely high alkalinity of Rincon Bayou often required additional aliquots of acid addition until a proper pH of <3.9 was obtained.

Sedimented Plankton (Microphytobenthos)

Chlorophyll – The chlorophyll content of sediment was determined at each site by sub-sampling a 5-cm core collected by hand. A 1-cc syringe was also used to collect the sample from the upper 0.5 cm of the sediment surface. Extraction and analysis of the chlorophyll/phaeopigment content were conducted according to the same procedures as the water samples.

Primary Productivity – The primary production of microphytobenthos was determined on 1-cc mud samples from the top of 5-cm cores collected by hand. The sediment was suspended in 25 ml of filtered water collected at the site. Replicate ^{14}C incubations were incubated in natural sunlight for 3 to 4 hours.

RESULTS

HYDROGRAPHY

Temperature

Temperature is generally not a strong controlling factor on water column primary production, but seasonal temperature changes may have a secondary effect on production processes. Temperature data were most useful in characterizing rapid changes in environmental conditions, such as sudden changes of weather during winter cooling events (*e.g.*, fronts). Long extended periods of high temperature were used to identify periods of drought and other times of stress on the plant and animal populations in the upper delta.

Salinity

Salinity is a conservative variable because its concentration is altered only by physical processes. As precipitation or evaporation occurs, salinity can be used to produce an accurate estimate of the quantity of water added or subtracted from an estuary. In addition, salinity values also give a good indication as to the spatial extent of freshwater inflow events.

In general, the upper Nueces Delta experienced a wide variance of salinity concentrations during the demonstration period, ranging from over 120 ppt (Station 65) to less than 1 ppt (*e.g.*, Station 66) (Figure 4-2). The incomplete salinity graphs with missing data mostly resulted from dry periods when there was no standing water at the stations. The Nueces River site (Station 68) had the lowest salinity at all times except on September 16, 1999. This sampling date was at the conclusion of Event 36 (Chapter 3), when a large volume of water previously diverted into the Rincon Bayou during the event had flowed back into the Nueces River (Figure 3-9) likely transporting acquired salt from the upper delta.

Measurements of freshwater flow into and out of Rincon Bayou (Chapter 3), and direct precipitation were compared with water column salinity data (Table 4-1 and Figure 4-3). Because salinity at the water column stations was measured monthly, daily rain and inflow data were summed by water column sampling dates. The variations in average salinity at each site over time clearly showed the highly variable amounts of precipitation and evaporation over the five year sampling period (Figure 4-3). During the months following high freshwater inflow periods in summer 1997 (Events 16 and 17), fall 1998 (Events 23 through 27) and fall 1999 (Events 36 and 37), the upper Rincon Bayou site (Stations 65 and 66) had lower salinity values than those in the central Rincon Bayou site (Stations 61 and 62), and often times lower than the Reference sites (63 and 64). This condition (*i.e.*, salinity concentrations lowest in the upper delta) represents a "normal" estuary salinity gradient typically found in unperturbed systems. During dry periods and drought (*e.g.*, the last part of 1995 through the first part of 1996, as well as summer 1998), a "reverse estuary" condition was observed (*i.e.*, the highest salinity concentrations were found in the upper delta), where the upper Rincon Bayou site was predominantly saltier than Reference or central Rincon Bayou sites (Figure 4-3). These observations conformed closely to the project design in that medium to high river flow events circulated through the historical Rincon Bayou channel.

NUTRIENTS

Inorganic nutrients are utilized by plants to produce organic matter through the process of photosynthesis. The concentrations of nutrients available and amount

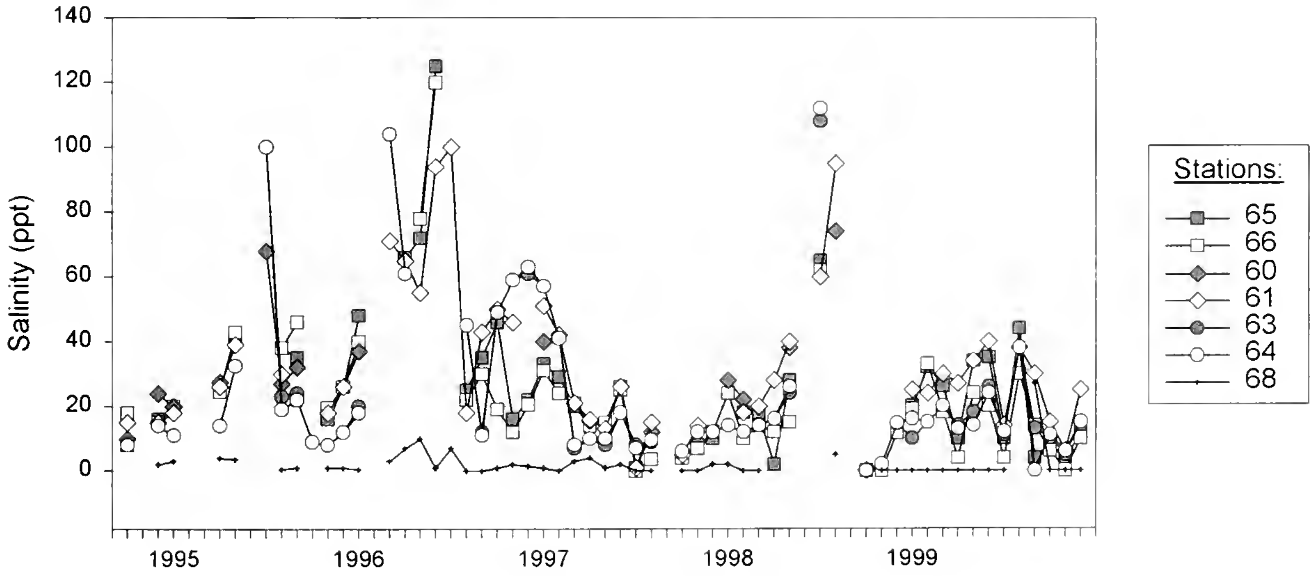


Figure 4-2: Salinity at all water column stations (except Station 62) for each sampling date. Data from Station 62 were not plotted because the Tidal Flat site was frequently dry resulting in significant data gaps.

Table 4-1: Hydrographic events (from Table 3-3) occurring prior to each water column sampling period. Daily values for net flow and total precipitation were summed between sampling intervals. In some cases, sampling occurred during an event. The Nueces Overflow Channel was completed on October 26, 1995, so flow prior to that date was zero. Precipitation data for sampling dates prior to May 16, 1996 were that recorded at the Corpus Christi International Airport. Hyphens (-) indicate missing or incomplete data.

Water Column Sampling Date	Hydrographic Events (Table 3-3)	Total Net Flow Through Rincon Bayou (acre-ft)	Total Precipitation (inches)
28-Oct-94		0	7.37
17-Nov-94		0	0.20
07-Dec-94		0	2.17
11-Jan-95	1	0	6.35
13-Feb-95		0	0.44
15-Mar-95		0	6.33
17-Apr-95		0	0.99
16-May-95		0	0.48
17-Jun-95	2	0	4.10
20-Jul-95	3	0	1.14
17-Aug-95	4	0	4.46
27-Sep-95	5	0	4.81
25-Oct-95		0	0.36
28-Nov-95	6	-	12.83
14-Dec-95	7	-	0.04
17-Jan-96	8, 9, 10	-	0.51
17-Feb-96		-	0.04
20-Mar-96		-	0.00
10-Apr-96		-	1.11
15-May-96		-	0.47
17-Jun-96		21	0.66
21-Jul-96		0	1.58
27-Aug-96	11	18	4.94
30-Sep-96		21	4.54
30-Oct-96	12, 13	247	0.80
18-Nov-96	14	47	0.18
10-Dec-96		14	1.16
30-Jan-97		2	2.32
06-Mar-97		20	1.41
24-Mar-97		19	5.05
21-Apr-97	15	-15	4.95
29-May-97		33	5.99
18-Jun-97		-9	1.32
14-Jul-97	16, 17	1386	1.95
07-Aug-97		163	0.08
17-Sep-97		13	0.19
28-Oct-97	18	265	11.36
04-Dec-97		-6	2.66
17-Dec-97		0	0.08
27-Jan-98		3	0.56
24-Feb-98		35	3.01
24-Mar-98		-3	2.01
08-Apr-98	19	19	0.00
02-May-98		21	0.15
05-Jun-98		4	0.00
08-Jul-98	20	-9	0.82
19-Aug-95	21	-2	4.67
29-Sep-98	22, 23, 24	649	4.39
24-Oct-98	25	4246	9.15
18-Nov-98	26, 27	130	3.95
18-Dec-98		-14	0.60
12-Jan-99		-3	0.50
24-Feb-99		-6	0.51
18-Mar-99	28	13	0.06
15-Apr-99	29	130	2.29
24-May-99	30, 31	-135	3.81
09-Jun-99	32	2	1.08
21-Jul-99	33, 34	15	6.89
19-Aug-99	35	-16	0.26
16-Sep-99	36	821	7.25
28-Oct-99	37	-54	3.60
17-Nov-99		-5	0.00
08-Dec-99		18	0.28

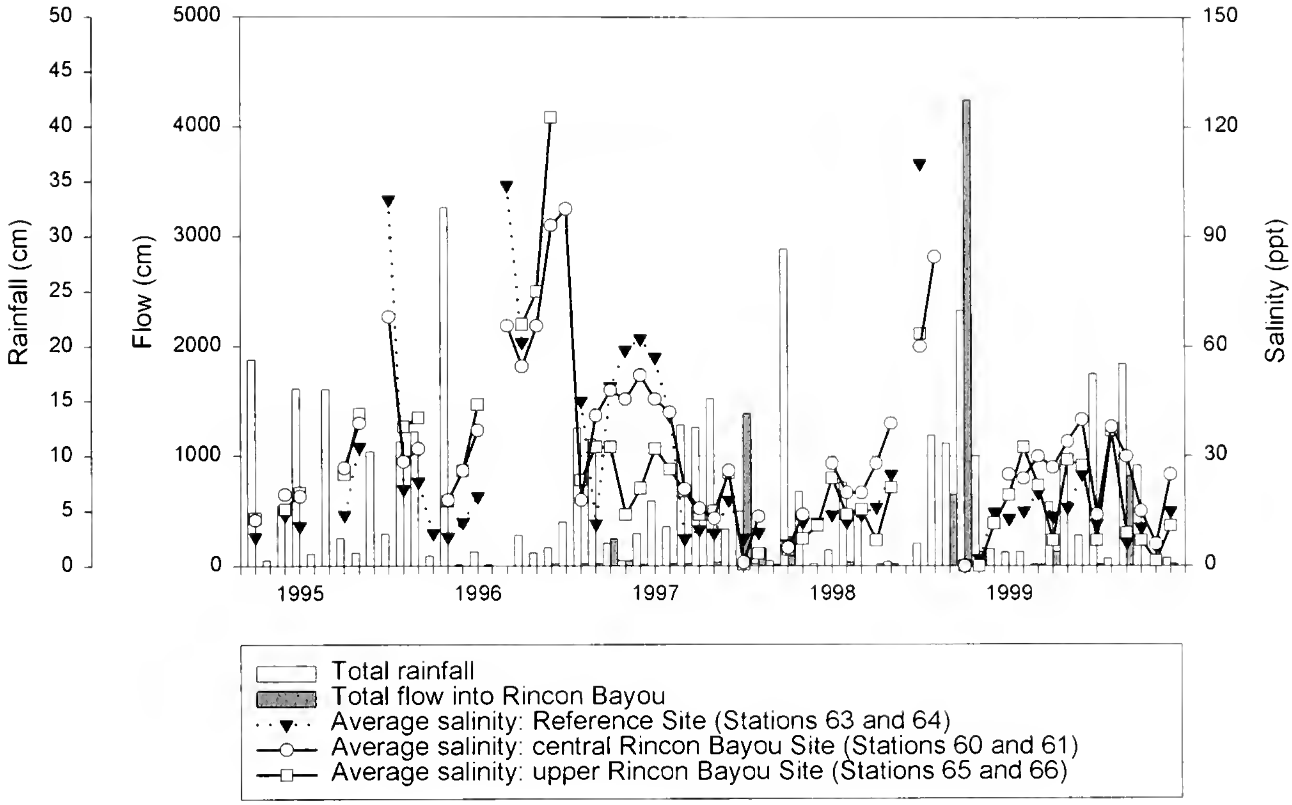


Figure 4-3: Average salinity at each sampling site for each sampling date. Cumulative daily rainfall and inflow into Rincon Bayou also plotted for each monthly period between sampling dates.

of sunlight often determine the amount of biological productivity in an estuary. Organic matter from the plants may go through several pathways depending on whether it was eaten, decomposed or buried in the sediments. Organic matter that is consumed may be excreted back into the environment or be incorporated into the animal tissue. Microbial populations can also absorb or breakdown organic matter and return it to the environment. Both organic matter pathways, through higher animals or microbes, produce regenerated nutrients which enhance nutrient concentrations in the water and again become available for uptake by plants. The relative amounts of the original nutrients and the regenerated nutrients can often provide rate process estimates for turnover of organic matter in estuaries.

The relative importance of different nutrients varies in freshwater and marine environments. As a result, the importance of phosphorus nutrients are often clearly observed in freshwater segments, while nitrogen nutrients are most important in saline segments. These differences are caused by many physical and biological processes that vary over short time and spatial scales.

Nitrate (NO_3)

Nitrate is the most common form of nitrogen nutrient in oxygenated environments. The concentrations of nitrate in many rivers has increased over the past five decades as a result of increased usage of agricultural fertilizer and wastewater effluents.

The nitrate content of the Nueces River and the Nueces Delta stations (Figure 4-4) were relatively low (< 2 µmole/l). Less than 1% of the data were > 2 µmole/l and usually occurred during flooding events. The largest concentrations of nitrate (> 20 µmole/l) were only found at the Reference site (Stations 63 and 64) and only during 1999. The relatively low nitrate concentrations observed throughout the data record would provide a low level maintenance for phytoplankton growth but would certainly not provide nutrients needed to fuel bloom conditions.

Ammonium (NH_4)

Ammonium is the form of nitrogen most commonly released by recycling of organic matter or excretion by higher organisms. Accordingly, ammonium is often called "regenerated" nitrogen. Shallow environments such as the Nueces Delta and Nueces Bay tend to increase the relative amounts of regenerated nitrogen compared to nitrate (which is often called "new" nitrogen because it has been newly added to the ecosystem by advection or inflow).

The concentrations of ammonium observed during the demonstration period were usually larger than nitrate concentrations (Figure 4-5). The Nueces River station (Station 68) often had the smallest ammonium levels, while the upper Rincon Bayou stations (65 and 66) were sometimes largest. The central Rincon Bayou stations (60 and 61) occasionally contained the largest ammonium concentrations. There was no obvious direct relationship between salinity and ammonium at any of the station sites.

Nitrite (NO_2)

Nitrite is the form of nitrogen that is intermediate between nitrate and ammonium for its valence state and is not typically observed in large concentrations in most estuarine or marine environments.

During the demonstration period, the small concentrations of nitrite resulted from either nitrification or denitrification processes (Figure 4-6). Estuary ecosystems tend to have both nitrification and denitrificaion processes occurring at the same time by specific microbes for each. Large concentrations of nitrite (*e.g.*, >1 µmole/l) indicate that special conditions existed for a short time.

Dissolved Inorganic Nitrogen (DIN)

DIN is the sum of the nitrate, nitrite and ammonium forms of nitrogen. This amount represents the total inorganic nitrogen nutrients available for uptake by plants. Because all three forms of nitrogen are readily

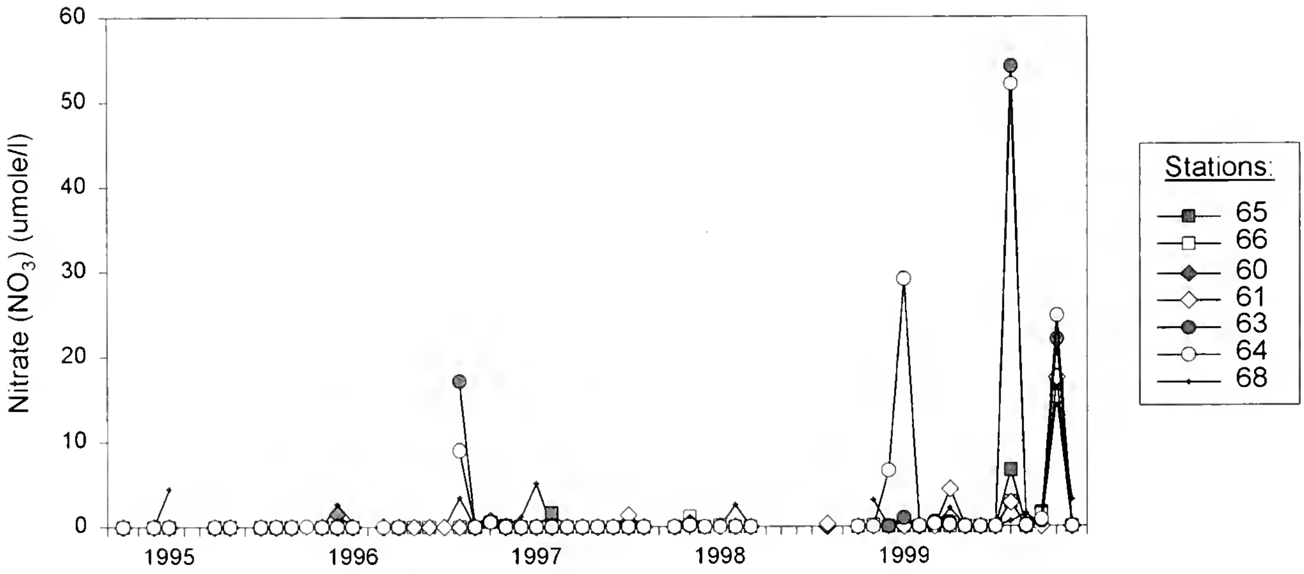


Figure 4-4: Nitrate concentrations at all water column stations (except Station 62) for each sampling date.

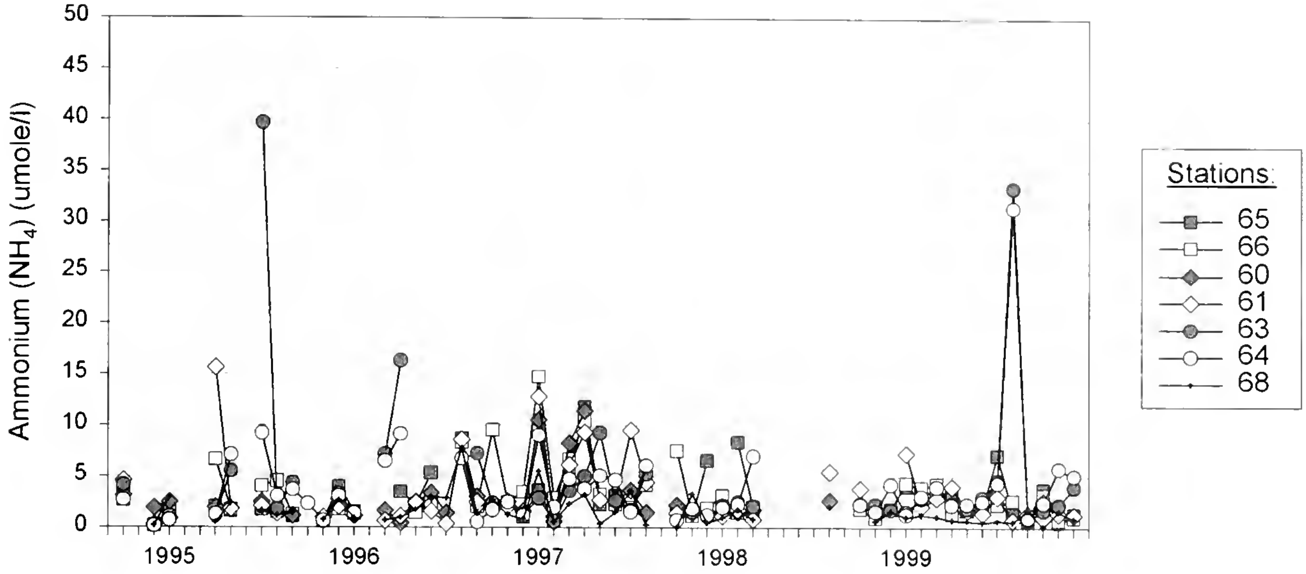


Figure 4-5: Ammonium concentrations at all water column stations (except Station 62) for each sampling date.

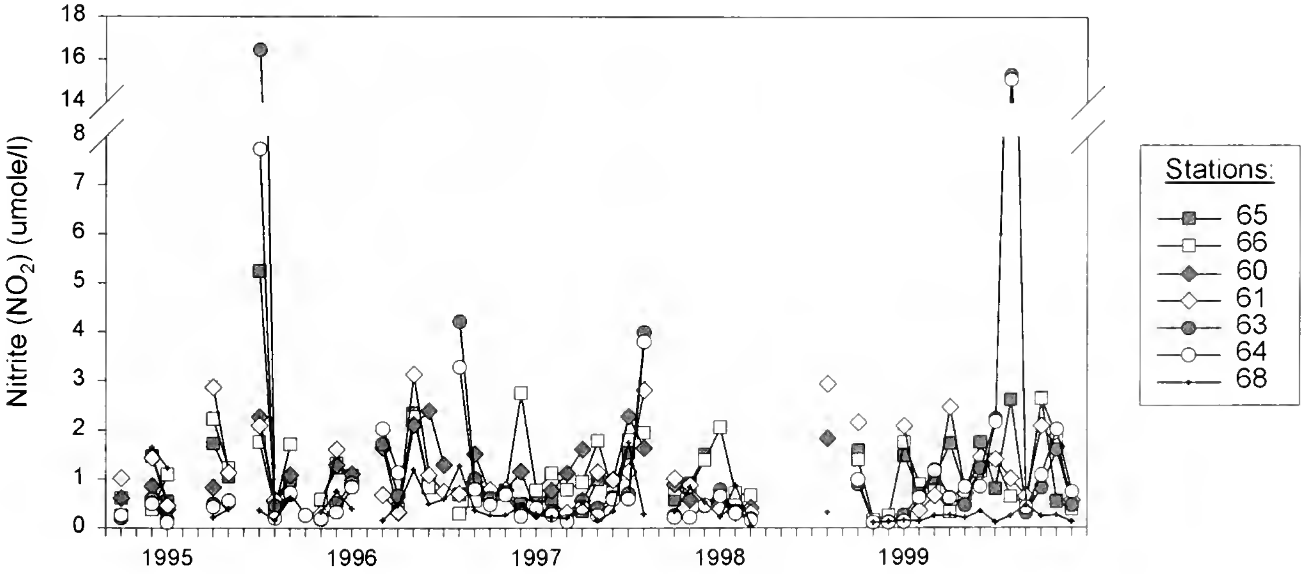


Figure 4-6: Nitrite concentrations at all water column stations (except Station 62) for each sampling date.

utilized by photosynthetic processes, DIN is often used to estimate nitrogen nutrient availability.

The concentration of DIN at most stations was < 10 µmole/l, and, on only six sampling dates, it was larger than 20 µmole/l, of which five were at the Reference site (Figure 4-7). In general, the Reference site (Stations 63 and 64) displayed most of the largest concentrations of DIN, which likely was a result of unusually large inputs from local runoff. The Nueces River (Station 68) generally had the lowest DIN concentrations.

The largest contributor to the DIN pool was ammonium, as indicated by its percentage of DIN (Figure 4-8). In only a relatively few samples (about 6%) was ammonium less than 40% of the DIN. During 1999, a relatively large number of samples contained 100% ammonium.

Phosphate (PO_4)

Phosphate (orthophosphate) is the primary phosphorus nutrient, and it's dynamics vary widely in fresh and salt waters. During the demonstration period, phosphate concentrations were primarily about 5 µmole/l or lower, although several samples had values near 30 µmole/l (Figure 4-9).

Also, these concentrations represented high concentrations of phosphorus relative to nitrogen. For example, most values for the nitrogen to phosphorous (N:P) ratio calculated from phosphate and DIN concentrations were below 3.0 (Figure 4-10). A typical value of the N:P ratio for organic matter is about 15. During the demonstration period, only 5 samples had values larger than 15.0, indicating a possible shortage of phosphorus in the system. In contrast, there were a large number of samples with values < 5.0 for N:P, indicating that phosphorus was very abundant and nitrogen may be limiting autotrophic processes.

PHYTOPLANKTON PIGMENTS

Phytoplankton pigments are useful indicators of plant biomass. Chlorophyll A has been the primary pigment traditionally used, but better analytical methods since 1985 have allowed a large number of other pigments to be identified and measured accurately. Chlorophyll A

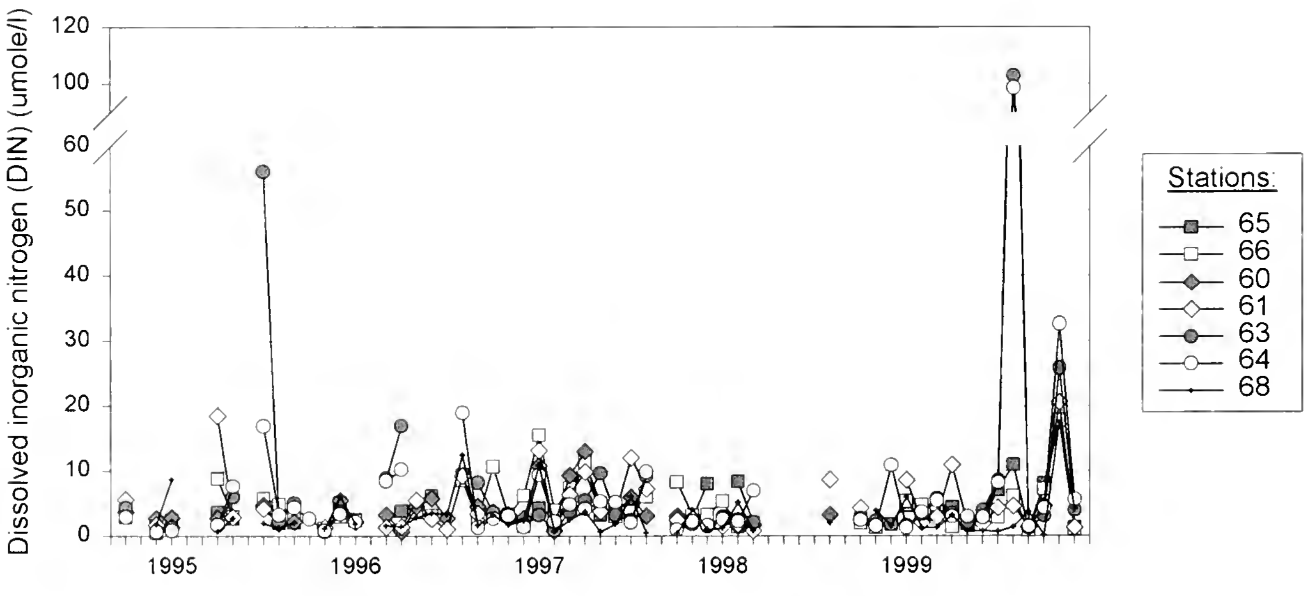


Figure 4-7: Dissolved inorganic nitrogen concentrations at all water column stations (except Station 62) for each sampling date.

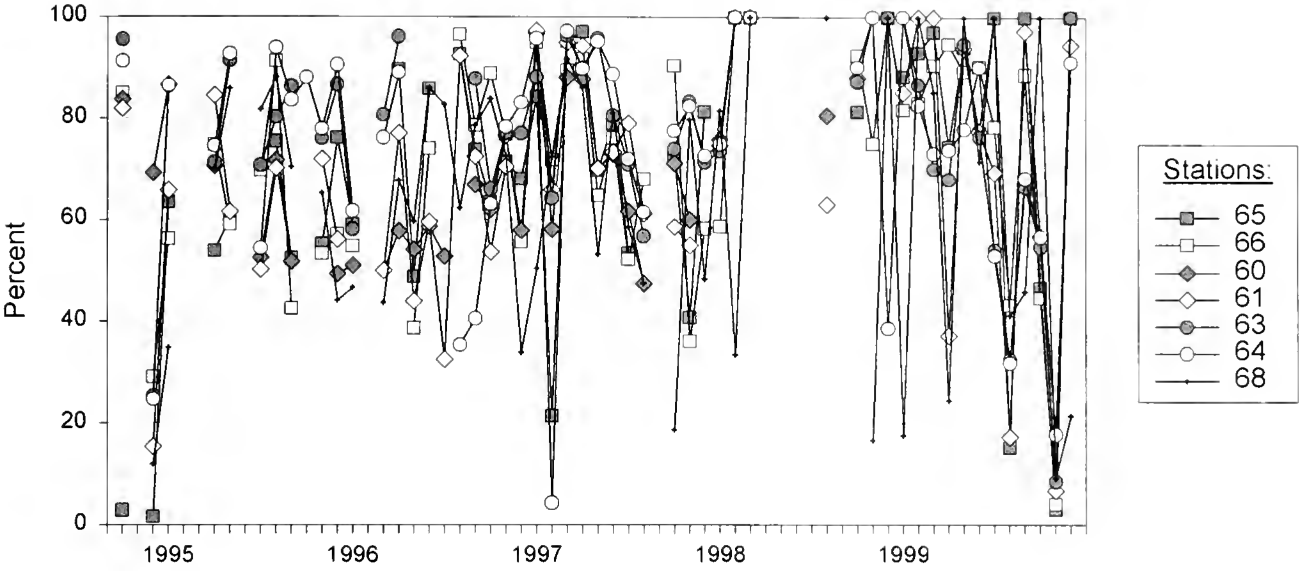


Figure 4-8: Percent of dissolved inorganic nitrogen contributed by ammonium at all water column stations (except Station 62) for each sampling date.

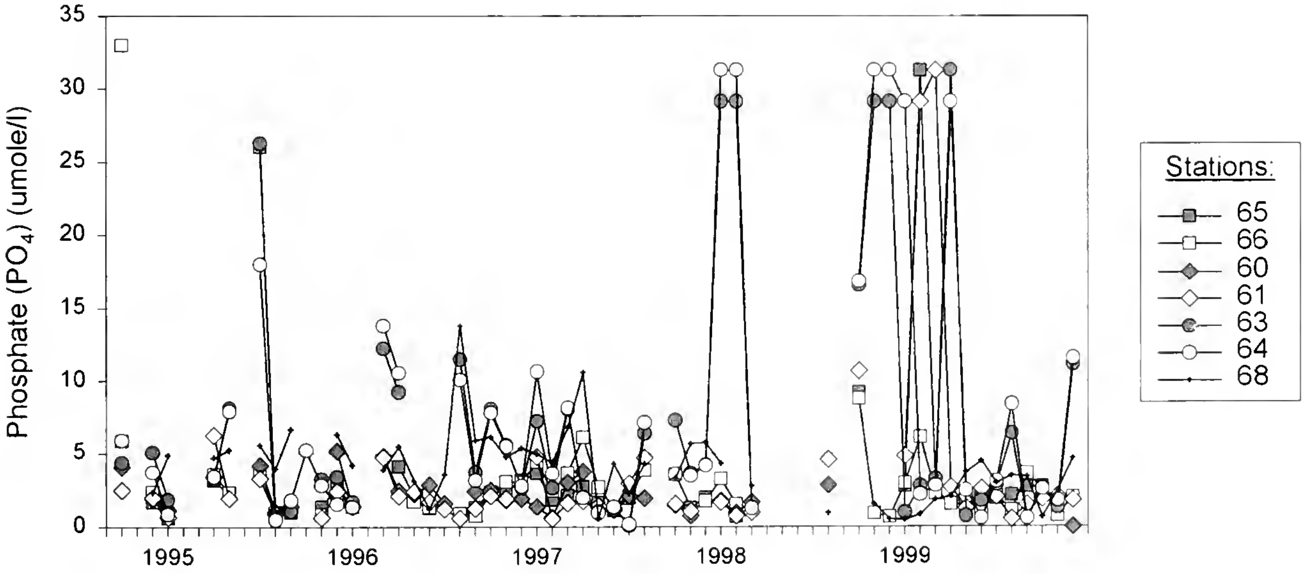


Figure 4-9: Phosphate concentrations at all water column stations (except Station 62) for each sampling date.

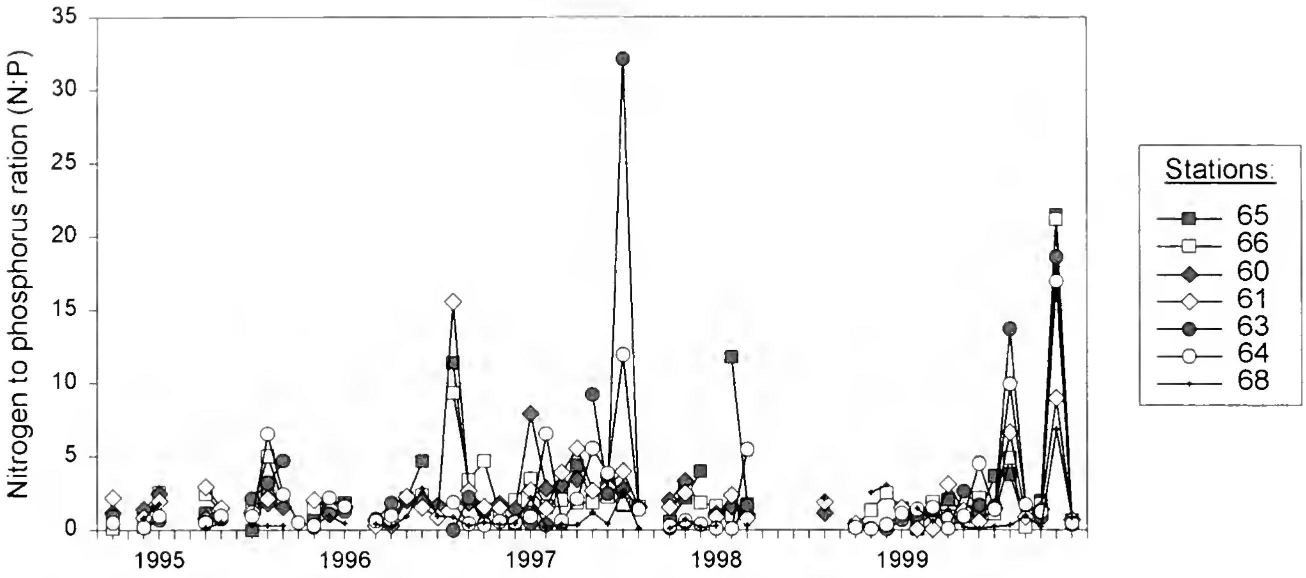


Figure 4-10: Nitrogen to phosphorous (N:P) ratios at all water column stations (except Station 62) for each sampling date.

remains the typical pigment measured by fluorometric techniques but is often accompanied by a phaeopigment estimate after the addition of acid.

Chlorophyll

Chlorophyll concentrations (which are an estimate of plant biomass in the water) were quite large during the demonstration period, with a large number of values > 100 µg/l (Figure 4-11). The smallest concentrations were mostly measured in the Nueces River (Station 68), but all other sites had some values > 150 µg/l, which could be described as bloom conditions. These biomass accumulations of plankton partially drive the large rates of primary production in the Nueces Delta.

WATER COLUMN PRODUCTION

Water column primary production is a combination of phytoplankton biomass and the growth rate of individual cells. Therefore, combinations of high biomass or high growth rates can produce large rates of primary production. The rate of primary production is a function of nutrient availability and incident radiation to the phytoplankton cells.

The ^{14}C experiment conducted as part of this demonstration project indicated that the average rate of primary production is about 3 gC/m^2/day (Figure 4-12), but higher values were typically as large as 10 gC/m^2/day. One extremely high rate (38 gC/m^2/day) was obtained at Station 63 before the opening of the Nueces Overflow Channel as a result of a bloom of filamentous blue-green algae. Frequently the Nueces River station (68) had the lowest rates, but all Rincon Bayou stations showed large responses during inflow events, particularly during the summers of 1997 (Events 16 and 17) and 1999 (Events 29 and 33). The observed rates of primary production in the upper Nueces Delta were larger than values for Nueces Bay (Stockwell 1989), and the highest rates were equal to the largest observed in up-welling areas in the ocean.

Assimilation Index

The assimilation index is the rate of primary production normalized to the chlorophyll biomass. This index is useful to determine if the specific growth rates of phytoplankton cells are large enough to create bloom conditions. Typical assimilation index values of 50 to 100 mgC/m^3/day/µgChl are observed for many phytoplankton spring blooms.

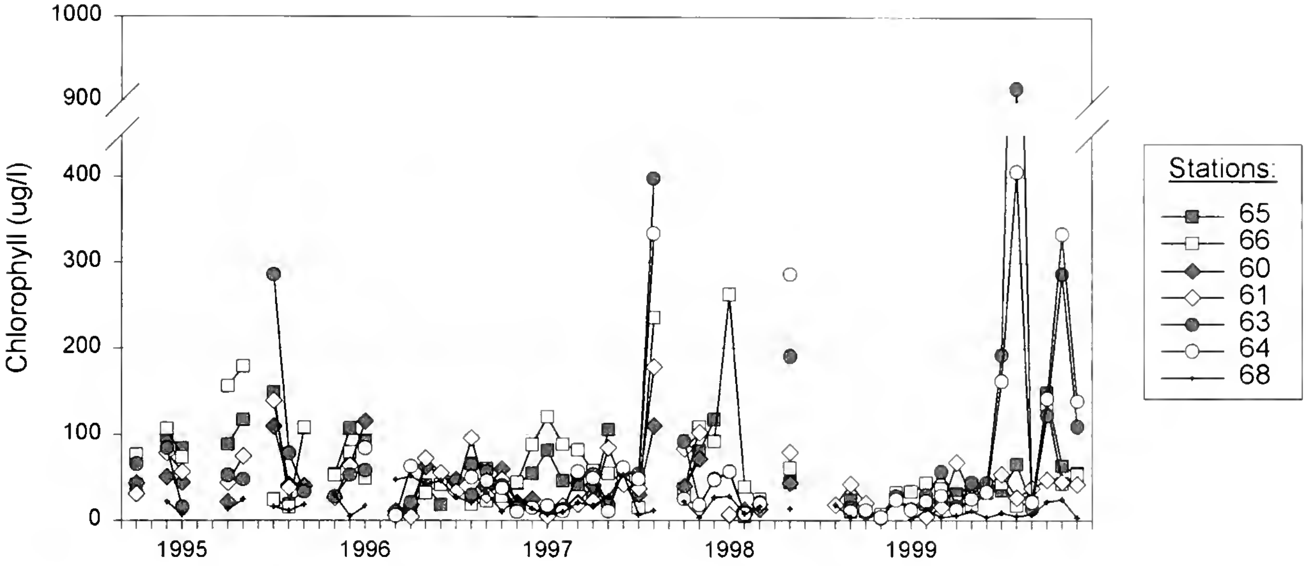


Figure 4-11: Chlorophyll concentrations at all water column stations (except Station 62) for each sampling date.

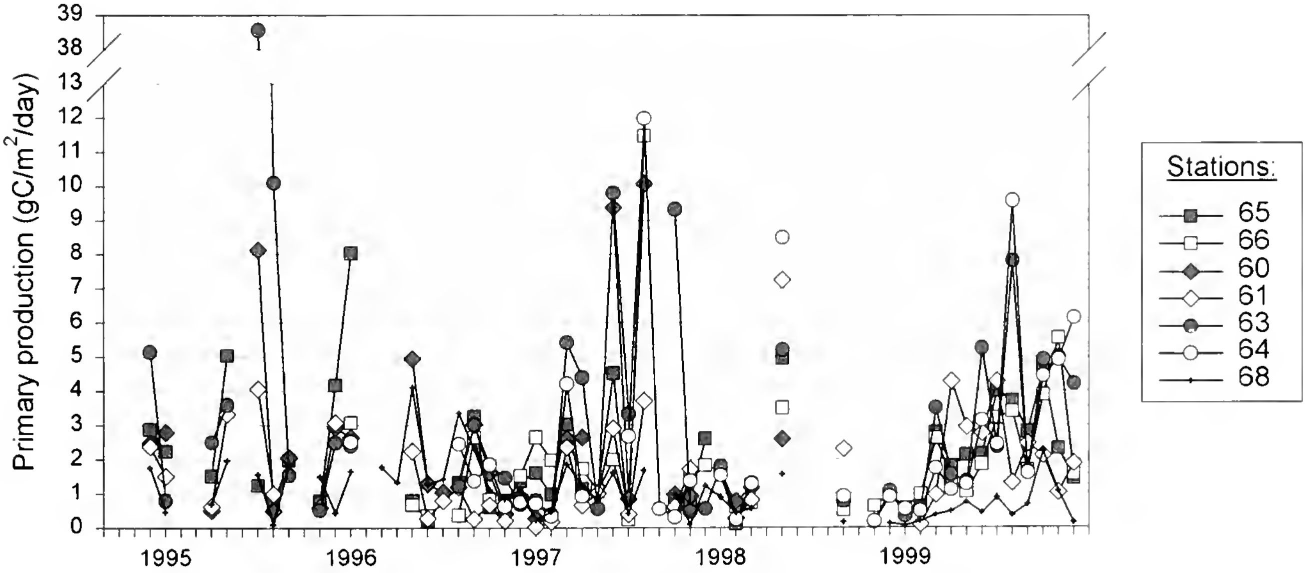


Figure 4-12: Primary production at all water column stations (except Station 62) for each sampling date.

The assimilation index for most stations had values of 20 to 100 mgC/m^3/day/µgChl (Figure 4-13). Many of the highest values observed before appreciable inflow passed through the Nueces Overflow Channel (*i.e.*, prior to October 1996) were measured at the Nueces River station (68). Later during the demonstration period, the upper Rincon Bayou stations (65 and 66) were much higher compared to earlier years, and most station samples gave higher results during the final year. This apparent increase at most of the sampling stations during the final year might be due to increased freshwater diversions.

NUTRIENT AMENDMENT BIOASSAYS

The nutrient amendment studies were undertaken to determine whether phytoplankton growth within the Nueces Delta could be stimulated by the addition of nitrogen, phosphorus or trace metal nutrients. The biomass of the phytoplankton as measured by chlorophyll was used to indicate biological response. The amount of change may be influenced by the incubation conditions, but the relative responses can provide valuable clues to the degree of limitation of an addition or set of additions. Two nutrient amendment experiments were performed in March and April 1997 during what was a relatively dry period in the delta. A final amendment experiment was undertaken in August 1997, after a large amount of summer-time freshwater inflow (Events 16 and 17).

Amendment Series 1: March 7, 1997

Station 68 – The two phosphate amendment additions responded equivalent to the control for the four day period (Figure 4-14a). All other additions showed increased chlorophyll concentrations compared to the controls. Trace metals, nitrate, nitrate plus phosphorus and silicon, and nitrate plus phosphorus had approximately twice the response compared to ammonium and ammonium plus phosphorus.

Station 63 – All amended samples showed a chlorophyll response for days 1 and 2 that was equivalent to the control with no additions (Figure 4-14b). On day 3, both concentrations of phosphate had no effect compared to the control, but all other additions enhanced chlorophyll production.

Station 66 – The two phosphate amendment additions showed responses equivalent to the control for the

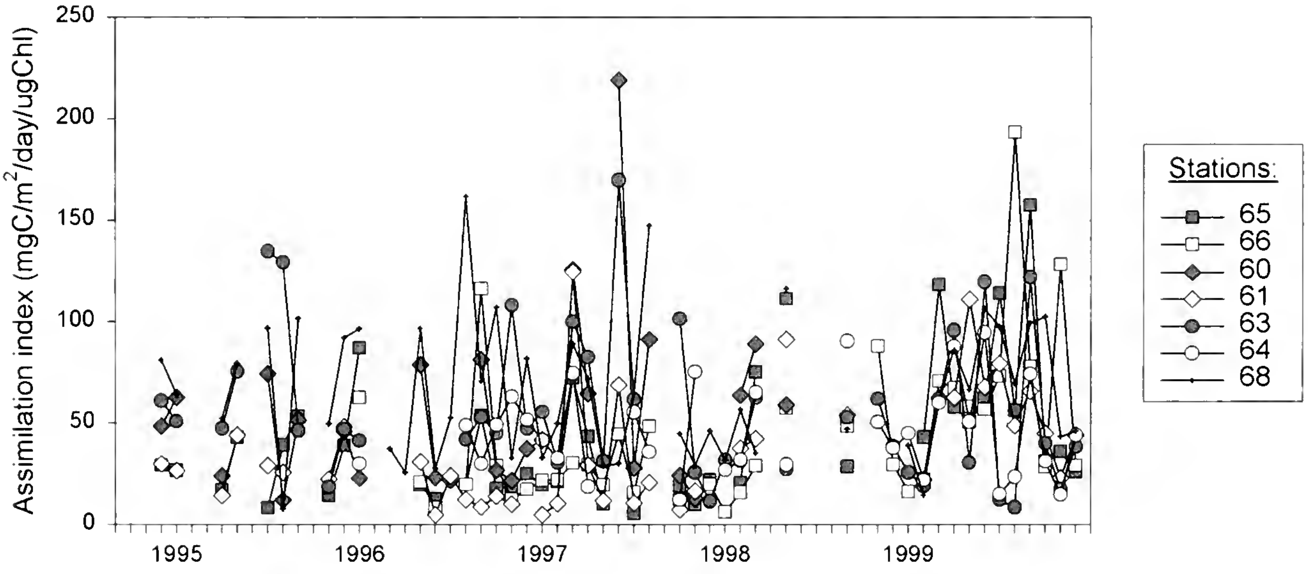
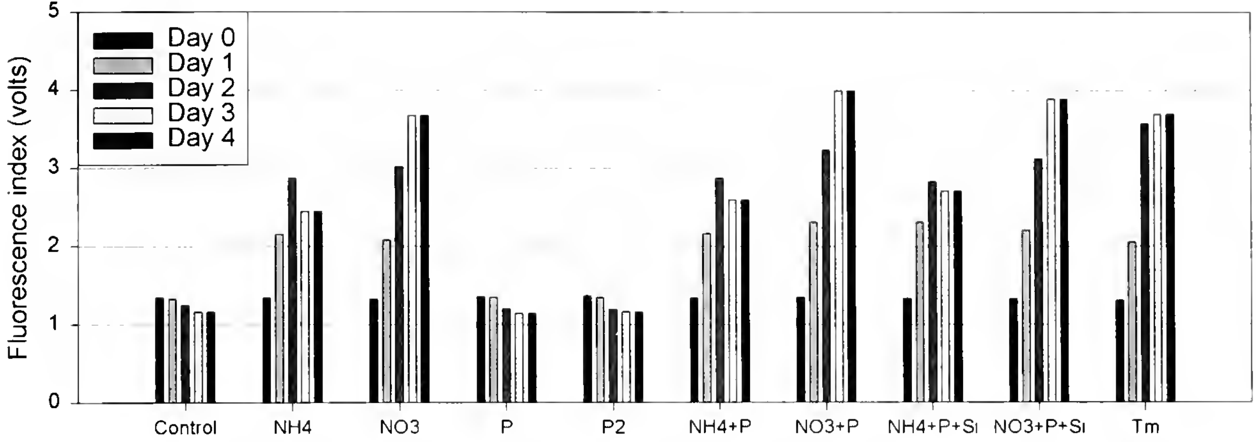
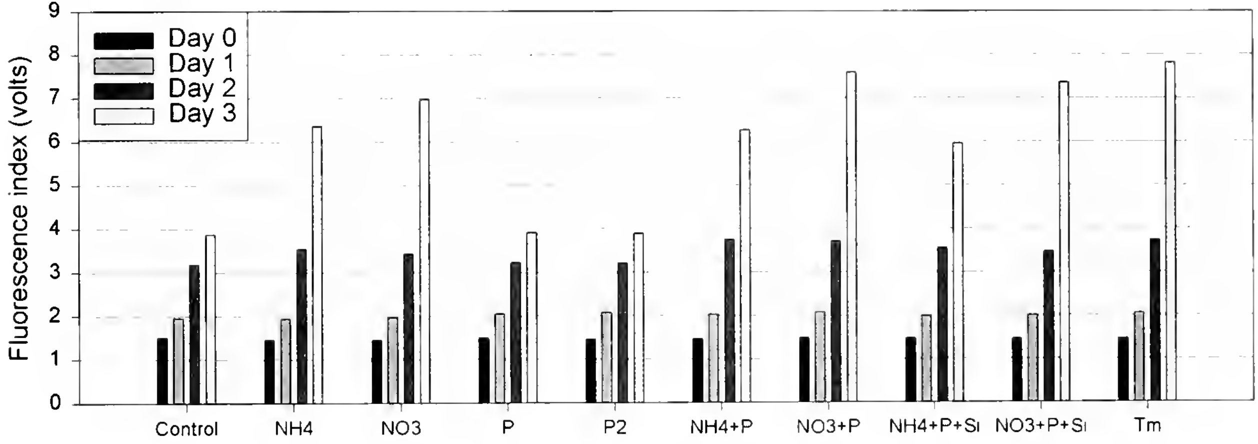


Figure 4-13: Assimilation index at all water column stations (except Station 62) for each sampling date.

(a) Station 68



(b) Station 63



(c) Station 66

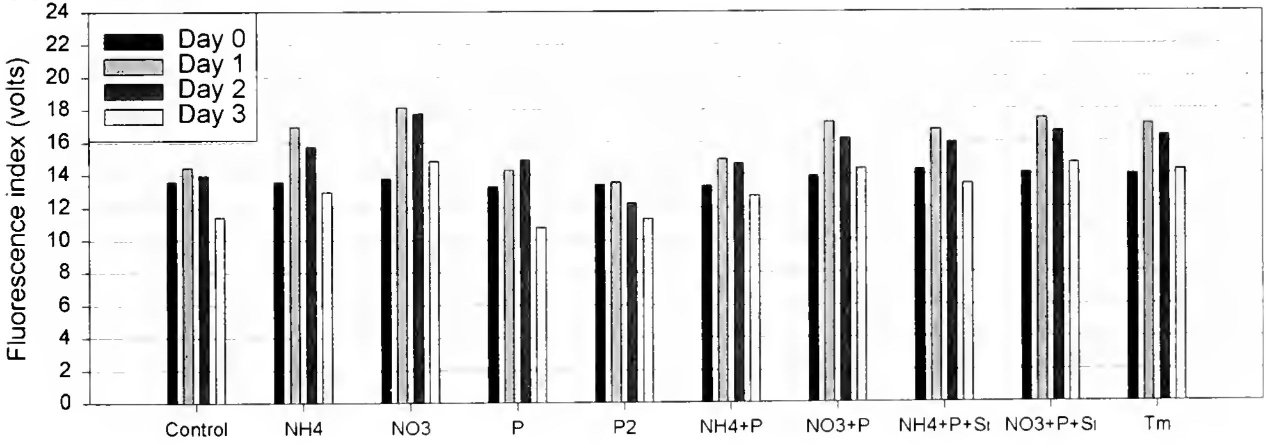


Figure 4-14: Results from nutrient amendment bioassays for selected stations: March 7, 1997. Chlorophyll response indicated by fluorescence. Each daily value represents the mean of four replicate samples.

three day period (Figure 4-14c). All other additions increased chlorophyll concentrations compared to the controls.

Amendment Series 2: April 22, 1997

Station 68 – All additions showed an increase in chlorophyll compared to the control except phosphate additions (Figure 4-15a). The chlorophyll enhancements were approximately doubled compared to the control.

Station 63 – All additions showed an increase in chlorophyll compared to the control except phosphate additions (Figure 4-15b). The chlorophyll enhancements were increased by approximately 50% over the control.

Station 66 – All additions showed an increase in chlorophyll compared to the control except phosphate additions (Figure 4-15c). While all samples showed a decreasing trend, the chlorophyll enhancements were approximately a 30% increase over the control.

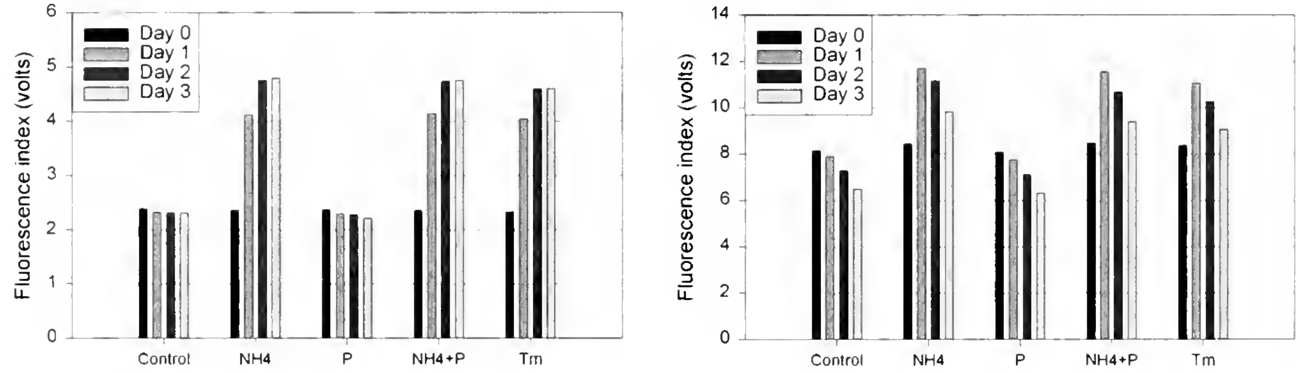
Station 60 – All additions showed an increase in chlorophyll compared to the control except phosphate additions (Figure 4-15d). The chlorophyll enhancements were approximately double when compared to the control.

Amendment Series 3: August 7, 1997

Station 68 – Additions of ammonium, nitrate, silicate and ammonium plus P showed increased chlorophyll responses compared to the control (Figure 4-16a).

(a) Station 68

(b) Station 63



(c) Station 66

(d) Station 60

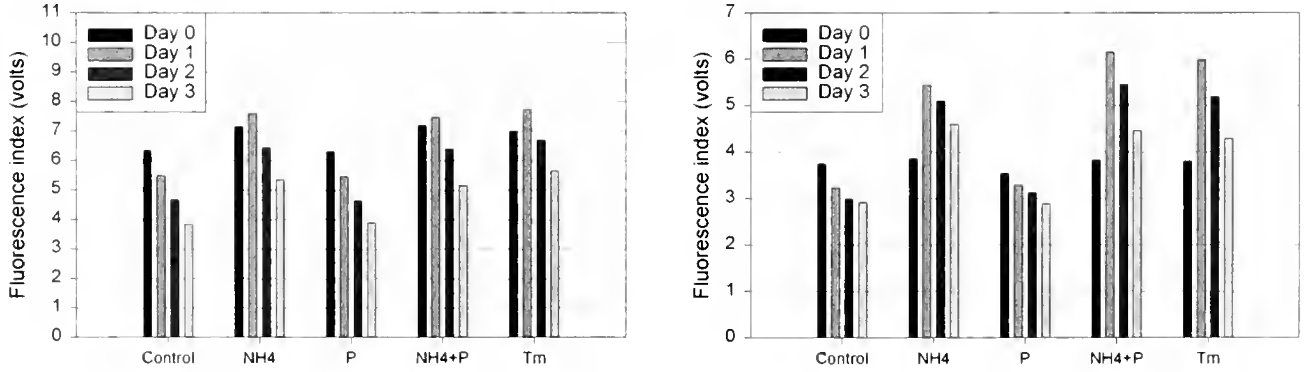


Figure 4-15: Results from nutrient amendment bioassays for selected stations: April 22, 1997. Chlorophyll response indicated by fluorescence. Each daily value represents the mean of four replicate samples.

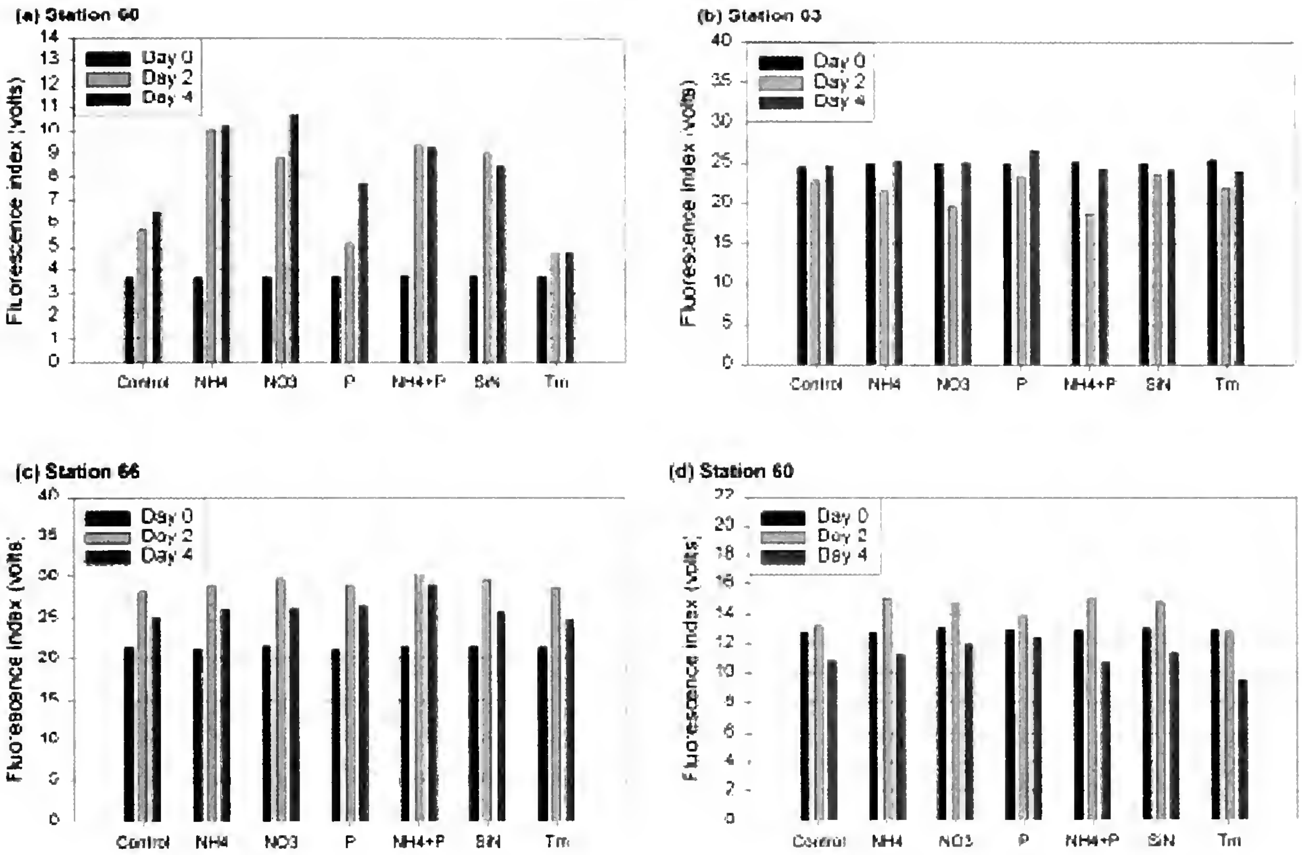


Figure 4-16: Results from nutrient amendment bioassays for selected stations: August 7, 1997. Chlorophyll response indicated by fluorescence. Each daily value represents the mean of four replicate samples.

Phosphate and trace metals stimulated small chlorophyll responses and were probably not significant.

Station 63 – No chlorophyll increases were observed with any of the amendment additions (Figure 4-16b)

Station 60 – All additions showed an increase in chlorophyll compared to the control except phosphate additions (Figure 4-15d). The chlorophyll enhancements were approximately double when compared to the control.

Amendment Series 3: August 7, 1997

Station 68 – Additions of ammonium, nitrate, silicate and ammonium plus P showed increased chlorophyll responses compared to the control (Figure 4-16a).

Phosphate and trace metals stimulated small chlorophyll responses and were probably not significant.

Station 63 – No chlorophyll increases were observed with any of the amendment additions (Figure 4-16b)

Station 66 – No chlorophyll increases compared to the control were observed with any of the amendment additions (Figure 4-16c).

Station 60 – Only trace metal additions enhanced chlorophyll compared to the control (Figure 4-16d). Other additions produced no significant effects in chlorophyll concentration.

MICROPHYTOBENTHIC SEDIMENT BIOMASS AND PRODUCTION

The shallow water environment of the Nueces Delta allows a large fraction of water column phytoplankton to settle to the sediment. These benthic cells may become attached to the sediment surface or remain unattached to potentially re-suspended with wind induced mixing.

The absence of data during the period with the most freshwater inflow (*e.g.*, summer 1997 through fall 1999) precluded a full assessment of the demonstration project's effects on microphytobenthic communities, but some results were observed from the data available.

Sediment Chlorophyll

The biomass of microphytobenthic cells is often estimated by chlorophyll concentrations, but there is no method to determine if the cells are attached and growing in place or merely deposited temporarily until re-suspension. Therefore, estimates of microphytobenthos production include both types of plankton.

The sediment chlorophyll declined at all stations during the course of the demonstration period (Figure 4-17), but no causal mechanisms were apparent. Because two stations at the Reference site (63 and 64) also exhibited the decline, it is likely that the trend was not related to the effects of the demonstration project.

The ratio of chlorophyll to phaeopigments in the sediment varied within a typical range during the demonstration period (Figure 4-18). The several high ratios of chlorophyll compared to phaeopigments at Stations 65 and 66 (upper Rincon Bayou site) during 1996 indicate that chlorophyll production occurred more rapidly than did pigment decomposition during that period.

The inventory of chlorophyll in the water column and sediment was not closely related to salinity, but the combined chlorophyll biomass was largest at salinity concentrations below 60 psu (Figure 4-19). This observation can partially be attributed to reciprocal concentrations of high sediment and low water column chlorophyll (Figure 4-20). Much of the time, sediment chlorophyll was high when water column chlorophyll was low, but at other times, low sediment chlorophyll occurred when the water column chlorophyll concentration was large.

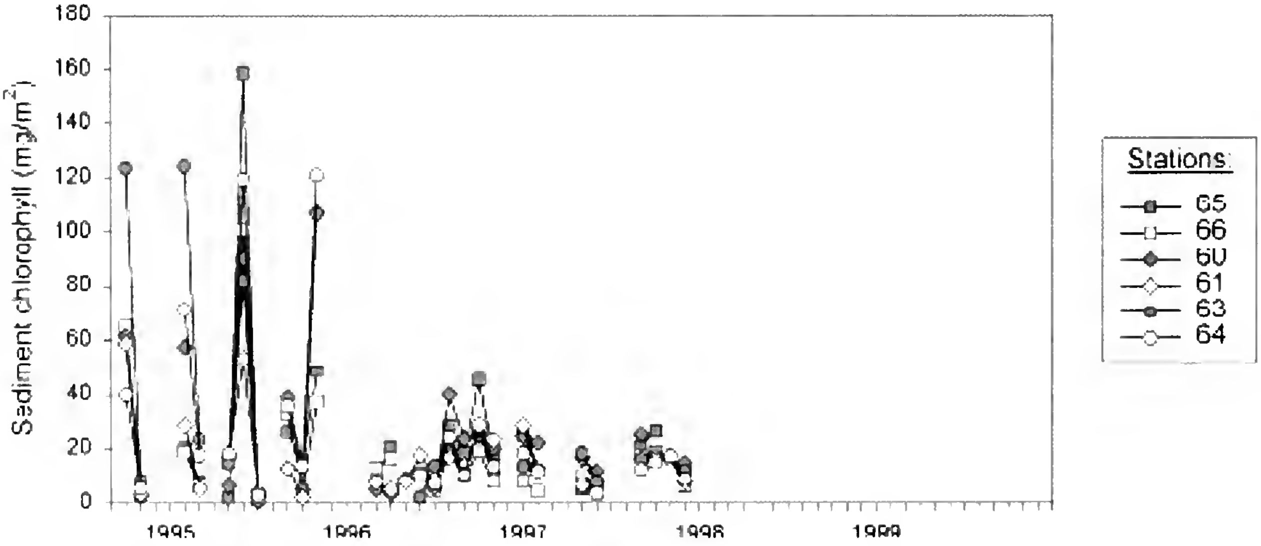


Figure 4-17: Sediment chlorophyll concentrations at all water column stations (except Stations 62 and 68) for each sampling date.

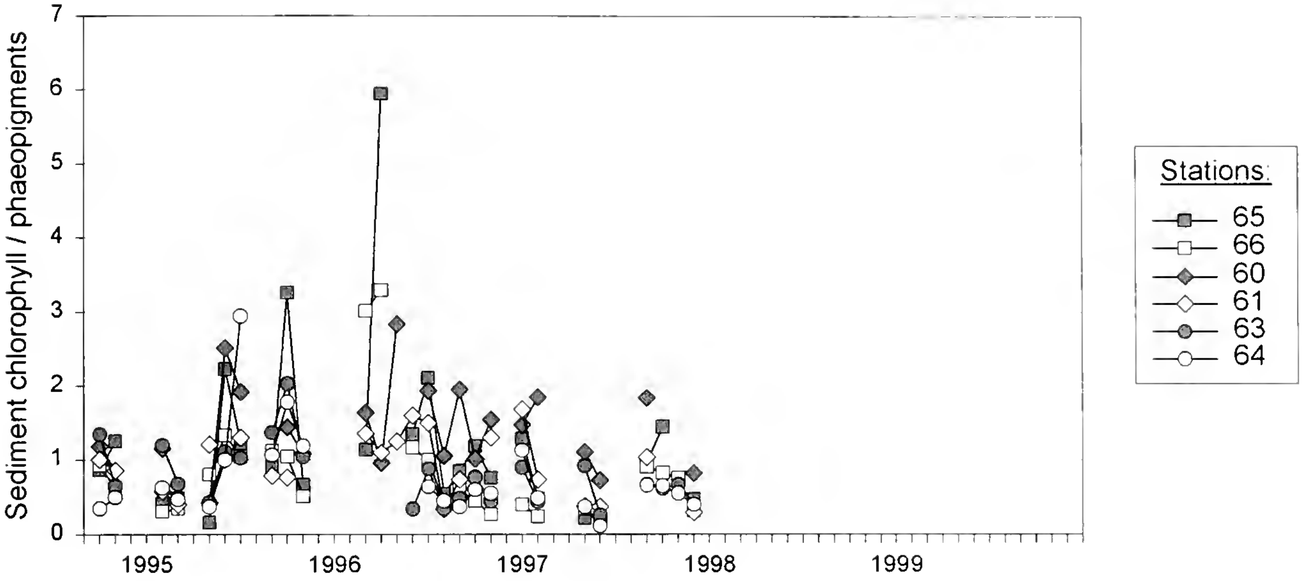


Figure 4-18: Sediment chlorophyll to phaeopigments ratio at all water column stations (except Stations 62 and 68) for each sampling date.

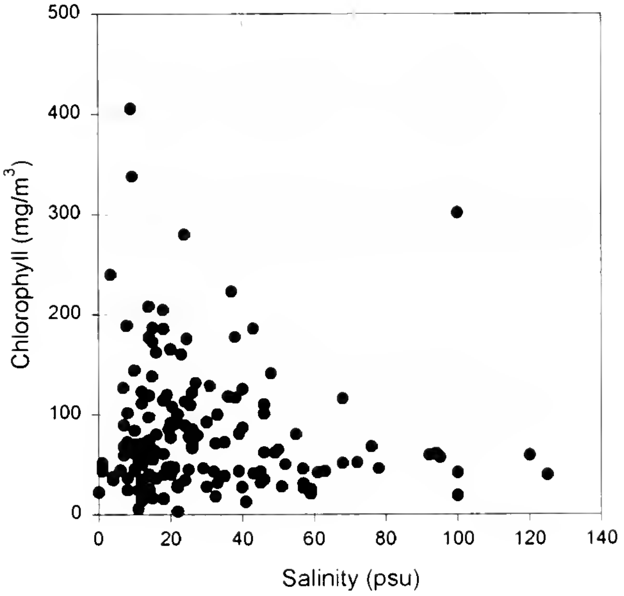


Figure 4-19: Total sediment and water column chlorophyll and salinity.

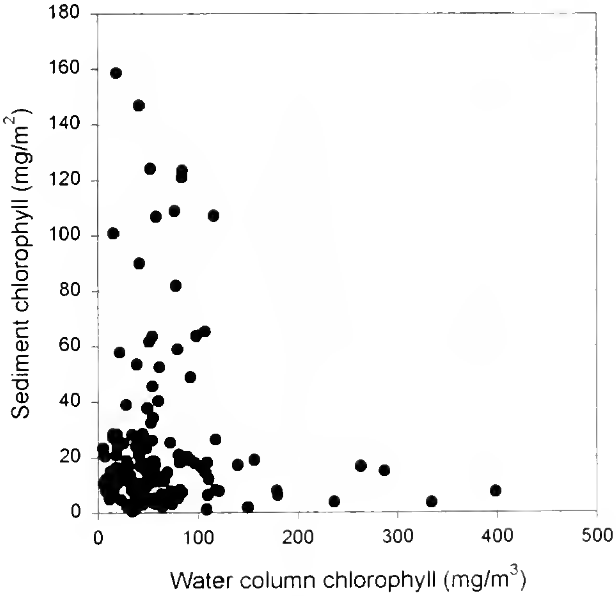


Figure 4-20: Sediment chlorophyll and water column chlorophyll.

Microphytobenthic Production

The primary production of microphytobenthos was generally similar to water column rates, although the range of water column primary production values was more than two times larger (compare Figures 4-21 and 4-12). There was some indication that sediment production was more likely to be high during winter months, while water column production tended to be highest in the summer, especially at the two Reference stations.

The sediment chlorophyll was not strongly related to sediment primary production values (Figure 4-22). This indicates that chlorophyll accumulation in the sediments did not necessarily dominate the flux rates of sediment primary production and was probably attributed to a rather short residence time for chlorophyll in the sediments before degradation occurred. A direct comparison of water column and sediment primary production rates indicates that there was no correlative relationship (Figure 4-23) and that most of the water column rates were 2 to 4 times larger than the sediment rates.

The total combined water column and sediment primary production rates did not have a strong relationship to salinity (Figure 4-24), but there was certainly a general trend that showed the largest production rates were at salinity concentrations below 60 psu. The upper limits of total primary production over the entire range of salinity clearly showed an inverse relationship with salinity.

Benthic Assimilation Index

The primary production assimilation index for the microphytobenthos (Figure 4-25) was not nearly as dynamic as the water column index. During only one monthly sampling period in the summer of 1995 did the sediment assimilation index exceed a value of 30 gC/m^2/day/Chl. This low range probably indicates that severe conditions of limited light, low nutrients and possibly high temperatures found in the sediments were not conducive to high rates of primary production per unit of chlorophyll.

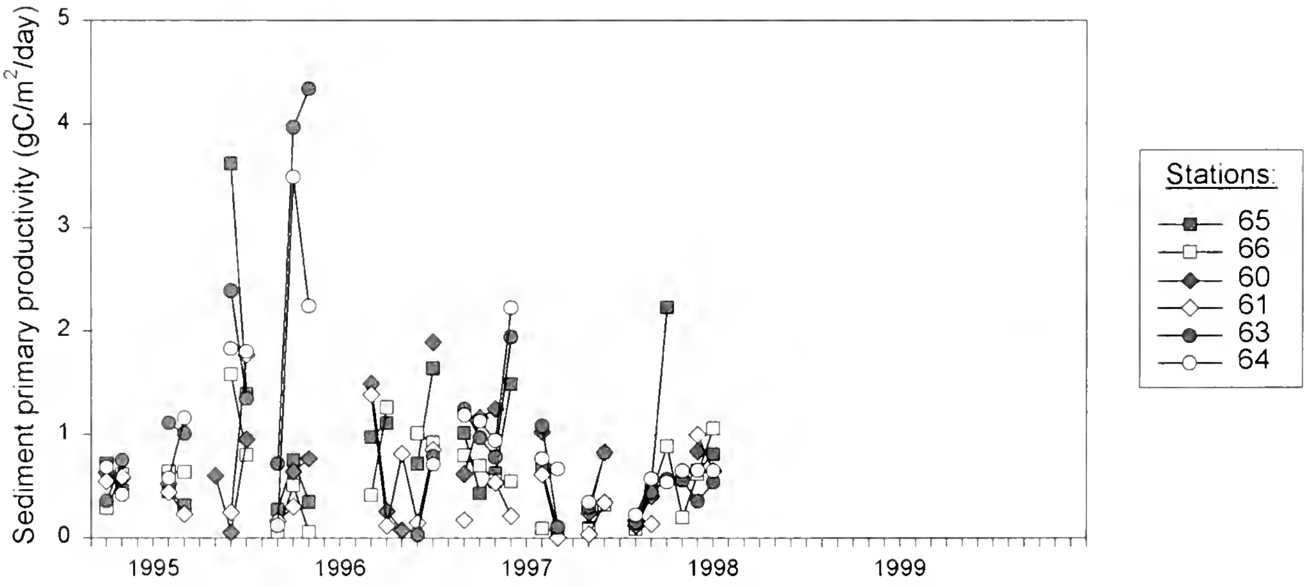


Figure 4-21: Sediment primary productivity concentrations at all water column stations (except Stations 62 and 68) for each sampling date.

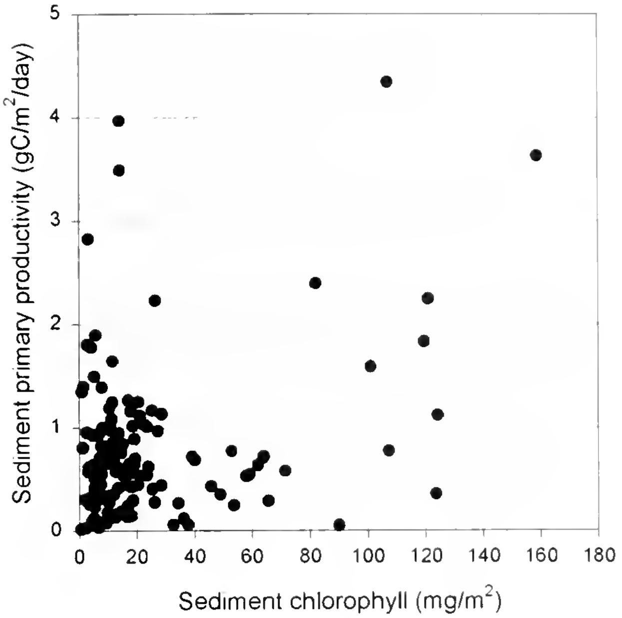


Figure 4-22: Sediment chlorophyll and sediment primary productivity.

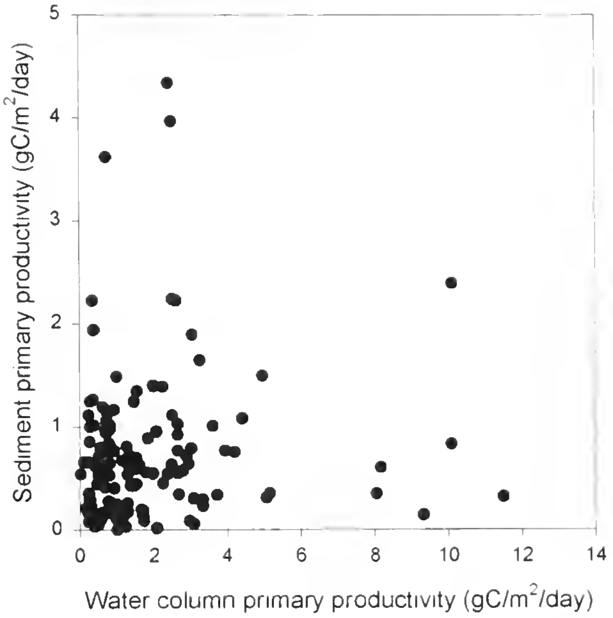


Figure 4-23: Sediment primary productivity and water column productivity.

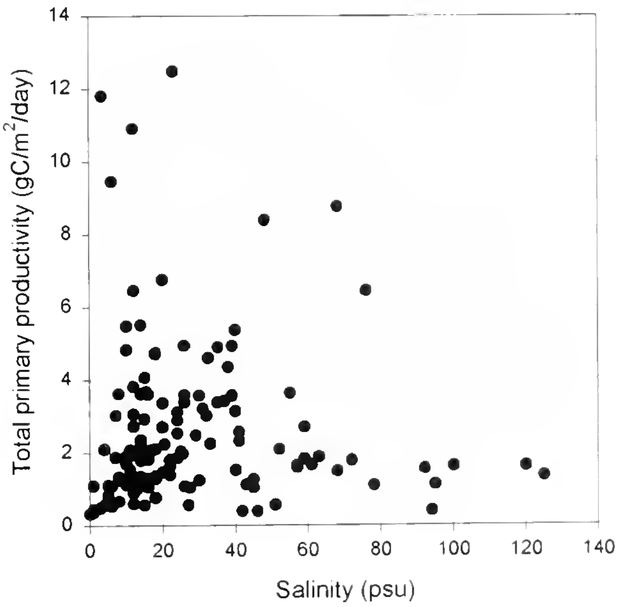


Figure 4-24: Total primary productivity (sediment and water column) and salinity.

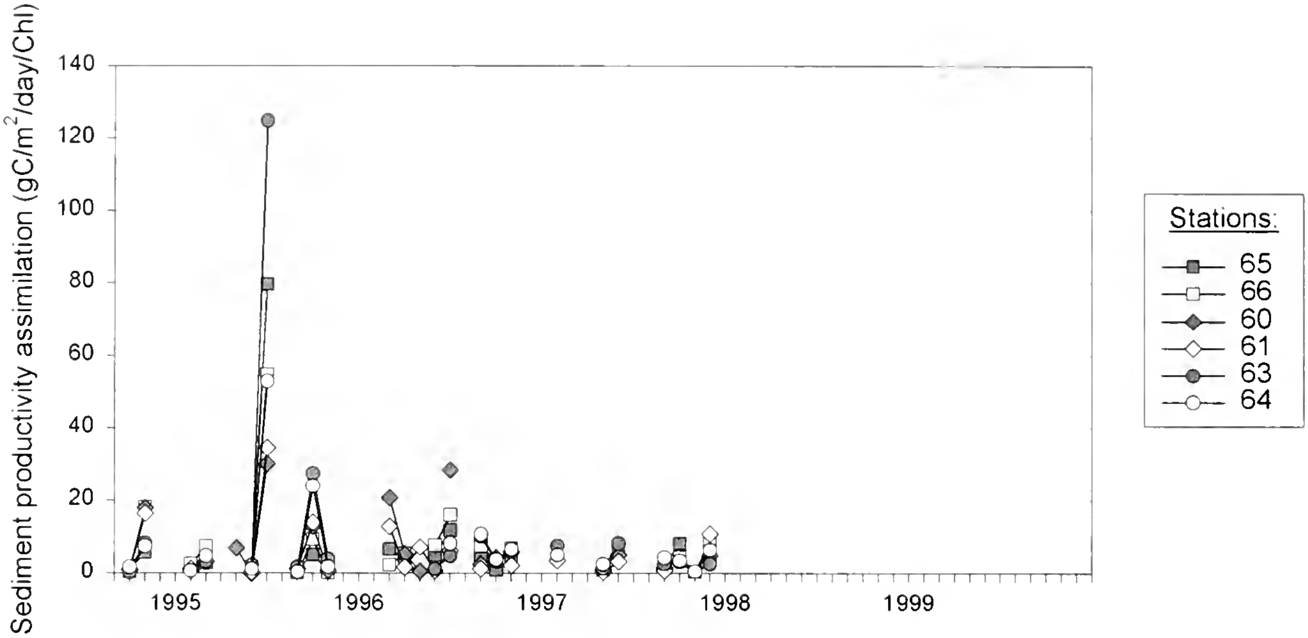


Figure 4-25: Assimilation index at all water column stations (except Stations 62 and 68) for each sampling date.

DISCUSSION

The extreme environment of Rincon Bayou is readily apparent when the wide ranges of temperature and salinity are considered. The nutrient content of the water column required for primary production to occur was quite variable during the demonstration period. The combination of water column inventories of nutrients and chlorophyll pigments with instantaneous measurements of primary production provided some indications of resources available and their rates of utilization. However, the relatively small area and volume of water contained in the Rincon Bayou ecosystem reduced residence times and accelerated fluxes through the marsh. The monthly sampling schedule was therefore not generally sensitive enough to fully analyze the effects of freshwater inflow events on phytoplankton production and growth. However, even with the constraints of monthly sampling intervals, it was quite apparent that positive water column nutrients and primary production effects resulted from the demonstration project.

First of all, nutrient amendment experiments were performed in March and April 1997 to ascertain what element(s) limited phytoplankton production in the waters of Rincon Bayou. A subsequent amendment experiment was undertaken in August 1997, after a large amount of freshwater inflow (Events 16 and 17), to determine if nitrogen was still the limiting nutrient. Before freshwater inflow, ammonium additions increased chlorophyll production compared to control samples from several sites. Those experiments also indicated that vital trace metals used in "f" media also stimulated chlorophyll production. Additions of nitrate also stimulated chlorophyll production to about the same extent as ammonium, but very small ambient concentrations of nitrate were observed at the sampling sites. In August, after a significant inflow of riverine fresh water, no nutrient additions increased chlorophyll production at any station in the delta, indicating that nutrients were no longer limiting phytoplankton production.

These nutrient amendment bioassays were the primary indicator of the relatively rapid nutrient utilization and phytoplankton response. Initial responses to the single and multiple nutrient and/or trace metal additions were on the order of a day and continued for 2 to 3 days. It has been clearly demonstrated from other analyses of freshwater inflows that nitrate utilization increased primary productivity in the Nueces River and

Nueces Bay (Whitledge and Stockwell 1995). Therefore, the rapid uptake of nitrate due to freshwater inflow very likely occurred in the upper Nueces Delta shortly after numerous hydrographic events during the demonstration period, even if these responses were not readily observed within the (infrequent) sampling intervals.

Second, the total of water column and sediment primary production in the delta had an inverse relationship with salinity. Although the water column contributed the largest fraction of the total (*ca.* 75%), the sediment production rates also provided a significantly large amount. As salinity values in Rincon Bayou declined below 60 psu, the range of primary production increased. Therefore, the diversion of an estimated 8,810 10^3 m^3 (7,142 acre-ft) of water into Rincon Bayou during the demonstration period lowered salinity concentrations, the osmotic stress on individual organisms lowered and almost certainly increased primary production in those waters.

Third, although the increase of N:P was not strongly correlated with inflow events, at least four sampling dates had values near or exceeding 15 which were likely the result of new nitrogen being added to the study area by river inflow. In general, the nutrient concentrations in the water column, especially dissolved inorganic nitrogen, were within the range to allow large amounts of primary production. Most (50 to 90%) of the DIN was in the form of ammonium, which is readily utilized by both water column and benthic phytoplankton. The shallow water environment enhanced nutrient remineralization, so both the ability to utilize and produce nutrients were relatively large. The N:P ratio indicated that nitrogen was typically the nutrient in lowest concentration.

Fourth, the species composition of phytoplankton apparently remained dominated by primarily small diatoms during most of the monitoring period. However, several observations of blooms of other phytoplankton were noted immediately after freshwater inflow events. These blooms were typically comprised of single celled blue-green algae (not the filamentous cyanobacteria of algal mats) normally present in fresh water or very low salinity environments. Although typically short-lived, (persisting no more than a few days), the presence of these blooms did not frequently occur in the study area prior to the demonstration project except under natural freshening events that occurred every several years. The more frequent presence of these blooms in the upper and central Rincon Bayou was an indication that the water column ecosystem was showing a more typical response to freshwater inflow.

Finally, the lack of regularly observed chlorophyll biomass accumulation was likely a result of the rapid flux of water through the monitoring area during inflow events. However, the occasional observation of high chlorophyll biomass during periods of moderate salinity concentrations of 30-60 psu showed that phytoplankton could remain in the monitoring area for a sufficient time period to accumulate biomass. This analysis is supported by the assimilation index, which is the rate of carbon growth per unit of chlorophyll. The assimilation index for sampling stations in Rincon Bayou was often in the range of 50-100 mg C/m2/day per unit of chlorophyll, which is a typical value for estuarine systems. There were also numerous assimilation values > 100 mg C/m2/day per unit of chlorophyll at several sampling stations. These values indicate that rapid primary production per unit of phytoplankton biomass was occurring, especially during 1999, which was a consistently wet year in terms of project diversions (Chapter 3).

In general, the temporal responses of the phytoplankton were too rapid to intensely observe nutrient accumulation, chlorophyll increases or primary production stimulation to specific inflow events. Therefore, the nutrient amendment bioassays were the primary data to demonstrate immediate phytoplankton responses to freshwater inflow events in the Rincon Bayou. Future monitoring of nutrient and water column primary production should employ automated sampling instrumentation that responds to inflow events with increased sampling frequency. The increased number of samples plus the temporal correlation with other recorded variables, such as salinity, would greatly improve the understanding the dynamics and importance of deltaic habitat for phytoplankton.

SUMMARY

Fresh water diverted by the demonstration project stimulated primary productivity in the water column and on the sediment surface by importing nutrients required for plant growth and lowering salinity concentrations. During the demonstration period, phytoplankton and microphytobenthos rapidly responded to the inputs of riverine nutrients with increased growth rates and accumulation of biomass. The increased primary production rates were especially prominent during periods when salinity was less than 60 psu. The assimilation index (*i.e.*, the relative amount of growth per cell) was also generally higher during periods of low salinity, indicating that inherent growth rates were also increased by project diversions.

CHAPTER FIVE

Benthic Communities

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> ***"The bottom of an estuary regulates or modifies most physical, chemical, geological, and biological processes throughout the entire estuarine ecosystem via what could be called a benthic effect."***
>
> ❖ Day *et al.* (1989)

INTRODUCTION

The three major habitats in estuarine marshes are the vegetated tidal marshes, the water column and the sediments. The sediments are both tidal (ranging between the tides) and subtidal (below the tidal elevation range). Benthos (bottom dwelling organisms) live in association with sediments. Benthic invertebrates live either in (infauna) or on (epifauna) the sediments. Estuarine benthic infauna are particularly susceptible to major changes in salinity regimes in the environment because of limited mobility (Kalke and Montagna 1991; Montagna and Kalke 1992; 1995; Mannino and Montagna 1997). Freshwater species, which tolerate salinity concentrations, ranging from 0 to 0.5 parts-per-thousand (ppt), are typically found where rivers meet marshes. Oligohaline species live in the upper reaches of estuaries where salinity ranges from 0.5 to 5 ppt. Brackish or estuarine species can accommodate large variations in salinity ranging from 5 to 25 ppt. Marine species generally can not accommodate salinity values lower than 25 to 30 ppt and are limited to the more saline portions of the estuary. Salinity is temporally dynamic at any given location, changing with floods and droughts. Thus, locations of salinity preference zones for various organizations change within an estuary throughout the year. The interaction between dynamic hydrography and salinity preference means the spatial and temporal dynamics of benthic infaunal populations are sensitive indicators of freshwater inflow effects (Montagna and Kalke 1992; 1995).

Abundance and biomass of infauna may increase if nutrient loading from river input is transformed into food for benthic animals (Montagna and Yoon 1991).

This occurs when nutrients introduced from a river stimulate primary production (Deegan *et al.* 1986; Nixon *et al.* 1986). The primary production can be deposited, but it may also be advected and deposited further downstream, potentially increasing benthic productivity away from the river inflow source. This assumes that fresh water and low salinity do not have a negative effect. Salinity stress on physiology (Finney 1979) and hypoxia (Ritter and Montagna 1999) could reduce benthic populations. The net effect of freshwater inflow on biological processes (*i.e.*, enhanced productivity, recruitment gains and losses via low-salinity intolerance) is therefore a function of the interaction between physical processes (*i.e.*, sedimentation, re-suspension, advection and seawater dilution) and chemical processes (*i.e.*, nutrient enrichment and cycling).

If freshwater inflow enhances benthic productivity, then increased abundance and biomass should be found if inflow were re-introduced into Rincon Bayou and the upper Nueces marsh. Benthic infauna are useful indicator species in studies of long-term effects, because they are relatively immobile and long-lived compared to plankton of similar size. The larger macrofauna (organisms greater than 0.5 millimeters (mm) in length) and smaller meiofauna (between 0.5 and 0.063 mm in length) have different ecological roles in marine ecosystems (Coull and Bell 1979; Coull and Palmer 1984). Therefore, macrofauna and meiofauna could respond to freshwater inflow at different spatial and temporal scales. Macrofauna, with planktonic larval dispersal, indicate effects over larger spatial scales and longer temporal scales. Meiofauna, with direct benthic development and generation times as short as one month, indicate effects over smaller spatial scales and shorter temporal scales. Even where meiofauna share ecological properties with macrofauna, the meiofaunal processes operate on much smaller spatial and temporal scales (Bell 1980).

OBJECTIVES

1) To assess the effect of the demonstration project on benthic infauna biomass, abundance and diversity;
2) To assess the response of different trophic levels by examining meiofauna and macrofauna; and
3) To assess the utilization of marsh habitats by infaunal species.

METHODS AND APPROACH

STUDY DESIGN

Increased opportunity for freshwater inflow into the study area was accomplished by lowering the Nueces River bank leading to Rincon Bayou (Nueces Overflow Channel) just east of where U.S. Highway 37 crosses the Nueces River (Chapter 1). A Before *vs.* After/ Control *vs.* Impact (BACI) experimental design (Green 1979) was used to determine effects of the demonstration project on benthos. Samples were taken both before and after the Nueces Overflow Channel was opened. During each sampling period, "control" and experimental impact sites were sampled (Figure 5-1). An experimental control did not really exist, because the system could not be sampled "with" and "without" an overflow channel at the same time. In addition, there is large natural variability in hydrographic and organismal responses in this ecosystem. Therefore, a reference site was chosen that reflected changes caused by natural variability but not the overflow channel. The site, which was largely unaffected by the demonstration project, was considered a reference site to the sites affected by the project. The BACI design allowed establishment of two kinds of reference points to distinguish variability caused by the project from natural variability.

A second component of the experimental design was to replicate at the treatment level to avoid "pseudo-replication." Pseudo-replication occurs when treatments are confounded with replicates (Hurlbert 1984). For example, if each site were represented by

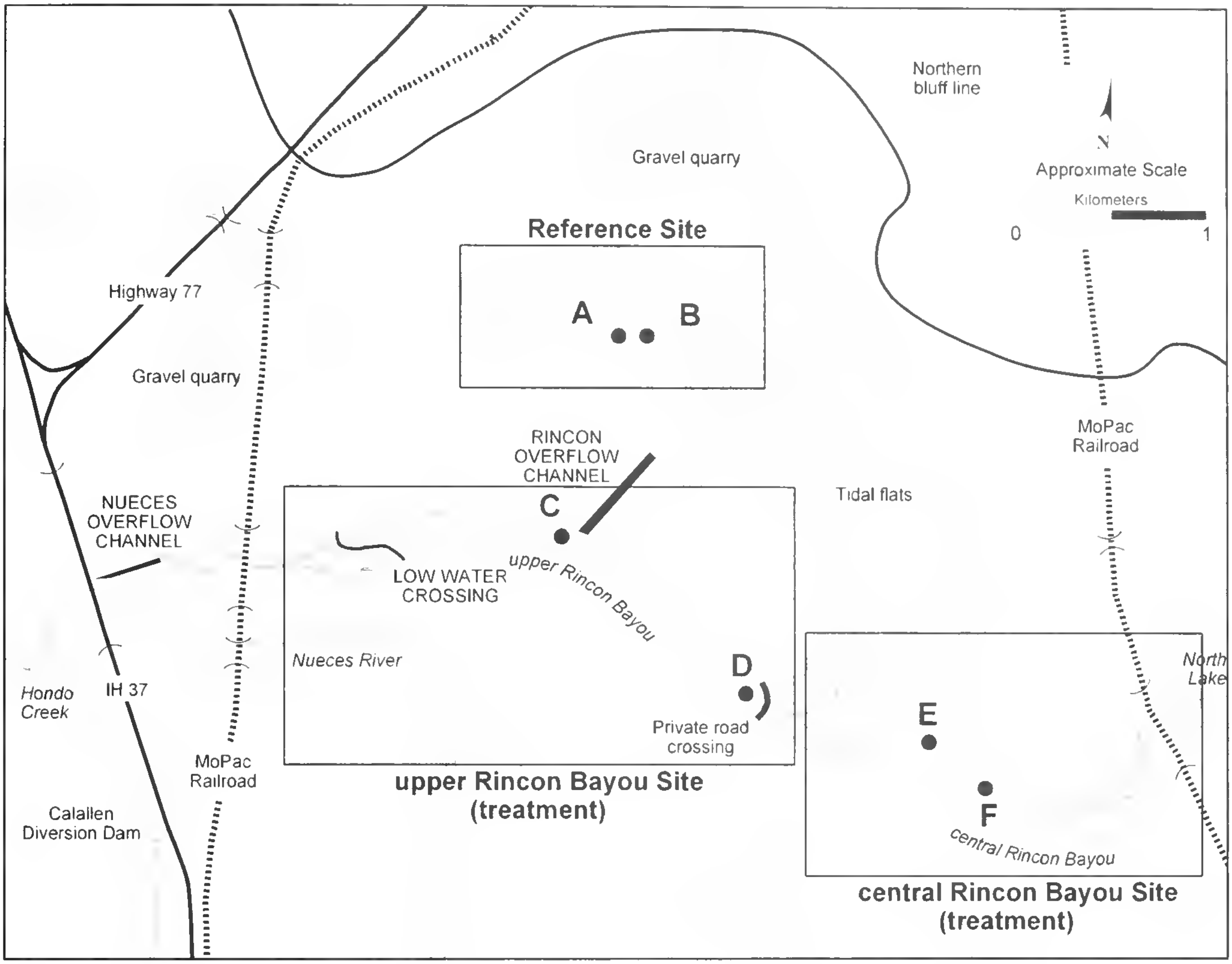


Figure 5-1: Locations of benthic sampling stations. The three sites included one reference site (Stations A and B) and two treatment sites, upper Rincon Bayou (Stations C and D) and central Rincon Bayou (Stations E and F).

only one station, then it could not logically be concluded that differences between stations were due to site differences, as the same magnitude of change could have occurred in two different stations within the same site. Therefore, two replicate stations were assigned to each site (or treatment level) within the project.

The reference site (Stations A and B) was located upstream from the overflow channels, reflecting natural variability but not effects from project diversion (Figure 5-1). Two experimental (treatment) sites were also established: 1) the upper Rincon Bayou site, which was nearest the overflow channel and was most influenced by the Nueces River, and 2) the central Rincon Bayou site, which was located farther downstream and was less influenced by the river, but more by the tide. Two stations were located in the upper Rincon Bayou site (Stations C and D), and two stations were located in the central Rincon Bayou site (Stations E and F).

The study was a two-way factorial design where the main sources of variation were temporal and spatial treatments. The response variables measured were benthic macrofaunal biomass, abundance and diversity and meiofaunal abundance and major taxa diversity. Three replicate samples were taken at each station during each sampling date.

Benthic samples were taken quarterly in January, April, July and October of each year. This sampling regimen was chosen to compliment the timing of previous and current benthic monitoring programs (Kalke and Montagna 1991; Montagna and Kalke 1992; 1995; Montagna *et al.* 1993; Martin and Montagna 1995; Mannino and Montagna 1997; Ritter and Montagna 1999). During the initial programs, samples were taken monthly (Kalke and Montagna 1991) or bimonthly (Montagna and Kalke 1992). It was discovered that there were roughly four seasonal events each year, including winter and summer lows, and fall and summer highs. Based on the cyclical nature of benthic recruitment, growth and population losses, it was determined that seasonal sampling was sufficient to identify annual trends in long-term sampling programs. Sampling began (October 28, 1994) one year before the Nueces Overflow Channel was excavated (October 29, 1995), and continued for five additional years (through October 28, 1999). Because the first sample of the second year was taken early (October 3, 1995), there were five pre-treatment samples and sixteen treatment samples.

MEASUREMENTS

Hydrography

The physical hydrographic conditions of the water column overlying sediments was measured at each station during each sampling period. Measurements were collected at the surface and near the bottom and recorded on the field log sheet. Conditions recorded during sampling included location, date, time, water depth and weather conditions. Water quality was measured with a multi-parameter instrument (Hydrolab Surveyor II). A sonde unit was also lowered to just beneath the surface and to the bottom. The instruments allowed collection of a variety of water quality parameters rapidly. The following parameters were read from the instrument's digital display unit (accuracy and units): temperature (± 0.15 degrees centigrade (°C)), pH (± 0.1 units), dissolved oxygen (± 0.2 milligrams per liter (mg/l)), specific conductivity (± 0.015 to 1.5 (millimhos per centimeter (mmho/cm), depending on range), redox potential (± 0.05 millivolts (mV)), depth (± 1 meter (m)) and salinity (reported in ppt, automatically corrected to 25 °C).

Benthos

Sediment was sampled by hand with core tubes to measure both meiofauna and macrofauna abundances. Macrofauna were sampled with a 6.7-cm diameter tube and sectioned at depth intervals of 0 to 3 cm and 3 to 10 cm; meiofauna were sampled with a 1.8-cm diameter tube and sectioned at depth intervals of 0 to 3 cm only. Samples were preserved with 5% buffered formalin. In the laboratory, meiofauna were sorted on 0.063 mm sieves, macrofauna on 0.5 mm sieves. Macrofauna were identified to the lowest taxonomic level possible (usually the species level), counted and weighed to the nearest 0.01 mg for biomass. Meiofauna were identified to higher taxonomic levels (usually phylum, class or order) and counted.

Biomass of macrofauna was measured by combining individuals into higher taxa categories (*i.e.*, Crustacea, Mollusca, Polychaeta and others). Samples were dried for 24 hours at 55 °C, and weighed. Mollusks were placed in 1 N HCl for 1 minute to 8 hours to dissolve carbonate shells and washed before drying.

All meiofauna and macrofauna data were digitized and proof-read. For macrofauna, species diversity was calculated by replicate and by pooling all replicate cores for each site. Diversity was calculated using Hill's diversity number one (N1) (Hill 1973). It indicates the number of abundant species in a sample and is a measure of the effective number of species (Ludwig and Reynolds 1988). The effective number of species is a measure of the degree to which proportional abundances are distributed among species (Hill 1973). It is calculated as the exponentiated form of the Shannon diversity index:

$$N1 = e^{H'}$$

As diversity decreases, N1 will tend toward 1. The Shannon index is the average uncertainty per species in an infinite community made up of species with known proportional abundances (Shannon and Weaver 1949; Hutcheson 1970). It is calculated by:

$$H' = \sum_{i=1}^{S} \left[\left(\frac{n_i}{n} \right) \ln \left(\frac{n_i}{n} \right) \right]$$

where n_i is the number of individuals belonging to the ith of S species in the sample, and n is the total number of individuals in the sample. Hill's N1 was used because it is units of numbers of species and is therefore easier to interpret than most other diversity indices.

All statistical analyses were performed using SAS software (SAS Institute Inc. 1991). All data (except when calculating diversity) were log-transformed prior to analysis. A two-way ANOVA was used to test for differences in meiofauna and macrofauna abundance, biomass and diversity among treatments and sampling dates. Where treatment effects were significant, Tukey multiple comparison procedures were used to find pairwise, *a posteriori* differences among sample means within a treatment. The Tukey test finds significant differences among sample means, while maintaining the experimentwise error rate (*i.e.*, the probability that one or more erroneous statements will be made in an experiment) at 0.05 (Kirk 1982). This method, therefore, ensured that study data were not (incorrectly) analyzed independently.

Community structure of macrofauna species was analyzed by multivariate methods. The species data were prepared for analysis by making a matrix where each row represented an observation of the average number of individuals in each station, or station-date combination, and each column represented a unique species. The data set was multivariate because there were more than one species, which were the response variables for the analysis. A common problem with such matrices is that many of the variables (*i.e.*, columns) covary. The covariance can be either positive (two or more species responding similarly to a stimuli) or negative (two or more species responding in opposite fashion to a stimuli). An example of a positive covariance is when all species increase in response to increased food. An example of a negative covariance is where one species competes with or preys upon another. Complex interactions among multiple response variables requires multivariate analysis to illuminate the common patterns in the data set.

Principal components analysis (PCA) is a multivariate method that is also a variable reduction technique. PCA is a useful tool because it transforms the species data matrix into new variables that can be: 1) mutually orthogonal (*i.e.*, the new variables are uncorrelated to one another) and 2) extracted in order of decreasing variance (*i.e.*, much of the information of the original set, like variance, of variables is concentrated in the first few principal components (PCS)). The PCS can also be used as predictors in regression analysis because they are orthogonal and collinearity (*i.e.*, a linear relationship between variables) does not exist. All multivariate analyses were performed with the SAS FACTOR procedure (SAS Institute Inc. 1991), using the PC method on the covariance matrix. When performing PCA on the covariance matrix, the analysis does not treat all the variables as if they have the same variance. All count or measurement data was log transformed prior to multivariate analysis.

Results of the PCA are visualized in bivariate plots. Generally, only the first two PC factors (PC1 and PC2) are used in the plots. The results are visualized in two ways: as factor patterns and as loading scores. Each data set is simply a matrix (*i.e.*, rows of observations versus columns of variables). The factor patterns are the PC coefficients for each variable or column. These vector patterns were used to interpret what PC1 and PC2 represent by plotting the column heading as the symbol for each point. Next, the loading scores for each observation were plotted using the site name as the symbol for each point. The plot of the loading scores allowed visualization of the relationships or correlation among the sampling units, stations in the present study.

RESULTS

SALINITY

The water column overlying sediments in the study area changed on varying temporal scales because of natural conditions (*e.g.*, wet and dry periods) as well as hydrographic events through the Nueces Overflow Channel (Figure 5-2). Salinity ranges during the demonstration period were extreme in Rincon Bayou, varying from freshwater conditions (< 0.5 ppt) to hyper-saline conditions (> 36 ppt). The highest recorded salinity was 160 ppt (Station C) during July 1996. Salinity trends appeared similar at different stations but were not always the same (Figure 5-3). For example, during summer 1995, Stations A and B had the lowest salinity values while Station E had the highest. During summer 1996, Stations C and D had the highest concentrations but, during summer 1998, Stations A and B had the highest. Floods during the summers 1997 (Events 16 and 17) and 1999 (Events 33 and 34) maintained salinity values much lower than during the other summers.

Figure 5-2: View of benthic Station C in upper Rincon Bayou under dry (above) and wet (below) conditions. The dry conditions were during the summer of 1996, and the flooding conditions during the summer of 1997 (Event 16).

Photo courtesy of the University of Texas Marine Science Institute.

In the analysis of the hydrographic effects of the demonstration project (Chapter 3), a total of 37 events were identified during the study period (Table 3-3). Measurements of freshwater flow into and out of Rincon Bayou, as well as direct precipitation, were compared with benthic salinity data. Because salinity at benthic stations was measured quarterly, daily rain and inflow data were summed by sampling date (Table 5-1). Although data from the Rincon gauge was not available prior to May 1, 1996, flow into Rincon Bayou prior to the opening of the Nueces Overflow Channel was zero (Chapter 3). During the period after the overflow channel was excavated but before the Rincon gauge was in place, there were some small exchange events (*e.g.*, Event 6, which resulted from locally heavy rainfall), but these were not considered to result in substantial inflow into Rincon Bayou (Chapter 3). Over the entire period, rainfall events occurred frequently, but there were only four sampling dates prior to which significantly large inflows of fresh water were recorded (Table 5-1), including July 1997 (Events 16), October of 1997 (Events 17 and 18), October 1998 (Events 21 through 25), and October 1999 (Events 35). Only four of the 37 events identified during the demonstration period (Events 16, 18, 25 and 36) were sufficiently large to result in delta inflow without the demonstration project and, of these, only one did so appreciably (Event 25) (Chapter 3).

Rainfall and freshwater inflow data were used to determine the cumulative effects of dilution on the average salinity at each site (Figure 5-4). Hypersaline conditions likely resulted from near zero flows and high evaporation rates, which typically occurred in summer. The differences between the two treatment sites indicate that "reverse estuary" conditions had existed in Rincon Bayou before freshwater diversions

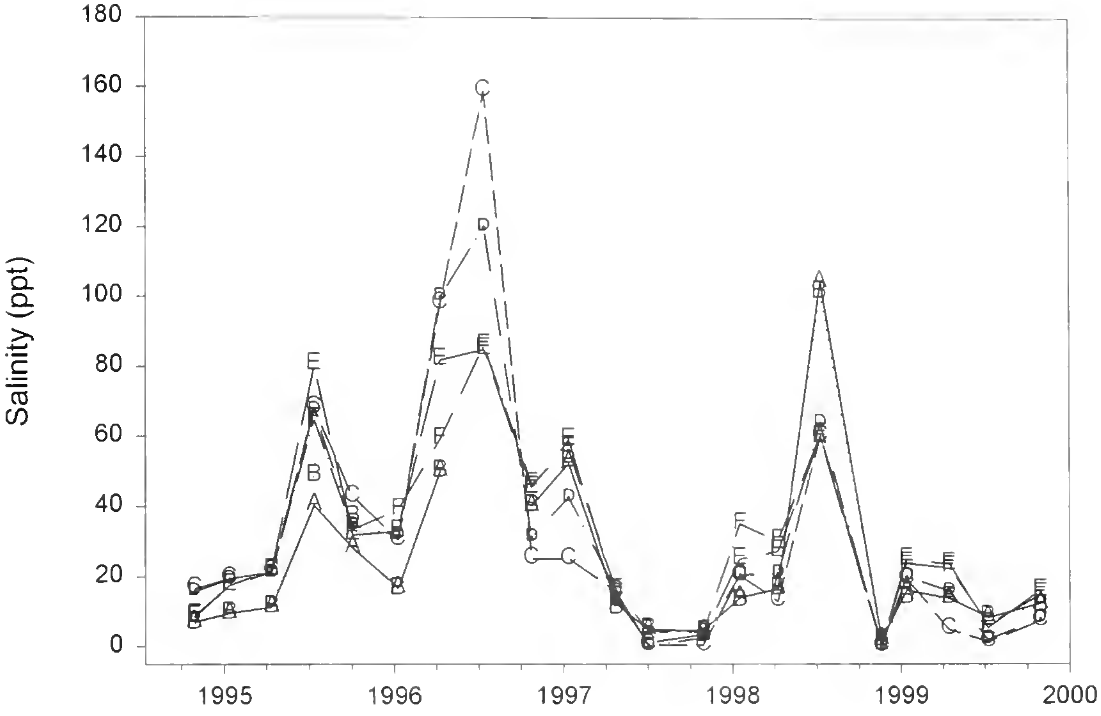


Figure 5-3: Salinity at all benthic stations (A through F) for each sampling date.

began (*i.e.*, higher salinity concentrations in the delta than in the bay). Early in the study period, the upper Rincon Bayou site often exhibited higher salinity values than did the central Rincon Bayou site, but later in the demonstration period, this relationship reversed (Figure 5-4). Also, a comparison between the reference site and the upper Rincon Bayou site indicate the influence of freshwater diversions on the later. Before diversions began (*i.e.*, October 1996), the reference site (which is subject to runoff from rainfall northwest of Highway 77) was predominantly fresher than either of the two treatment sites in Rincon Bayou. Beginning with the inflow occurrence of fall 1996 (Event 12 through 14), the upper Rincon Bayou reference site was predominantly fresher than the reference site (Figure 5-4).

TEMPERATURE

Temperature rose in summer to 33 to 40 °C and dropped in winter to about 12 °C following an expected seasonal pattern. Generally, Stations E and F had the highest temperatures, and Stations A and B had the lowest. Although absolute differences in water temperature among stations were quite small, the differences are likely due to differences in water depth because greater volumes of water change temperature more slowly. There was considerable variation in station differences between years. Overall, temperature differences among stations were not sufficient to cause differences in benthic responses.

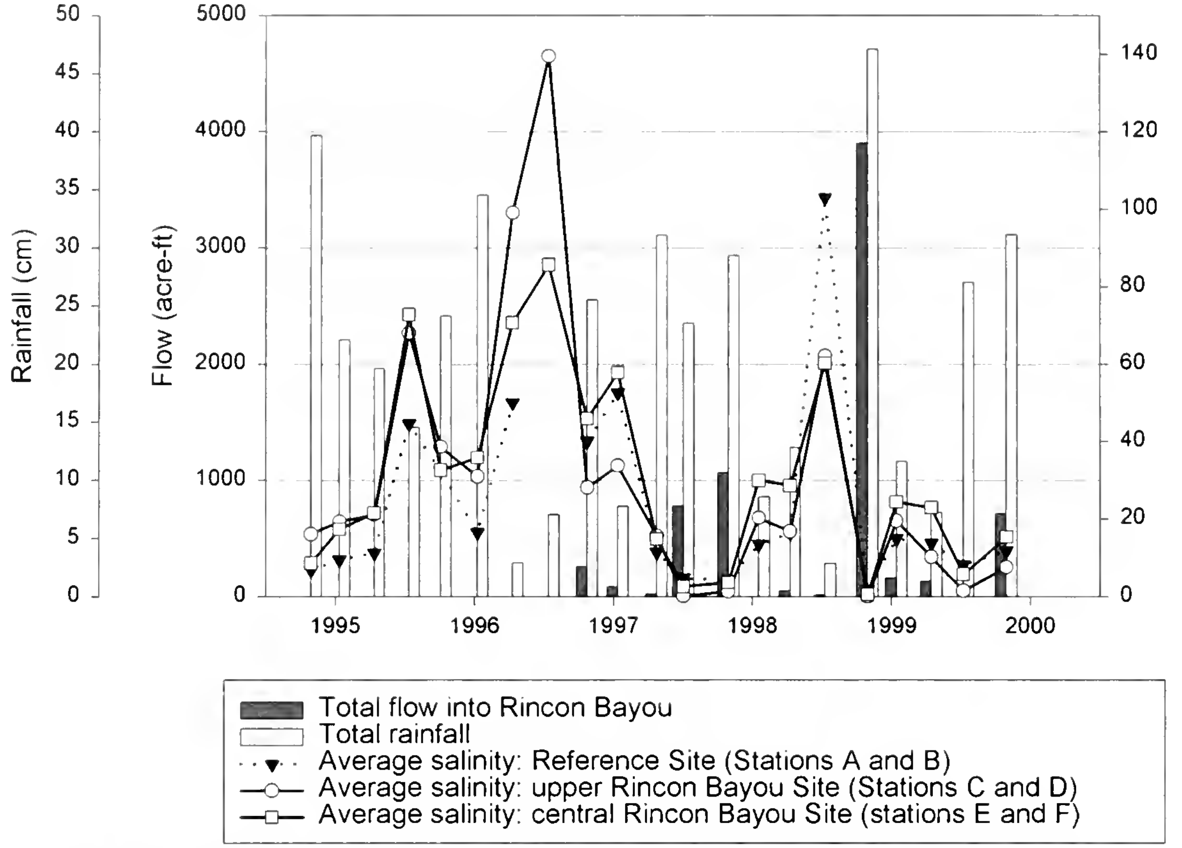


Figure 5-4: Marsh-wide average salinity at each sampling site for each sampling date. Cumulative daily rainfall and inflow into Rincon Bayou also plotted for each quarterly period between sampling dates.

DISSOLVED OXYGEN

Dissolved oxygen (DO) concentrations varied widely during the study period, from hypoxic (< 2 mg/l) to super-saturated (Figure 5-5). Stations A and B were most likely to be hypoxic. These stations have sea grasses, so decay of organic matter or night time respiration likely caused the hypoxia, which was mostly likely to occur in summer. The solubility of oxygen in sea water decreases with increasing temperature and salinity, both of which increased in summer.

BENTHOS

To indicate the importance of freshwater inflow, the average salinity at all stations (instead of at each site) was evaluated against many organismal response variables.

Macroinfauna

There was a strong significant interaction (P = 0.0001) between stations and dates for both log-transformed biomass and log-transformed abundance. Station C, the most directly affected by diversion from the Nueces Overflow Channel, had the highest biomass and abundance of macrofauna (Table 5-2). However, because of the significant interactions, differences among stations means could not be determined with a simple *post hoc* comparison, and examination of the interaction itself was necessary.

At various times, Stations E and F had the lowest biomass, or Stations A and B had the lowest (Figure 5-6a). Station C had the highest abundance of all stations during periods of peak biomass blooms. Station C was the station most directly influenced by inflow from the project. There was a strong seasonal

Table 5-1: Hydrographic events (from Table 3-3) occurring prior to each benthic sampling period. Average salinity concentrations reported for all benthic stations (A through F). Daily values for net flow and total precipitation were summed between sampling intervals. In some cases, sampling occurred during an event. The Nueces Overflow Channel was completed on October 26, 1995, so flow prior to that date was zero. Precipitation data for sampling dates prior to May 16, 1996 were that recorded at the Corpus Christi International Airport. Hyphens (-) indicate missing or incomplete data.

Benthic Sampling Date	Hydrographic Events (Table 3-3)	Total Net Flow Through Rincon Bayou (acre-ft)	Total Precipitation (inches)	Average Marsh-wide Salinity (ppt)
28-Oct-94		0	15.61	10.6
11-Jan-95	1	0	8.68	15.5
12-Apr-95		0	7.72	18.0
12-Jul-95	2, 3	0	5.72	61.7
3-Oct-95	4, 5	0	9.50	34.6
8-Jan-96	6, 7, 8, 9, 10	-	13.58	27.8
9-Apr-96		-	1.15	73.2
12-Jul-96		-	2.78	112.6
22-Oct-96	11, 12, 13	260	10.05	38.1
6-Jan-97	14	86	3.06	48.0
23-Apr-97	15	26	12.24	14.0
2-Jul-97	16	782	9.26	2.6
28-Oct-97	17, 18	1,065	11.54	3.1
16-Jan-98		-6	3.37	21.3
8-Apr-98	19	54	5.04	20.7
9-Jul-98	20	15	1.12	75.0
28-Oct-98	21, 22, 23, 24, 25	3,900	18.53	0.8
12-Jan-99	26, 27	161	4.58	19.6
14-Apr-99	28, 29	136	2.86	15.7
7-Jul-99	30, 31, 32, 33, 34	-90	10.64	5.2
28-Oct-99	35	709	12.25	11.6

Note: 1 acre-ft = 1.2336 10^3 m^3; 1 inch = 2.54 cm

Table 5-2: Average benthos characteristics at all stations during the demonstration period.

Station	Macrofauna			Meiofauna
	Biomass (g/m^2)	Abundance (n/m^2)	Diversity (N1 $0.18/m^2$)	Abundance ($n/10\ cm^2$)
A	1.82	24,900	2.1	433
B	2.31	21,200	2.2	369
C	3.23	43,700	1.5	1,240
D	2.10	35,700	1.5	1,060
E	2.42	24,500	1.9	1,540
F	1.83	20,300	1.7	1,730

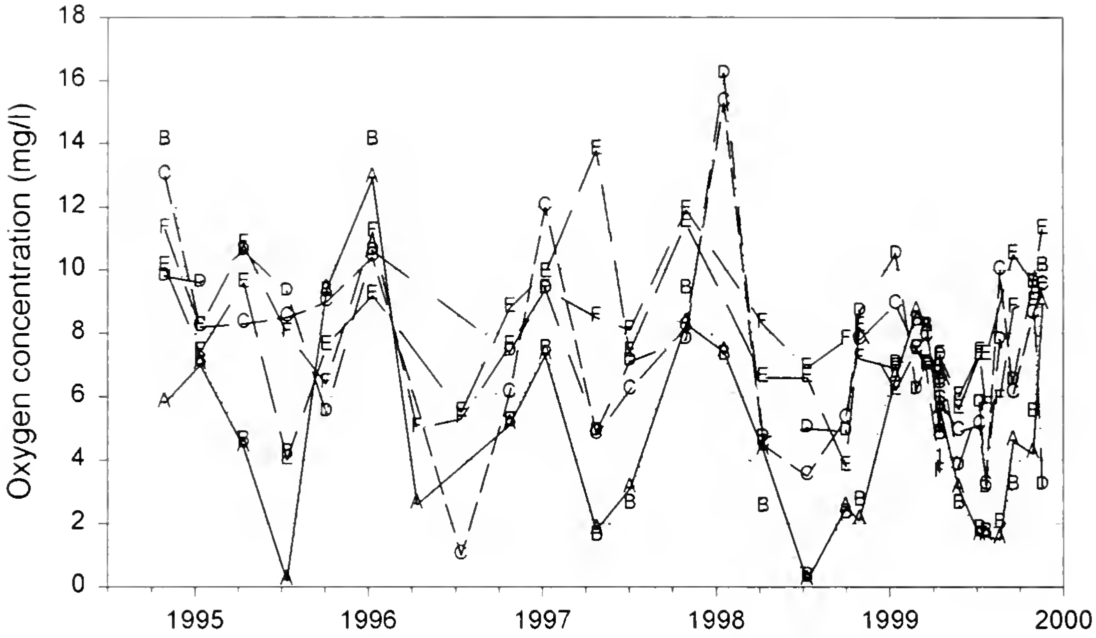


Figure 5-5: Dissolved oxygen at all benthic stations (A through F) for each sampling date.

trend, as the highest biomass occurred in spring (April), and lowest biomass in summer (July) or fall (October).

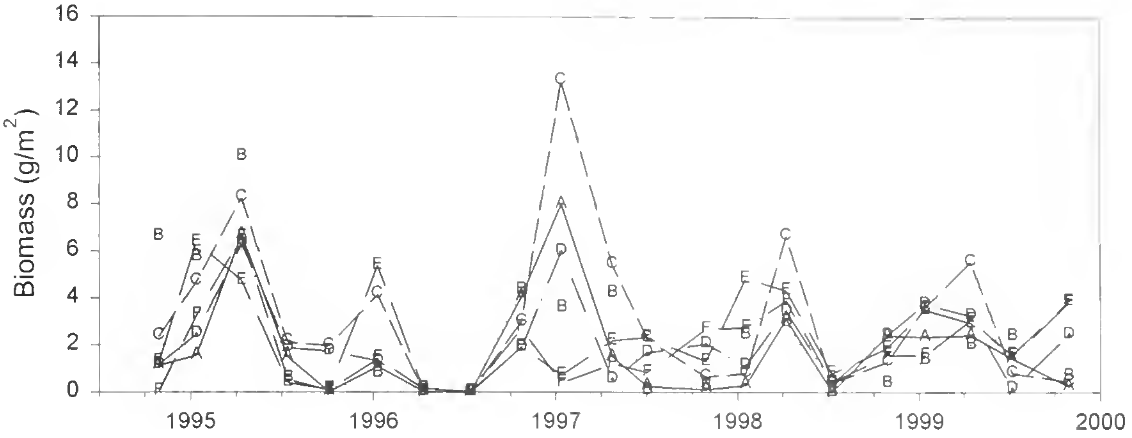
There was also a strong significant interaction (P = 0.0001) between stations and dates for log-transformed macrofauna abundance (Figure 5-6b). The nature of this interaction was much more complex than for biomass. No one station appeared to have the highest peaks, but Stations A and B (reference site) had almost always the lowest values. Again, low values had a tendency to occur in summer and higher abundances in fall or winter. This result indicated that Stations A and B, most removed from demonstration project effects, suffered from the consequences of evaporation and concomitant high salinity concentrations.

Macrofauna diversity was very low, ranging from zero to 11 species found at a station (Figure 5-6c). Because diversity was so low, all three replicates were pooled for species analyses leaving no replication. An interaction between stations and dates was evident. However, in 13 of 21 sampling periods, Stations A or B had the highest diversity. Diversity was highest when abundance was highest.

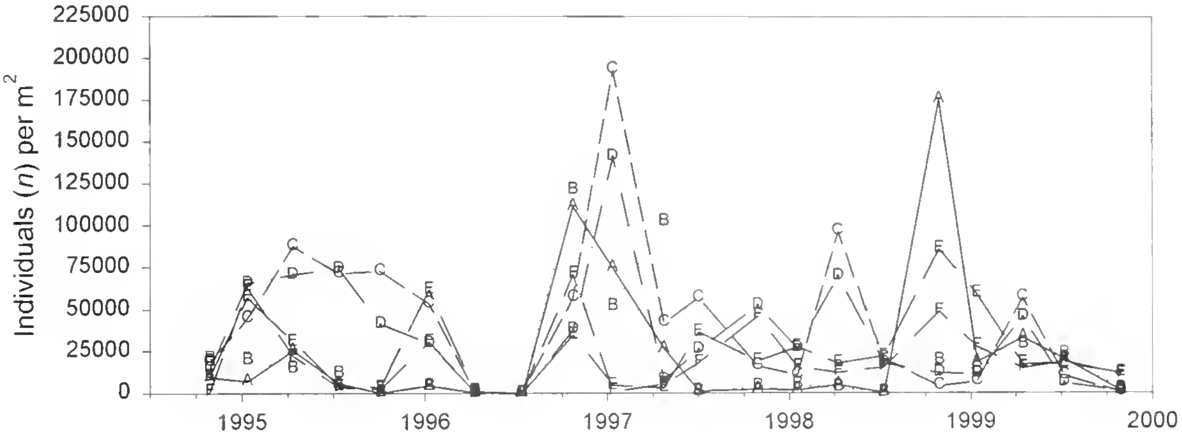
The seasonal and inter-annual trends were most evident when all samples at all stations were averaged together to form a marsh-wide average biomass (Figure 5-7a), or marsh-wide average abundance (Figure 5-7b). The marsh-wide averages were most useful because station differences were obscured by interaction effects with sampling dates. When the marsh- wide averages were compared to average salinity, the effect of inflow became apparent. When salinity values were high, biomass decreased, often to near zero. During periods following salinity declines due to inflow, biomass increased as evidenced in the summer through fall of 1997 and 1998. In contrast, salinity declines due to rainfall alone did not have the same effect. During April 1997, there was a large local rainfall event but little inflow (Table 5-1, Figure 5-4). Biomass continued to decline during spring and summer 1997. In contrast, when salinity declined due to an inflow event in fall 1997 (Event 18), biomass increased. There was a strong seasonal signal, with highest biomasses in January or April of each year, and lowest biomasses in July of each year. Another important trend was less variability in biomass fluctuations through time as the demonstration project progressed.

The marsh-wide average abundance trend (Figure 5-7b) was very similar to the biomass trend described

(a) Average macrofauna biomass (each station)



(b) Average macrofauna abundance (each station)



(c) Average macrofauna diversity (each station)

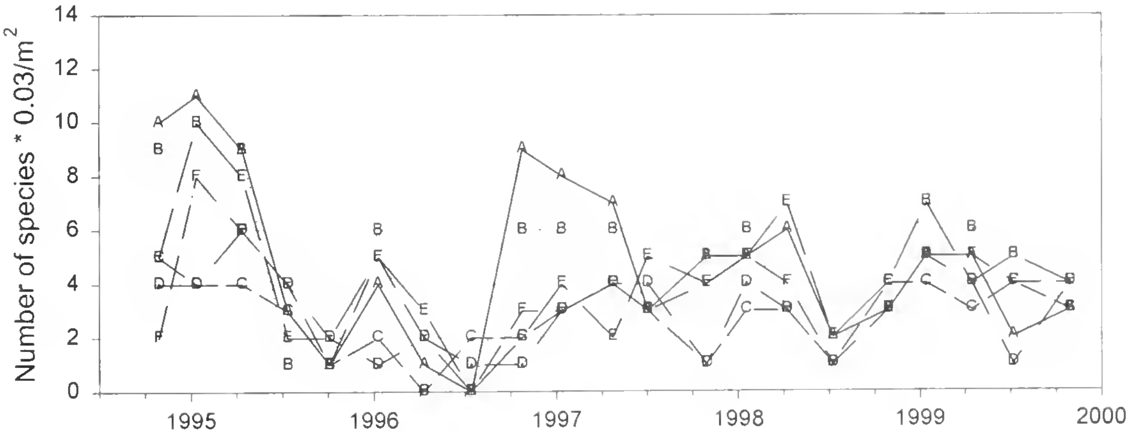
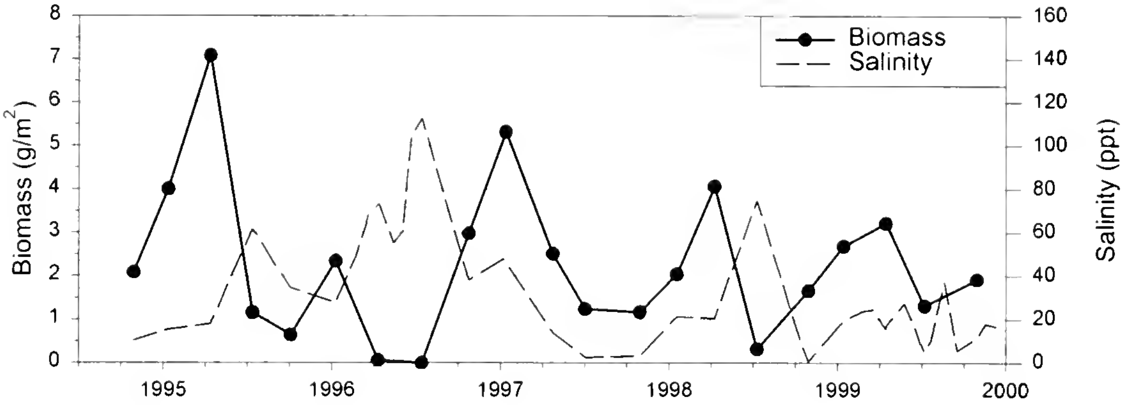
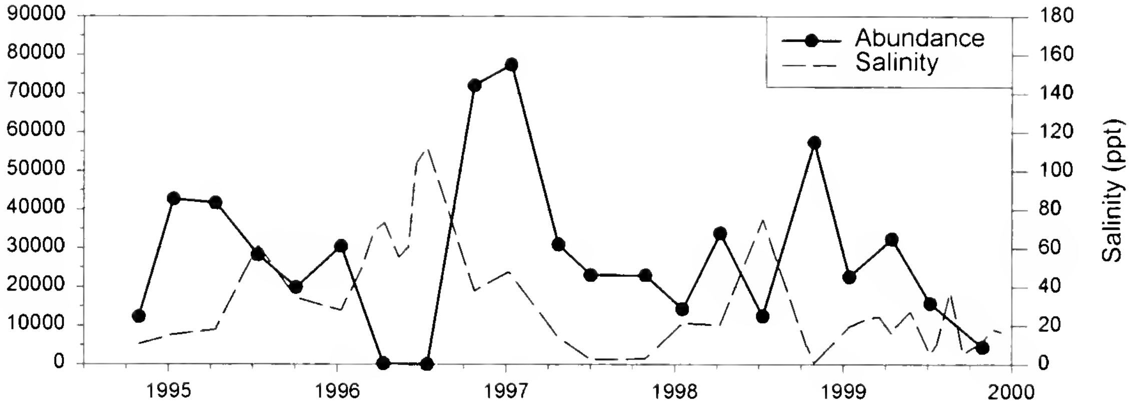


Figure 5-6: Average macrofauna biomass (a), abundance (b) and diversity at each station (A through F). Diversity values represent the mean of three samples at each station.

(a) Average macrofauna biomass (all stations)



(b) Average macrofauna abundance (all stations)



(c) Average macrofauna diversity (all stations)

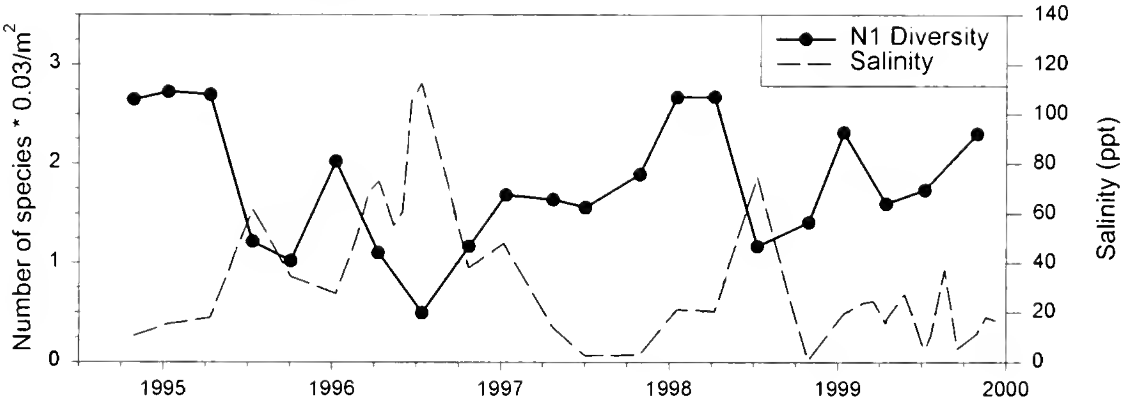


Figure 5-7: Marsh-wide averages of macrofauna biomass, abundance and diversity for all stations. Salinity values are averaged from all stations for each sampling period.

previously. Peak abundance occurred after inflow, lowest abundance during peak salinity concentrations. Blooms could result in very high abundances, greater than 40,000 individuals per m^2. This ecosystem was characterized by dominance of only a few species. The diversity index N1 was used to calculate the average number of dominant species among all stations at each sampling period, and then was compared to salinity (Figure 5-7c). Generally, no more than two dominant species were present at each sampling period. Diversity, measured as the number of dominant species, increased following periods of low salinity and decreased when salinity was high.

Macrofauna characteristics have a strong non-linear relationship with salinity, which appeared to be a bell-shaped curve skewed to the left with a long tail to the right (Figure 5-8).

A three parameter, log normal model:

$$Y=a*\exp(-0.5*(\ln(X/c)/b)^2)$$

was used to characterize the nonlinear relationship between biological characteristic (Y) and salinity (X). The three parameters characterize different attributes of the curves, where a is the maximum value, b is the skewness (or rate of change) of the response as a function of salinity, and c the location of the peak response value on the salinity axis. The models fit the data reasonably well, indicated by the coefficient of variation for each parameter ranging from 7% to 31% (Table 5-3). Using these parameters, abundance appeared to peak at a high salinity around 32.7 ppt, biomass at 18.7 ppt and diversity at 9.1 ppt. Lower skewness (b) parameters indicates more narrow ranges of responses values with respect to salinity. For the three characteristics, the salinity range of response (b) increased as the salinity peak value for the response increased (c) (Table 5-3).

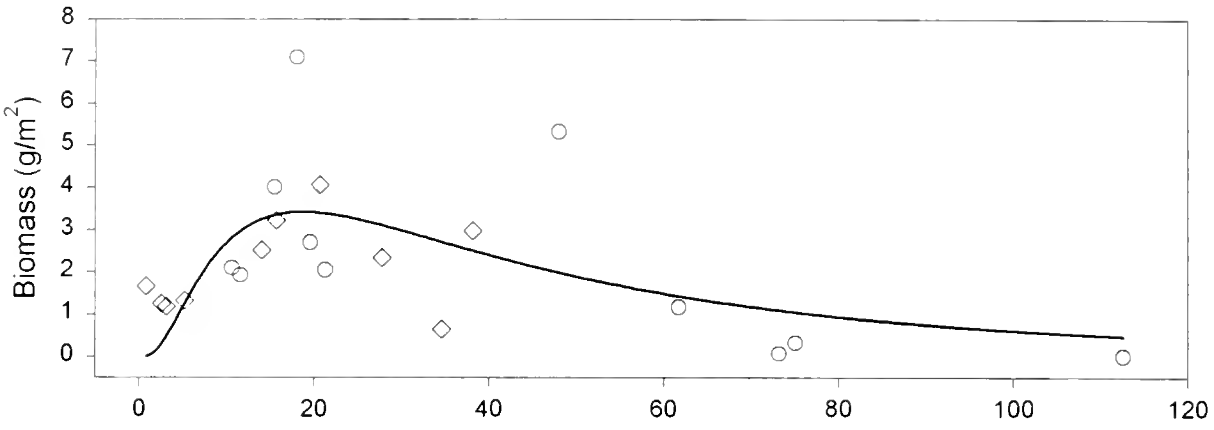
The direction of salinity change during a sampling period was important for diversity (Figure 5-8c), but not biomass (Figure 5-8a) or abundance (Figure 5-8b). The lowest values of all biological responses occurred at the highest salinity concentrations, and the highest concentrations always occurred during periods of rising salinity (note the circle symbols in Figure 5-8). Low diversity occurred when salinity values were decreasing (observations on graph with diamond symbols) and high diversity occurred when salinity values were rising within normal salinity ranges (*i.e.*, < 35 ppt).

In spite of the low average diversity on any given sampling date, a total of 37 species were found over the five year period of the study (Table 5-4). The polychaete, *Streblospio benedicti* (Figure 5-9) was an overwhelmingly dominant species at all stations and in the marsh overall (Table 5-5). In fact, *S. benedicti* represented 84% of all individuals found over the entire course of the study. Only four other species contributed as much of 2% of the community: the polychaete *Laeonereis culveri*, the snail *Assiminea succinea*, and unidentified species of ostracod, and unidentified chironomid larvae.

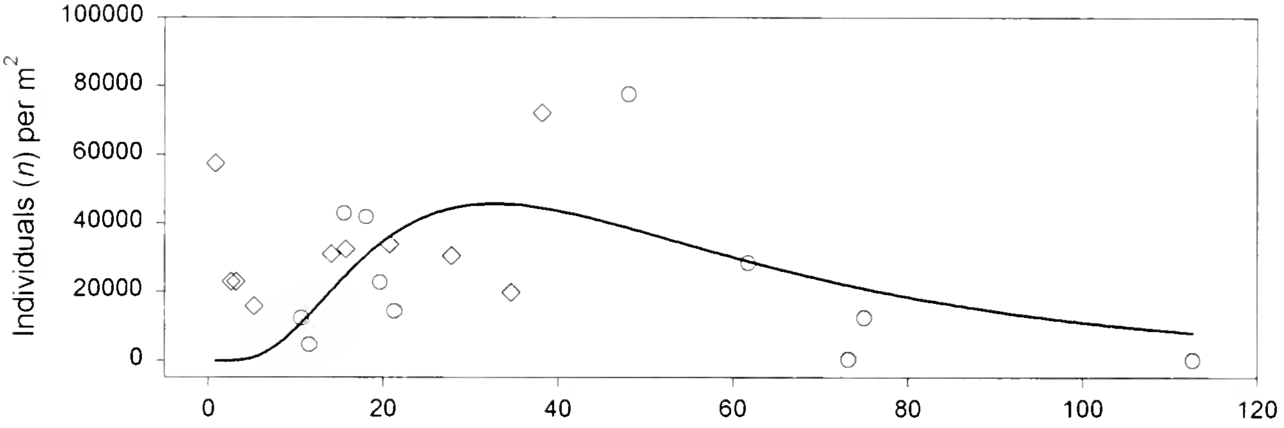
Table 5-3: Parameters from nonlinear regressions to predict macrofauna characteristics from salinity (Figure 5-8). Coefficient of variation for parameters in parentheses.

	Parameter		
Characteristic	*a*	*b*	*c*
Abundance	45,774 (25%)	0.6663 (31%)	32.7 (17%)
Biomass	3.426 (15%)	0.9048 (27%)	18.7 (24%)
N1 Diversity	2.361 (7%)	1.699 (13%)	9.08 (19%)

(a) Average macrofauna biomass (all stations)



(b) Average macrofauna abundance (all stations)



(c) Average macrofauna diversity

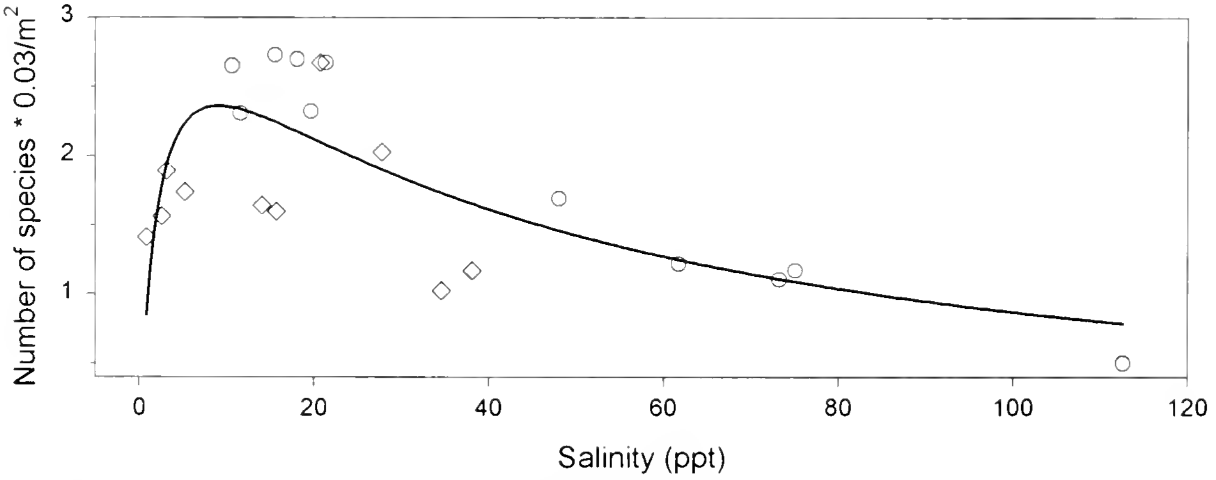


Figure 5-8: Relationship between average macrofauna characteristics and salinity. Circles (○) represent rising salinity, and diamonds (◇) represent falling salinity. Line is fit with a three parameter log normal regression model.

Table 5-4: List of species average abundances over the course of the study at each station.

Phylum	Class	Order	Family	Genus Species	A	B	C	D	E	F
Nemertinea				Nemertinea (unidentified)	5	0	18	5	14	18
Mollusca	Gastropoda	Ctenobranchia	Assimineidae	*Assiminea succinea*	2,103	2,845	0	0	27	5
		Pleurobranchia	Acteonidae	*Rictaxis punctostriatus*	18	9	0	0	5	27
	Pelecypoda	Hippuritoidea	Mactridae	*Mulinia lateralis*	171	108	5	5	32	27
			Tellinidae	*Macoma mitchelli*	0	0	0	0	9	0
Annelida	Polychaeta		Nereidae	*Laeonereis culveri*	675	896	1,913	1,175	2,157	1,702
			Spionidae	*Polydora ligni*	0	0	0	0	108	27
				Streblospio benedicti	19,152	15,064	40,961	32,91	19,256	16,870
			Capitellidae	*Capitella capitata*	5	0	23	0	356	54
				Mediomastus ambisela	9	9	0	0	792	500
	Oligochaeta			*Paranais grandis*	5	5	0	0	0	792
				Oligochaetes (unidentified)	9	5	0	63	5	95
Crustacea	Branchiopoda	Sidirdae		*Latonopsis occidentalis*	9	0	0	0	0	0
	Ostracoda			Ostracoda (unidentified)	252	392	423	1,004	2,040	45
	Copepoda	Harpacticoida		Diosaccidae sp. 132-MG	0	0	0	0	5	0
		Cyclopoida	Cyclopidae	*Hemicyclops* sp.	0	0	59	59	32	9
				Mesocyclops sp	0	0	0	9	5	5
	Malacostraca	Reptantia	Portunidae	*Callinectes sapidus*	5	0	0	0	0	0
		Mysidacea		*Mysidopsis* sp	0	0	5	5	0	0
				Mysidopsis almyra	0	5	0	0	5	0
		Amphipoda	Gammaridae	*Gammarus mucronatus*	0	0	0	0	5	0
			Corophiidae	*Corophium* sp.	0	81	0	0	0	0
				Corophium louisianum	50	32	0	0	0	5
Insecta	Pterygota	Diptera		Diptera (unidentified)	14	14	9	14	0	0
			Chironomidae	Chironomid pupae	9	14	0	0	0	0
				Chironomid larvae	2,134	995	302	410	59	149
				Pentneura sp. larvae	0	23	0	0	0	0
			Ceratogonidae	Ceratopogonid larvae	81	207	9	5	0	0
			Psychodidae	Psychodid larvae	0	5	0	0	0	0
			Tipulidae	Tipulid larvae	0	0	0	0	9	0
			Chaoboridae	*Chaoborus* sp. larvae	5	0	0	0	0	0
		Coleoptera	Hydrophilidae	*Berosus* sp.	99	342	5	5	0	0
				Hydrophilidae (unidentified)	9	45	0	0	0	0
			Helodidae	Helodidae larvae	5	0	0	0	0	0
		Hemiptera	Corixidae	*Tricho corixa*	32	36	0	5	5	0
		Odonata	Zygoptera	Damselfly nymphs	41	81	0	0	0	0
			Anisoptera	Dragonfly nymphs	0	5	0	0	0	0
TOTAL (all species)					**24,893**	**21,214**	**43,730**	**35,67**	**24,920**	**20,328**

Table 5-5: **Species overall dominance.** Percent of individuals in each sample.

Species Code	Taxa Name	Percent	Commutative %
81	*Streblospio benedicti*	84.4371	84.4371
491	*Laeonereis culveri*	4.9874	89.4245
381	*Assiminea succinea*	2.9154	92.3399
181	Ostracoda (unidentified)	2.4330	94.7729
487	Chironomid larvae	2.3698	97.1427
562	*Mediomastus ambiseta*	0.7671	97.9098
478	*Paranais grandis*	0.4692	98.3790
364	*Berosus* sp.	0.2636	98.6426
111	*Capitella capitata*	0.2557	98.8983
162	*Mulinia lateralis*	0.2030	99.1013
307	Ceratopogonid larvae	0.1766	99.2779
8	Oligochaetes (unidentified)	0.1028	99.3807
460	*Hemicyclops* sp.	0.0923	99.4730
71	*Polydora ligni*	0.0791	99.5521
734	Damselfly nymphs	0.0712	99.6233
201	*Corophium louisianum*	0.0501	99.6734
387	*Corophium* sp.	0.0474	99.7208
371	*Tricho corixa* sp.	0.0448	99.7656
7	Nemertinea (unidentified)	0.0343	99.7999
557	*Rictaxis punctostriatus*	0.0343	99.8342
595	Hydrophilidae (unidentified)	0.0316	99.8658
854	Diptera (unidentified)	0.0290	99.8948
494	Chironomid pupae	0.0132	99.9080
903	*Pentneura* sp. larvae	0.0132	99.9212
585	*Mesocyclops* sp.	0.0105	99.9317
488	*Macoma mitchelli*	0.0053	99.9370
802	*Latonopsis occidentalis*	0.0053	99.9423
428	*Mysidopsis* sp.	0.0053	99.9476
493	*Mysidopsis almyra*	0.0053	99.9529
345	Tipulid larvae	0.0053	99.9582
689	Diosaccidae sp. 132-MG	0.0026	99.9608
232	*Callinectes sapidus*	0.0026	99.9634
202	*Gammarus mucronatus*	0.0026	99.9660
312	Psychodid larvae	0.0026	99.9686
880	*Chaoborus* sp. larvae	0.0026	99.9712
906	Helodidae larvae	0.0026	99.9738
905	Dragonfly nymphs	0.0026	99.9764

The communities within the upper and central Rincon Bayou treatment sites were dominated by a few common species, evidenced by the stations clustering together on the first axis of the principal component analysis (PCA) (Figure 5-10). The PCA 1 axis, or first principal component (PC1), explained 70% of the variance in the data set, and PCA 2 axis (PC2) explained an additional 19% of the variance. The dominant organisms *Streblospio benedicti* (Sb), *Laeonereis culveri* (Lc), unidentified Ostracoda (Os) and Chironomid larvae (Ch) drove the trend for PC1 toward high positive values because they were part of the average dominant community (Figure 5-10a). Thus, all stations had high PC1 values (Figure 5-10b).

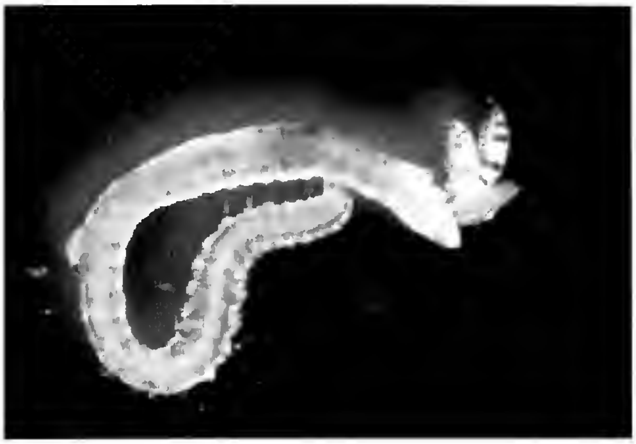


Figure 5-9: ***Steblospio benedicti.*** **This benthic organism is approximately 1 cm long.**

Photo courtesy of the University of Texas Marine Science Institute.

Other than the four dominant species, all other species were rare. The rare species were responsible for regional and station clustering along the PC2 axis. Presence of *Assiminea succinea* (As) at Stations A and B and of *Mediomastus ambiseta* (Ma) at Stations E and F were primarily responsible for separating stations. Stations A and B also had a higher incidence of insect larvae like Chironomid larvae (Ch) , *Berosus* sp. (Be), Ceratopogonid larvae (Ce) and Damselfly nymphs (Da). The three clusters (A and B, C and D, E and F) indicated the communities within the treatments were slightly distinct from one another. The stations within a treatment site (*i.e.*, upper and central Rincon Bayou) were more similar than the treatment sites themselves (Figure 5-10b). The community structure data presented in the PCA plots were the only macrofauna data that showed a strong treatment-site trend.

The six most dominant species (Table 5-5) were found continuously throughout the study, except when salinity concentrations were high (> 35 ppt) (Table 5-6). Rare species generally occurred during low salinity periods only. The only species to occur consistently during hyper-saline conditions was the insect, *Trico corixa* (SP 371), but it was also found when salinity values were brackish, so it was not considered an indicator species of freshwater inflow. Each drought period (*e.g.*, the summers of 1995, 1996 and 1998) appeared to be characterized by different species (Table 5-6).

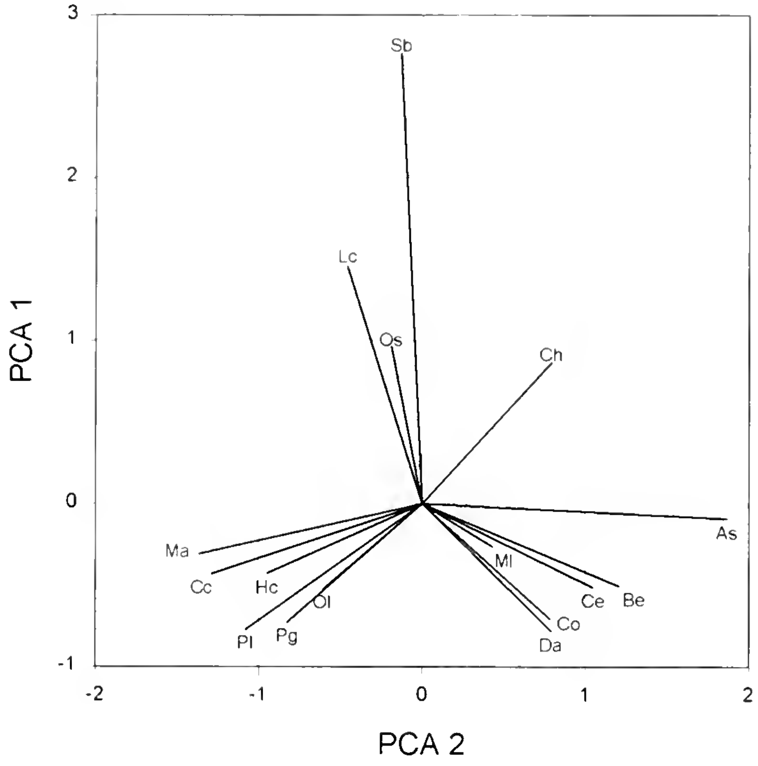
Meiofauna

The meiofauna community was composed of Nematoda, Copepoda (primarily Harpacticoida) and 16 other taxa. Nematodes comprised 71% of all organisms on average, and copepods comprised 9% (Table 5-7). Insect larvae comprised only 0.02% of the organisms found. The other metazoan taxa comprised only 4% of all other organisms found and included permanent meiofauna (Turbellaria, Gastrotricha, Tardigrada, Cnidaria, Rotifera and Kinorhyncha) and temporary meiofauna (Polychaeta, Oligochaeta, Gastropoda, Bivalvia, Ostracoda and Amphipoda). In addition, two groups of protozoans were found among the meiofauna, Ciliata and Foraminifera, which comprised about 15% of all meiofauna found.

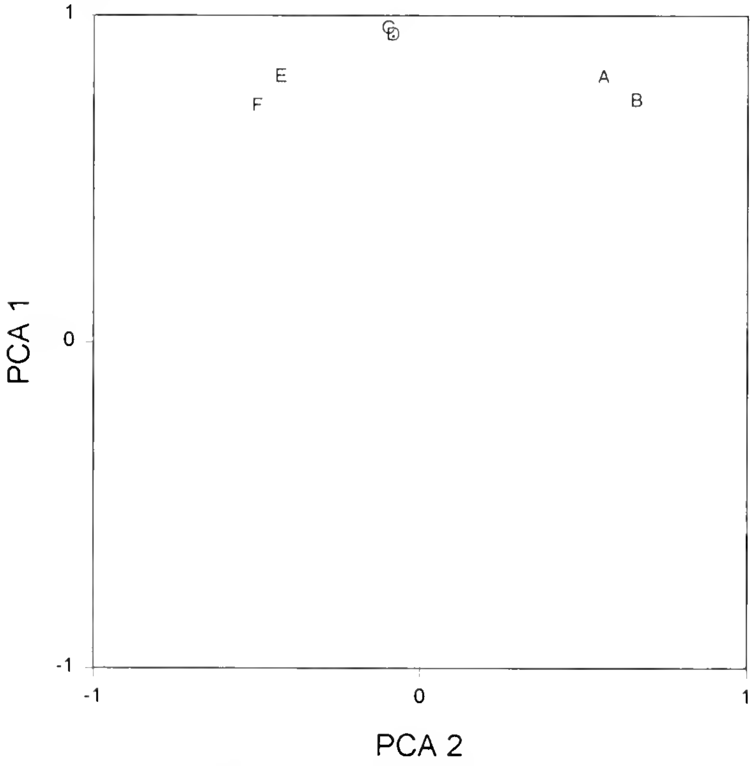
The average total number of meiofauna was 908,000 individuals per m^2 (Table 5-2). There was a significant interaction between stations and dates (P = 0.0001). In contrast to macrofauna, meiofauna abundance exhibited differences among treatments (Table 5-2, Figure 5-11a). Stations A and B always had the lowest abundances. In fact, the average abundance at Stations A and B was almost three times lower than the average at Stations C and D, and four times lower than the average at Stations E and F.

The average abundance of meiofauna among all stations at each sampling period changed with changing salinity conditions (Figure 5-11b). Abundances were lowest when salinity concentrations were highest, and recovered after periods of low salinity. In general, the pattern was similar to the pattern for macrofauna abundances. The lowest abundances were recorded during the dry periods of 1996. After significant freshwater inflow in 1997 (Events 16, 17 and 18), which lowered salinity, abundances recovered and reached the highest level in January 1998.

(a) Species loadings



(b) Station score

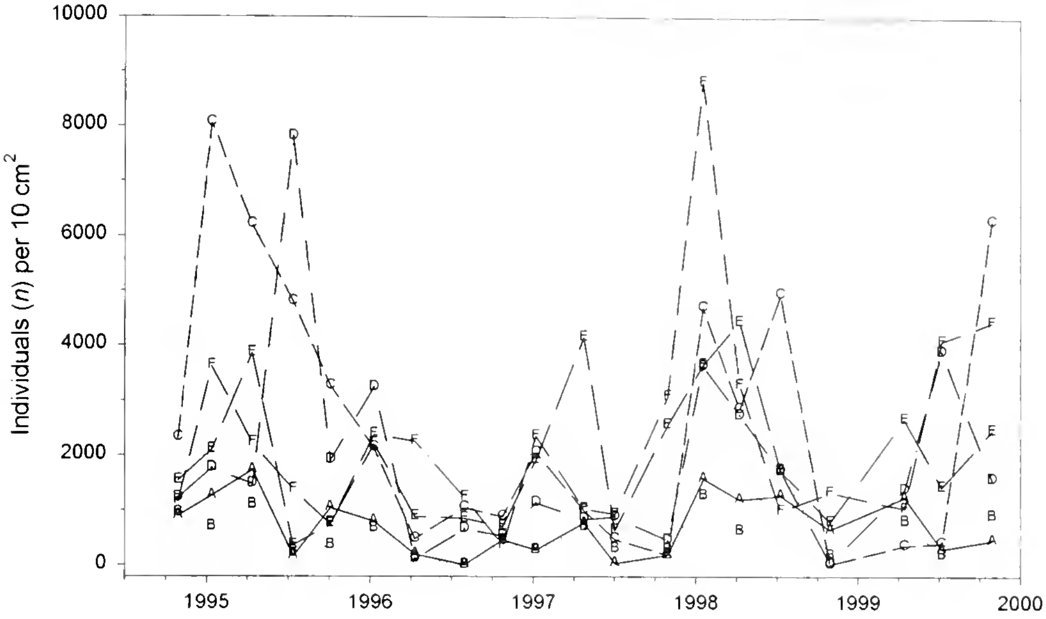


Abbreviation Key for species:

Sb = *Streblospio benedicti*
Lc = *Laeonereis culveri*
As = *Assiminea succinea*
Os = Ostracoda (unidentified)
Ch = Chironomid larvae
Ma = *Mediomastus ambiseta*
Pg = *Paranais grandis*
Be = *Berosus* sp.
Cc = *Capitella capitata*
Ml = *Mulinia lateralis*
Ce = Ceratopogonid larvae
Ol = Oligochaetes (unidentified)
Hc = *Hemicyclops* sp.
Pl = *Polydora ligni*
Da = Damselfly nymphs
Co = *Corophium*

Figure 5-10: Principal components analysis of 16 most common species, including species loadings (a) and station score plots (b).

(a) Average meiofauna abundance (each station)



(b) Average meiofauna abundance (all stations)

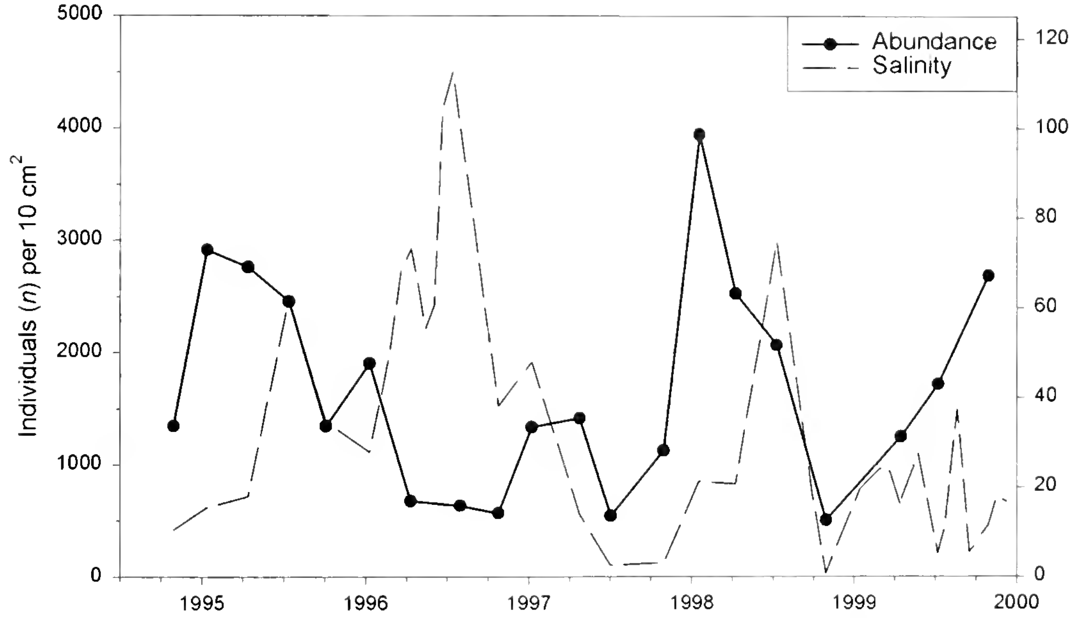


Figure 5-11: Average meiofauna abundance for each station (a) and marsh-wide (b). Salinity values are averaged from all stations for each sampling period.

Table 5-6: Temporal species abundance (*n* individuals found in all 6 stations, 18 samples) per sampling period. Multiply by 15.76 to get n m^2, Species code as in Table 5-5, period. Hyphen (-) indicates species was missing from sample.

Sp. Cd.	Salinity (ppt) and Date																				
	11	16	18	62	35	28	73	113	38	48	14	3	3	21	21	75	1	20	16	5	12
	Oct94	Jan95	Apr95	Jul95	Oct95	Jan96	Apr96	Jul96	Oct96	Jan97	Apr97	Jul97	Oct97	Jan98	Apr98	Jul98	Oct98	Jan99	Apr99	Jul99	Oct99
81	397	1568	1816	1537	1262	1721	1	-	4344	4546	1796	1357	1387	519	1774	791	3589	1142	1815	601	69
491	13	338	307	10	-	60	3	-	5	162	37	58	11	255	180	-	16	60	103	73	201
381	153	180	163	180	4	13	-	-	163	167	44	16	1	1	3	-	-	6	11	1	-
181	96	310	295	72	1	41	11	-	7	5	7	1	24	5	12	-	-	26	1	9	-
487	21	4	20	-	-	54	-	-	1	-	52	8	18	27	41	-	37	196	133	283	4
562	8	46	8	1	-	25	-	-	1	-	1	1	6	70	76	1	-	4	7	24	7
478	-	178	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
364	34	29	10	-	-	-	-	2	5	2	-	1	10	5	2	-	-	-	-	-	-
111	2	3	1	-	-	2	-	-	-	-	4	22	-	8	53	-	-	-	1	1	-
162	-	2	1	-	-	2	-	-	50	18	1	-	-	-	-	-	-	-	3	-	-
307	3	41	11	-	-	-	-	1	2	-	2	-	-	1	-	1	5	-	-	-	-
8	1	-	-	-	-	20	-	-	1	-	-	-	-	-	14	-	2	-	1	-	-
460	22	8	2	2	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
71	-	-	-	-	-	-	-	-	-	9	19	-	-	-	-	-	-	-	-	-	2
734	25	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	1	-	-	-
201	-	3	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
387	-	-	-	-	-	-	-	-	-	-	-	-	-	18	-	-	-	-	-	-	-
371	-	2	1	1	-	-	2	-	1	1	5	-	1	2	1	-	-	-	-	-	-
7	-	1	-	-	-	-	-	-	-	1	-	-	-	-	-	-	1	4	1	5	-
557	-	-	-	-	-	-	-	-	-	13	-	-	-	-	-	-	-	-	-	-	-
595	-	-	-	-	-	-	-	-	-	-	-	-	9	3	-	-	-	-	-	-	-
854	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	5	1	1	2
494	-	2	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
903	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
585	-	-	-	-	-	-	-	-	-	-	-	4	-	-	-	-	-	-	-	-	-
802	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
488	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
345	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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905	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
906	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
202	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
232	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
312	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
689	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-

Table 5-7: Composition of the meiofauna community.

Taxa	Percent
Nematoda	71.10
Copepoda	9.39
Other metazoa	4.17
Insects	0.02
Protozoa	15.32

DISCUSSION

MACROFAUNA AND MEIOFAUNA

The upper Nueces Delta is an unusual marsh, with extreme environmental variability. The variability is evidenced by wide ranges in salinity (from 0 to 160 ppt), high temperatures (12 to 40 °C) and a tendency toward reverse salinity gradients, with higher salinity concentrations in the upper marsh area. These environmental extremes drive the response patterns of benthic resources. Macrofauna diversity in Rincon Bayou was generally lower than found in either Nueces Bay or Corpus Christi Bay. The average number of dominant species (diversity index N1) per station was only 1.8 in Rincon Bayou, while, in contrast, the average N1 value was 3.5 in Nueces Bay stations (Mannino and Montagna 1997) and 7.0 in Corpus Christi Bay (Ritter and Montagna 1999). For comparison, hypoxic stations in Corpus Christi Bay averaged an N1 value of 1.5 (Ritter and Montagna 1999). The low diversity in Rincon Bayou reflects a relatively greater degree of stress on benthos caused by the higher environmental variability, particularly in salinity extremes.

Macrofaunal abundance and biomass, which are indicators of productivity, were in a range typically found in Nueces and Corpus Christi bays. This observation indicates that environmental variability affected benthic community structure but was not likely to affect secondary productivity. However, marsh habitats typically have greater productivity than open bay habitats (Day *et al.* 1989), so it was not known if production in the Nueces marsh was optimal or suboptimal.

Overall, there is strong evidence that the demonstration project increased productivity and ameliorated stresses on biodiversity. These positive effects were caused by increased opportunities for freshwater inflow into the marsh and responses of the benthos to this inflow. Seasonal increases of biomass occurred in spring, when salinity values were lowest and water

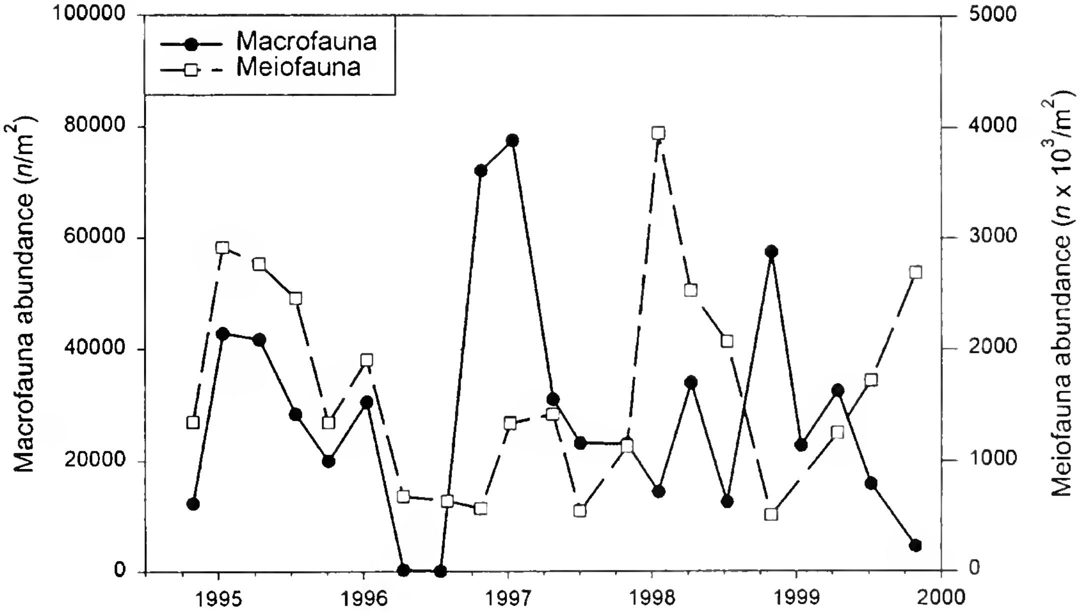


Figure 5-12: Marsh-wide average abundance of meiofauna and macrofauna.

levels were highest. In contrast, during summer when salinity values were highest and water levels were lowest, biomass was always lowest (Figure 5-7). Inflow events triggered bursts of productivity as indicated by increased abundance and biomass following periods of lower salinity concentrations. Biodiversity increases just after inflow events and as salinity was rising again indicated more species were utilizing the marsh habitat as a result of increased inflow events, although different species appeared after each inflow event (Table 5-6). The responses to inflow were found by following changes after inflow events that filled Rincon Bayou with fresh water.

Interestingly, prior to overflow channel construction, brackish conditions in April 1995 resulted in decreased diversity. In contrast, after the Nueces Overflow Channel was excavated, brackish conditions in April (1997 to 1999) resulted in increased diversity (Table 5-6). The responses of increased abundance to inflow by macrofauna and meiofauna were similar (Figure 5-12), indicating that both trophic levels of benthos were responding to inflow events through the overflow channel.

The mechanisms of infaunal response to inflow were likely trophic as well as physiological. The physiological responses were controlled by increased survivability and tolerance to specific salinity ranges caused by inflow events. Trophic responses were indirect and related to responses by potential food items. When primary producers responded to inflow by increased biomass, then increased food levels led to increased secondary production. Therefore, the trophic link between primary producers and secondary consumers was demonstrated by correlated, or lagged, abundance patterns.

Standing stocks of macrofauna and chlorophyll were somewhat concordant. Peaks of macrofauna biomass followed periods of increasing chlorophyll (Figure 5-13a). The only exception was in summer 1997, when meiofauna abundance was more concordant with chlorophyll biomass (Figure 5-13b). Peaks of meiofauna abundance followed periods with high concentrations of chlorophyll in the overlying water. Meiofauna are known to be grazers and to favorably respond to the presence of chlorophyll (Montagna 1995; Montagna *et al.* 1995). In San Antonio Bay, meiofauna respond to freshwater inflow and increased chlorophyll with increased grazing rates (Montagna and Yoon 1991).

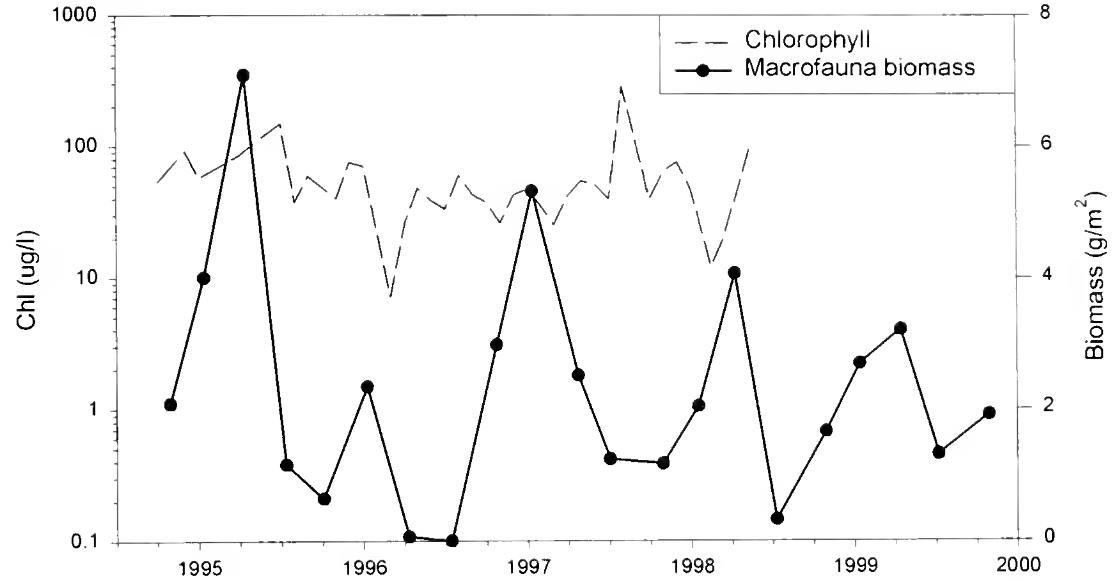
TROPHIC LINKS

There was evidence (Riera *et al.* 2000) that the demonstration project also restored the function of the Nueces marsh as a nursery habitat for development of juvenile brown shrimp, *Penaeus aztecus.* Brown shrimp spawn offshore in the Gulf of Mexico. Post-larvae are carried by on-shore water movement and enter bays, ultimately finding productive shallow estuarine waters protected from storms and predators (Day *et al.* 1989). Most of the larval brown shrimp enter marine bays from late winter through early spring, spend about three to four months in estuarine nursery grounds and return to the offshore Gulf of Mexico in early summer (Moffett 1970).

As a sub-component to this benthic analysis, the trophic dynamic links and migratory behavior of juvenile brown shrimp were investigated from Aransas Pass to Corpus Christi Bay to Nueces Bay and to the Nueces Delta (Riera *et al.* 2000). Stable isotopes ratios of carbon and nitrogen ($\delta^{13}C$ and $\delta^{15}N$) of shrimps and their potential food sources were measured between December 1995 and July 1996. Stable isotopes of carbon and nitrogen change as a function of the food an organism eats (DeNiro and Epstein 1978; Fry and Parker 1979). Because food sources change in different habitats, stable isotopes can also be used to assess migration of shrimp (Fry 1981).

During the study, shrimp lengths increased from 10 to 11 mm when the animals entered Corpus Christi Bay as larvae, to 80 to 90 mm when they returned to the Gulf of Mexico as subadults. Brown shrimp exhibited spatial and temporal $\delta^{13}C$ variation (from -25.2 to 12.5‰), indicating a high diversity of food sources throughout their migration. From examination of the $\delta^{13}C$ values, it appears the main food sources used by juvenile brown shrimp in Rincon Bayou were *Spartina alterniflora*, *Spartina spartinae*, detritus and benthic

(a) Average macrofauna biomass (all stations)



(b) Average meiofauna abundance (all stations)

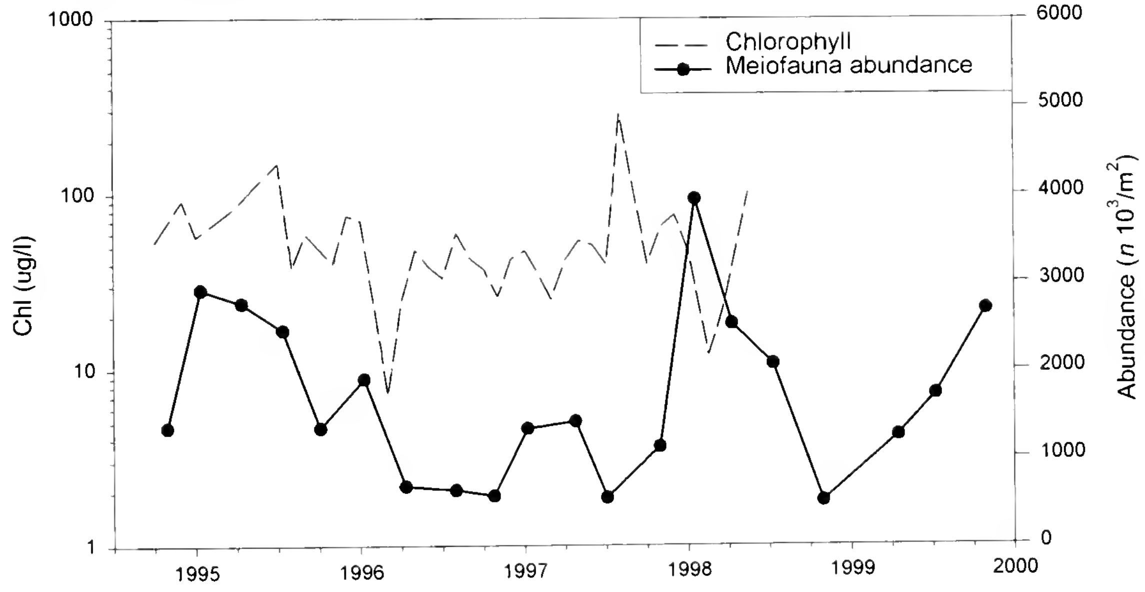


Figure 5-13: Comparison of marsh-wide average chlorophyll biomass with macrofauna biomass (a) and meiofauna abundance (b).

diatoms (Riera *et al.* 2000). From $\delta^{13}C$ and $\delta^{15}N$ values, it appears organic matter inputs carried by river inflow could also contribute significantly to the feeding of migratory brown shrimp. In the marsh habitats of Rincon Bayou and the Nueces Delta, shrimp isotopic ratios changed rapidly, indicating high tissue turnover rates and rapid growth. Therefore, re-introduction of fresh water to the marsh results in conditions within nursery areas (*e.g.*, higher benthic biomass) favorable for feeding and growth of juvenile brown shrimp. Further discussion of the approach and results of the stable isotope analyses conducted by Riera *et al.* (2000) has been included as Appendix E of this Concluding Report.

EFFECTS OF DIVERSIONS AS DISTURBANCES

Rapid changes in salinity due to flooding events can be classified as a disturbance. The frequency and timing of these freshwater inflow events into Rincon Bayou were very important. The effects of disturbance frequency and altered flow on macro-benthic community structure and colonization in Rincon Bayou were also independently studied during the demonstration period (Ritter and Montagna 2000). Abundance and biomass decreased with increasing disturbance frequency, indicating post-disturbance community persistence is important in regulating community structure. There was higher abundance and biomass in defaunated sediments relative to background sediments, indicating disturbance plays an important role in community production of early succession communities. The collection date was the most important factor determining community structure, thus natural variability overwhelmed effects of both the flow and disturbance frequency manipulations. The temporal changes were driven by a *Streblospio benedicti* recruitment event (resulting in abundances as high as 1.3 10^6 m^2) captured June 20, 1997 (one day before the beginning of Event 16) and during the subsequent freshwater event. After the event, *S. benedicti* abundance declined rapidly, and freshwater species invaded, leading to the progression of three distinct community states (*i.e.*, community structure and species dominance changed three times) over the 14-week period of the study. The overwhelming significance of "temporality" (*i.e.*, short-term temporal change in community structure) was the unexplained temporal component of community variation in experimental manipulations. Temporality is simply a smaller temporal scale than seasonality. The importance of short term changes relative to flood events indicated that the demonstration project was responsible for high productivity during the summers of 1997 through 1999. Further discussion of the approach and results of the stable isotope analyses conducted by Ritter and Montagna (2000) has been included as Appendix F of this Concluding Report.

SUMMARY

Benthos in Rincon Bayou are normally under great stress due to high salinity concentrations, especially during summer. The benthos responded positively to inflow events by increased biomass, abundances and diversity. Direct and indirect mechanisms were responsible for the benthic response. The direct mechanism included increased physiological tolerance to oligohaline and estuarine salinity concentrations relative to hyper-saline conditions. Inflow events at various times during the year, but especially in the spring and fall, were likely cues for benthic reproduction and settlement of planktonic larvae. Trophic interactions and habitat utilization represented indirect mechanisms to which benthos responded. Increased microalgal food and marsh habitat availability stimulated secondary production. As the frequency and magnitude of freshwater inflow events increased due to the demonstration project, the opportunity for positive responses also increased. Without the demonstration project features, Rincon Bayou would experience considerably less inflow, and revert to a reverse estuary with consequentially less biodiversity and productivity.

CHAPTER SIX

Vegetation Communities

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> ***"Ye marshes, how candid and simple and***
> ***nothing withholding and free***
> ***Ye publish yourselves to the sky and offer***
> ***yourselves to the sea!***
> ***Tolerant plains, that suffer the sea and the***
> ***rains and the sun. . ."***
>
> ❖ Sidney Lanier (1878)

INTRODUCTION

A primary factor affecting the growth and distribution of coastal halophytes (salt-tolerant plants) is soil salinity (Chapman 1974; Ungar 1974; Riehl and Ungar 1982; Clewell 1997). Halophytes are able to tolerate relatively high concentration of sodium (Na^+) and chlorine (Cl^-) because of physiological mechanisms allowing them to exclude, compartmentalize or extrude salts (Badger and Ungar 1990). Several halophytes, including *Salicornia* sp. and *Suaeda* sp., even exhibit stimulated growth at some salinity levels (Ungar 1991). However, there is for each species a salinity concentration at which the effectiveness of these mechanisms is compromised, and growth and reproduction are limited (Adam 1990).

High soil salinity negatively impacts the reproductive ability of halophytes by decreasing seed viability. Hypersalinity can result in a reduction in the number of seeds germinating, a delay in the initiation of germination and an increase in the number of seeds remaining dormant (Ungar 1962; Chapman 1974; Philipupillai and Ungar 1984; Ungar 1995). Each of these consequences ultimately leads to decreases in plant cover and increases in bare soils, which can persist indefinitely until freshwater inundation (via either precipitation or flooding) occurs diluting the soils, alleviating the salinity stress and breaking the osmotically induced seed dormancy (Ungar 1962; Ungar 1978; Ungar 1995). Once germination takes place, successful seedling growth is also salinity mediated. The period of seedling development is probably the most sensitive time during the life cycle of a halophyte because the seedlings develop close to the soil surface, exposing them to salinity levels 2 to 100 times that of the subsoil (Ungar 1978).

While adult plants have been reported to tolerate salinity levels 10 to 100 times greater than seedlings (Mayer and Poljakoff-Mayber 1963), high soil salinity levels can negatively affect adult plant growth as well. Plant survival does not necessarily mean plant growth, as a plant may continue to survive at a particular salinity level without increasing in size or actively reproducing. Several primary mechanisms have been suggested to explain the negative effects of hypersalinity on halophytes. These include ion toxicity of internal cells, interference with the uptake of essential nutrient ions, lowered external water potential and energy constraints (*e.g.*, a large amount of energy is required to actively salt ions) (Greenway and Munns 1983; Yeo 1983).

Most halophytes can survive over a range of salinity concentrations, but no species has been reported to have maximal growth rates at salinity levels at or above seawater concentration (35 parts-per-thousand (ppt)) (Ungar 1991). For example, *Spartina foliosa*, a California salt marsh plant, was found to have 50% less dry mass production in sea water than in fresh water, with only 39% of the plants surviving in the saltwater treatment (Phleger 1971). Barbour (1970) reported growth reductions in *Salicornia virginica* and *Distichlis spicata* at salinity values ranging from 5 to 22 ppt. Adams (1963) noted that in North Carolina salt marsh plants could not tolerate soil salinity levels over 70 ppt. Allison (1992) found a reduction in species number in a California salt marsh after periods of low freshwater availability suggesting that only a few stress-tolerant species could survive the high salinity.

In many instances, short-term freshwater flooding of hypersaline marshes leads to an increase in primary productivity. Zedler (1983) found biomass of *Spartina foliosa* to increase 40% in the Tijuana Estuary, California, after two months of flooding rains. Covin and Zedler (1988) noted a 60% increase in the stem density of *S. foliosa* after summer reservoir discharges and sewage spills along the Mexico border. They also found near extinctions of *Salicornia bigelovii* and *Suaeda esteroa* during a drought period in 1984 that led to hypersaline conditions.

In the Nueces Delta, hypersalinity occurs as a result of both natural and human-induced conditions. The region is semiarid, having low annual rainfall (70 centimeters (cm) or 28 inches per year) and hot, dry summers. A net annual water deficit is common, as evaporation (152 cm or 60 inches per year) often exceeds precipitation (Longley 1994). These conditions produce hypersaline soils that are diluted only through direct precipitation or by flooding of the Nueces River. The natural salinity stress is accentuated in the Nueces Delta because considerable harnessing of river water for municipal, agricultural and industrial purposes has reduced the opportunity for freshwater flooding events into the marshlands (Irlbeck and Ward 2000). In years prior to the demonstration project, the river breached its banks and flooded the marsh only during infrequent flooding events.

OBJECTIVES

1) To determine the effects of the demonstration project on the open water and pore water salinity and nitrogen levels; and
2) To determine the project effects on the distribution and abundance of emergent marsh vegetation at three different stations over four growing seasons in the upper Nueces Delta.

MATERIALS AND METHODS

MONITORING STATIONS

The emergent vegetation and related physio-chemical parameters (*i.e.*, salinity and nitrogen levels) were quantified at three sampling stations in the upper Nueces Delta, including one reference station and two treatment stations (Figure 6-1). Station I (Reference Station) was located west of the tidal flats area of the upper delta, about 0.9 km from the outfall of the Rincon Overflow Channel. This location was selected to limit the amount of influence by fresh water diverted by the demonstration project, but also to

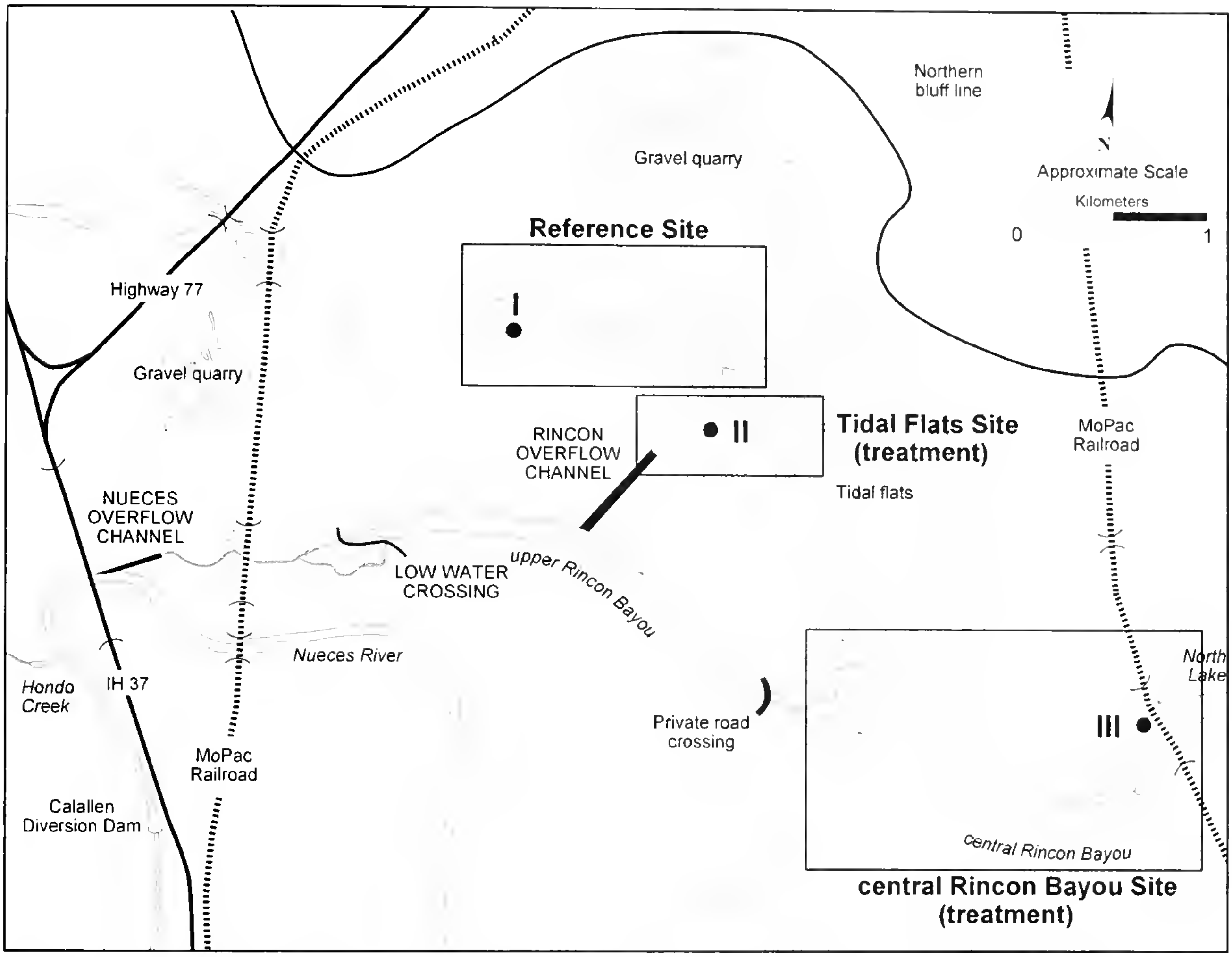


Figure 6-1: Location of vegetation sampling stations in the upper Nueces Delta. The study design included one reference site and two treatment sites (Tidal Flats and central Rincon Bayou), with one sampling station per site.

allow to the same meteorological influences as the other two treatment stations. Station II was located in the tidal flats area about 1.2 km downstream from the Reference Station and about 0.5 km downstream from the Rincon Overflow Channel. Freshwater flow through the Rincon Overflow Channel directly impacted Station II. Station III was located adjacent to the central Rincon Bayou channel about 2.7 km downstream from Station II, 3.1 km from the Rincon Overflow Channel and 5.7 from the Nueces Overflow Channel. Station III was closest to Nueces Bay (about 7.4 km via channels). Vegetation at Station III was potentially influenced by fresh water entering the marsh via the Nueces Overflow Channel and was subjected to tidal inundation of saline waters from the bay.

The vegetation at the three stations was diverse, including both annual and perennial species. Annual plants differed from perennial plants in that they complete their life cycle within one year and reproduce by seeds (sexual reproduction). Perennial plants can live for more than a year and reproduce both sexually by seeds and by asexual vegetative growth (*i.e.*, expansion of above-ground tissues and below-ground rhizomes). The dominant vegetation species at the three stations were the perennial plants *Borrichia frutescens*, *Batis maritima*, *Monanthocloe littoralis* and *Distichlis spicata*. The perennial succulent *Salicornia virginica* was dominant at Station III but was rarely found at the other two stations. The annual succulent, *Salicornia bigelovii*, was periodically present at all three stations. The annual species *Suaeda maritima*, *Lycium carolinianum*, and *Limonium nashii* were occasionally found at the stations.

OPEN WATER AND PORE WATER CHEMISTRY

Four replicate open water samples were collected from the water adjacent to the sampling transects. Two replicate sediment pore water samples were collected using lysimeters placed within the transect sediments at the 0, 49 and 99 m marks. Lysimeters were made of PVC pipes (6 cm diameter, 60 cm length) with horizontal slits cut in the lower 30 cm to allow for the passive movement of water into the pipe. Prior to sampling, lysimeters were pumped dry and allowed to refill. If water were unavailable, sediment samples were taken and later centrifuged to extract pore water. After being centrifuged, salinity of pore water samples was determined using a refractometer. Oftentimes, the sediment was too dry to extract any water, and therefore data were not acquired on several sampling dates. In the field, open water salinity was recorded with an Orion conductivity meter and reported in ppt. All samples were collected in bottles and placed on ice for later determination of ammonium (NH_4^+) and nitrite plus nitrate ($NO_2^- + NO_3^-$) levels. Concentrations of NH_4^+, and $NO_2^- + NO_3^-$ were determined using standard colorimetric techniques (Parsons *et al.* 1984).

Freshwater flow through Rincon Bayou and direct precipitation were also measured during the demonstration period (Chapter 3). Daily data for these two freshwater variables were summed according to the periods immediately preceding each vegetation sampling date to allow comparison with salinity values.

TRANSECT SAMPLING

Seasonal vegetation distribution and abundance were quantified using transect sampling (Bertness and Ellison 1987). Generally, sampling occurred in the late spring (~June), late summer (~September), late fall (~December) and mid-winter (~January). The sampling schedule was based on a previous study in the Nueces Delta, which suggested that the emergent vegetation exhibits peaks and declines in growth at different times of the year. Annual species were noted to increase in cover during the late spring but were non-existent throughout the summer, fall and winter. Additionally, many species exhibited a reduction in cover during the late fall because of the shedding of their leaves. Late summer sampling was chosen because the plants typically experience several months of increased temperatures and decreased rain. Mid-winter sampling was selected because it is the time of year when plant cover is typically low, but annual species seedling growth has begun.

In June 1995, three permanent transects were established, one at each station. The transects were 99 m long and 8 m wide (792 m^2) at the Reference Station and Station II (Figure 6-2), and 103 m long and 8 m wide (824 m^2) at Station III. At all three stations, the transect lines were spaced at 3 m intervals for the first 9 m of the transect. At the Reference Station and Station II, the lines were spaced at 10 m intervals between 9 and 99 m. Each transect extended perpendicularly from the vegetation line at the water's edge. The transect lines were spaced closest together near the water's edge because this was expected to be the part of the transect showing the greatest variation in degree of tidal inundation and soil moisture. Station III differed in transect size and sampling intervals because a small channel intersected the transect between the 47 m and 57 m marks, resulting in the occurrence of three water's edges at this station. The transect design for Station III was different from the Reference Station and Station II because there was no area large enough to encompass at least a 99 m transect directly along Rincon Bayou. However, the difference in transect design was inconsequential because the three stations were uniquely different, and direct statistical comparisons between the stations was not necessary. At Station III, the lines were spaced at 10 m intervals between 9 and 39 m, 8 m between 39 and 47 m, 10 m between 47 and 57 m, 3 m intervals between 57 and 63 m and 10 m intervals between 63 and 103 m. The transects were sampled at 2 m intervals along the horizontal transect lines, for a total

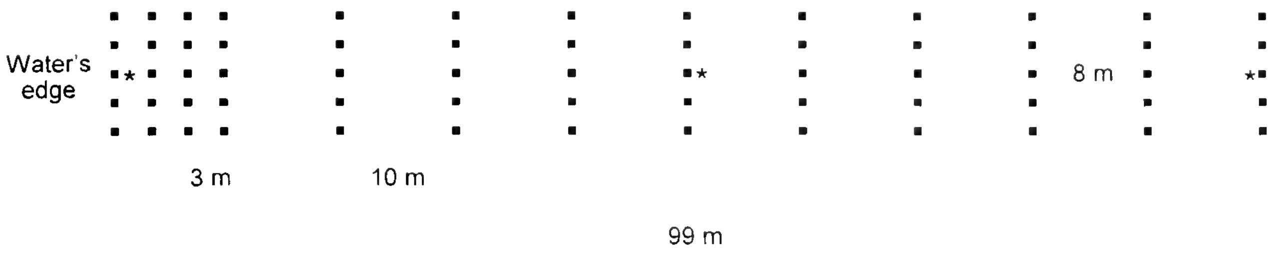


Figure 6-2: The layout and dimensions of a typical vegetation transect. The figure illustrates the transect design used at the Reference Station and Station II. Each dot is a sampling point for vegetation parameters (*i.e.*, percent cover and leaf area index). Asterisks (*) denote the sampling locations of pore water samples.

of 65 sampling points at the Reference Station and Station II and 75 sampling points at Station III.

PERCENT COVER AND LEAF AREA INDEX

Percent cover and leaf area index (LAI) were sampled seasonally from June 1995 to December 1999, for a total of 20 seasonal sampling dates. The three stations were sampled one additional time in June 2000, but only data for percent cover were acquired. However, the Station III transect was partially destroyed by livestock, and therefore percent cover data for that date were not collected.

A 0.25 m^2 quadrat subdivided into 100 cells was used to estimate the percent cover of each species at each sampling point. Cells with no vegetation and those covered with water or wrack (dead plant material) were considered bare area. LAI, a measure of plant foliage density and distribution, was quantified at each sampling point using a LAI-2000 Leaf Canopy Analyzer (LI-COR, Lincoln, Nebraska). LAI provided a non-destructive means of estimating foliage density by measuring the amount of light attenuated within the canopy. Each LAI measurement was an average of three individual readings taken at a sampling point. LAI readings for 1995 were not included in the analyses due to complications with the measuring technique at the beginning of the sampling period.

ANALYSES

Vegetation parameters were analyzed at two different spatial scales (792 or 824 m^2 transects and 0.25 m^2 quadrats interpolated to 0.25 m^2 grid cells). Large-scale analyses averaged data over an entire transect and utilized traditional methods, including graphs and tables. Small-scale analyses were accomplished through the use of a Geographical Information System (GIS). The GIS allowed each sampling point and corresponding data to be geographically represented, taking into account the spatial relationships between vegetation parameters. Analysis at two different scales was necessary because much of the heterogeneity found at small scales was lost when the data were averaged over an entire transect. Large-scale observations were useful in that they indicated general patterns and trends in vegetation parameters, such as seasonal peaks and declines, but small-scale analyses provided detailed information regarding changes in vegetation species distribution and abundance.

Large-Scale Analyses

Total transect average percent cover for each species was determined by adding together the percent cover of each species at each sampling point and then dividing by the total number of sampling points. Total LAI was calculated in the same manner. These total numbers provided an estimate of species percent cover and LAI on a large-scale basis.

Small-Scale Analyses

Individual species percent cover and LAI readings taken at each sampling point were analyzed on a small-scale basis by the means of a GIS. Each sampling point was given geographic coordinates (Universal Transverse Mercator; Zone 14) based on differential Global Positioning System (GPS) points taken in the field at the four corners of the transects. Percent cover and LAI data acquired in the field were assigned to the corresponding geographic location at each sampling point then incorporated from tabular format in Microsoft Excel to ArcView GIS software. The Inverse Distance Weighting function in ArcView's Spatial Analyst extension was used to interpolate grids for the area within the transect using the data points taken in the field as reference numbers. The method assumes that each point has a local influence that diminishes with distance so that points closer to the cell containing the field measurement have greater values than those farther away. A grid cell size of 0.25 m (the same size as the quadrat) was used, providing a means of small-scale analyses.

Maps of percent cover and LAI for each transect were analyzed to determine changes in species cover and bare area before and after hydrographic events at each station. For percent cover, vegetation maps for each sampling date were created by querying the data to find areas in the transect where cover for each individual species were greater than 50%. This allowed all species to be mapped together on the transect. Maps from the sampling date prior to an event were then compared to maps for the three sampling dates following the event. The conversion of the point data into interpolated surfaces allowed for mathematical manipulations and analyses in a spatially coherent, three-dimensional manner, which naturally represented the data.

BIOMASS

Four replicate samples of monospecific stands of *Batis maritima*, *Borrichia frutescens*, *Monanthocloe littoralis* and *Distichlis spicata* growing near the transect were sampled bi-annually (winter and spring) using a PVC corer (10 cm diameter, 30 cm length). The corer was placed around the vegetation and above-ground plant material clipped. The corer was then driven into the ground for collection of below-ground material. Plant material was sequentially sieved using a 1 cm sieve followed by a 1 millimeter (mm) sieve, sorted into above- and below-ground portions and dried at 60° C to a constant weight. Samples were weighed to the nearest 0.1 gram (g), and biomass was converted to an area basis. Root to shoot (R:S ratios) ratios were calculated from biomass measurements.

RESULTS

Vegetation and physio-chemical parameters (*i.e.*, salinity and nitrogen levels) were examined based on changes observed within and between the stations before and after periods with significant freshwater inflow or precipitation (Table 6-1). In general, vegetation from three different sampling periods exhibited measurable responses to these hydrographic influences: July 1997, October 1998 and September 1999. The major hydrographic events (Chapter 3) preceding each of these sampling dates include Event 16 (June 21 through July 3, 1997), Event 17 (July 4 through 26, 1997), Event 25 (October 16 through 29, 1998), Event 35 (August 19 through September 3, 1999) and Event 36 (September 4 through 20, 1999) (Table 6-1). Where any sampling period was preceded by more than one identified hydrographic event (*e.g.*, July 1997 and September 1999), it was assumed that any measurable change observed in the vegetation could be due to a combination of those events. Therefore, for the purposes of this vegetation analysis, the events preceding each sampling period during which a response was observed were collectively referred to as the composite hydrographic events of July 1997, October 1998 and September 1999. During each of these periods, the Rincon Overflow Channel was activated and Station II was subjected to the influence of project diversions.

Because salt marsh vegetation also often responds to direct precipitation, total monthly precipitation was reported separately to allow precipitation-mediated

Table 6-1: Hydrographic events (from Table 3-3) occurring prior to each vegetation sampling period. The three composite hydrographic events which stimulated a vegetative response (July 1997, October 1998 and September 1999) are indicated in bold. Cumulative flow, rainfall and average salinity concentrations also reported for all vegetation stations (1 through 3). Daily values for net flow and total precipitation were summed between sampling intervals. In some cases, sampling occurred during an event. The Nueces Overflow Channel was completed on October 26, 1995, so flow prior to that date was zero. Precipitation data for sampling dates prior to May 16, 1996 were that recorded at the Corpus Christi International Airport. Hyphens (-) indicate missing data.

Vegetation Sampling Date	Hydrographic Events (Table 3-3)	Total Net Flow Through Rincon Bayou (acre-ft)	Total Precipitation (inches)
6/29/95	1, 2, 3	0	6.06
8/25/95	4	0	4.84
11/7/95	5, 6	-	14.57
2/13/96	7, 8, 9, 10	-	3.62
5/22/96		-	1.64
9/5/96	11	41	9.37
11/6/96	12, 13, 14	250	3.26
2/17/97		79	4.29
6/2/97	15	57	16.66
8/29/97	**16, 17**	**1,542**	**3.35**
11/26/97	18	264	14.19
1/5/98		-1	0.38
6/1/98	19	78	5.45
10/2/98	20, 21, 22, 23, 24	670	9.89
12/2/98	**25, 26, 27**	**3,381**	**13.11**
1/13/99		-8	1.08
6/2/99	28, 29, 30, 31	-1	7.40
9/2/99	32, 33, 34, 35	-41	13.72
12/8/99	**36, 37**	**820**	**4.63**

changes to be identified (Figure 6-3). It should be noted that, although direct precipitation was not an effect of the demonstration project, it was a freshwater source to which vegetation responded, which could also be used to indicate the importance of freshwater diversions.

SALINITY

Open Water Salinity

Open water salinity values for all three stations increased and decreased simultaneously throughout the study period, although the magnitude of change varied between the stations (Table 6-2 and Figure 6-4a). Decreases in salinity were often seen following precipitation or flooding, and high salinity values were common during dry, hot periods. An important assumption was that changes in open water and pore water salinity values at the Reference Station were not due to the channels, being determined by environmental conditions such as precipitation, evaporation and run-off. This was important when comparing the salinity values between the stations and assessing the relative impacts of the channels.

When evaluating salinity levels, precipitation and flow effects were analyzed independently because changes in salinity could be due to one or both parameters (Table 6-1 and Figure 6-4a). The data acquired in this study indicated that heavy precipitation could occur independent of flow and result in low salinity values.

Therefore, when analyzing the salinity data, sampling dates that experienced prior heavy precipitation without heavy flow were treated separately from all other events (Figure 6-5). When interpreted in this manner, there was a positive correlation between increasing flow and decreasing salinity values at both

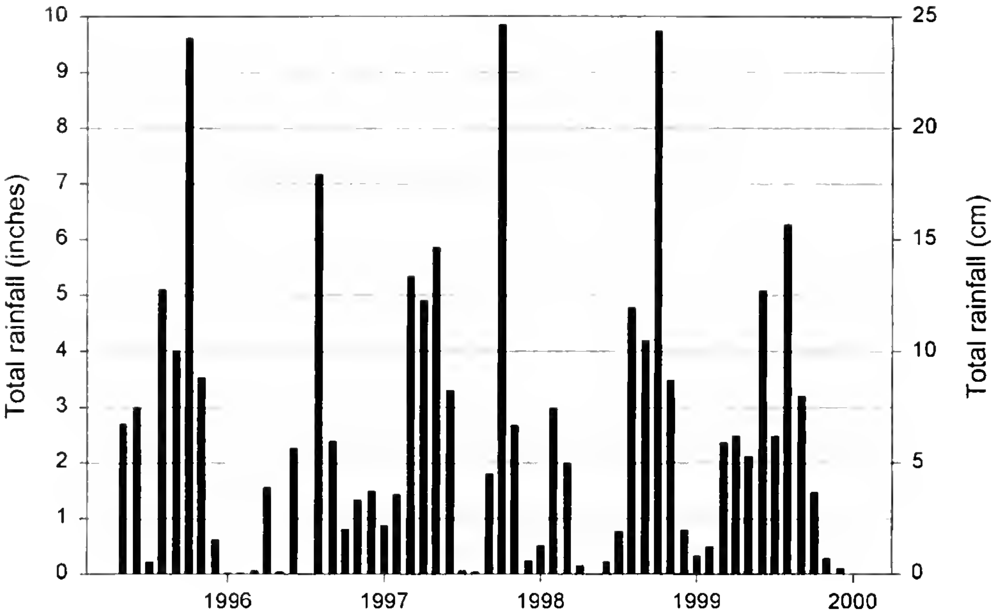
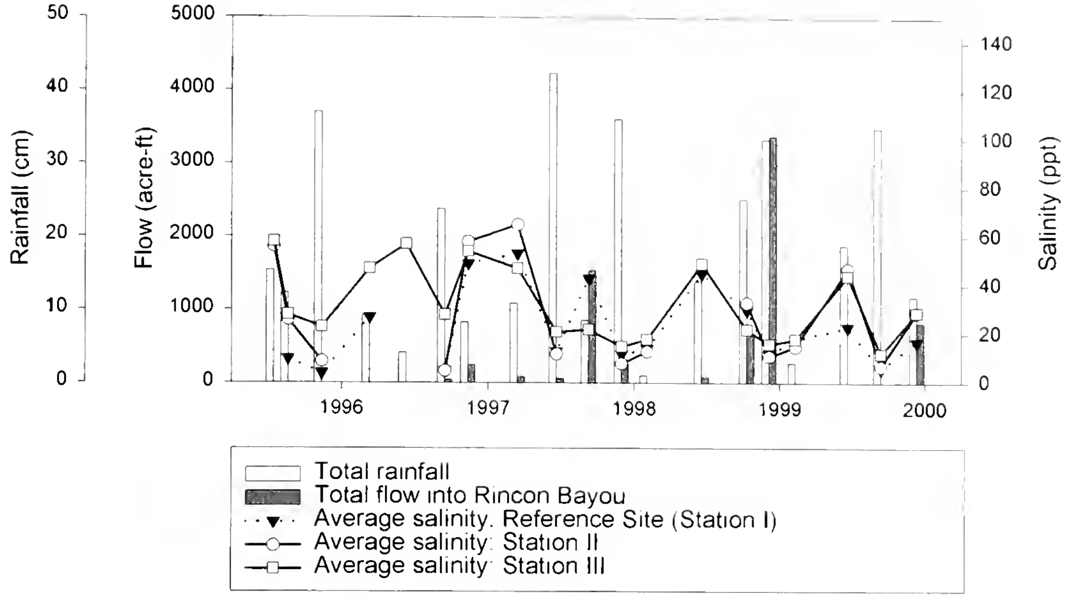


Figure 6-3: Total monthly precipitation during the demonstration period. Data from April 1995 through April 1996 are that reported from the Corpus Christi International Airport, and data from May 19996 through December 1999 are that recorded at the Rincon gauge.

Table 6-2: Mean open water (OW) and pore water (PW) salinity values at each station. Pore water samples taken at three locations (0, 49 and 99 m) along each transect. Hyphens (-) indicate missing samples because of dry open water channels or pore water holes. Each value reported reflects the average of two individual samples.

		Reference Station				Station II				Station III			
Yr	Mo	OW	PW			OW	PW			OW	PW		
			0 m	49 m	99 m		0 m	49 m	99 m		0 m	49 m	99 m
	Apr	14.8	20	-	-	23	36	-	-	30	-	32	-
95	Jun	-	-	-	-	56	50	65	69	58	-	-	-
	Aug	10	18	53	56	26	43	68	66	28	-	51	70
	Nov	4	29	51	36	9	30	70	47	23	38	33	36
	Feb	27	-	-	-	-	-	70	68	47	-	-	-
96	May	-	-	-	-	-	-	-	-	57	-	-	-
	Sep	5	44	68	74	5	28	79	-	28	-	-	62
	Nov	49	46	64	66	58	69	70	71	54	-	63	71
	Feb	53	49	-	-	65	59	76	61	47	-	-	-
97	Jun	13	27	-	-	12	13	70	-	21	-	-	-
	Aug	43	-	-	-	-	-	-	-	22	-	-	-
	Nov	12	26	61	52	8	8	36	54	15	-	-	40
	Jan	14	-	-	-	13	-	-	-	18	-	-	-
98	Jun	45	-	-	-	-	-	-	-	49	-	-	-
	Oct	30	46	81	-	33	40	48	62	22	52	41	73
	Dec	12	37	55	-	11	34	53	69	16	-	-	-
	Jan	18	-	-	-	15	-	-	-	18	-	-	-
99	Jun	23	30	72	-	47	54	80	83	44	54	51	81
	Sep	6	23	83	42	7	18	21	41	12	-	-	11
	Dec	17	29	82	87	29	60	85	82	29	46	51	92

(a) Open water salinity



(b) Pore water salinity (at 49 m along the transect)

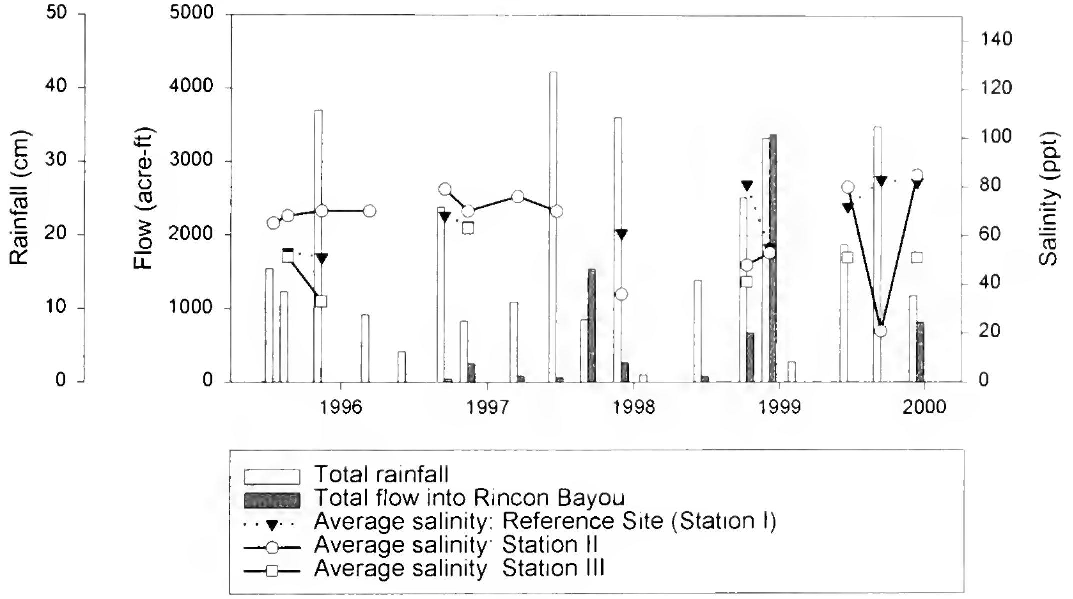
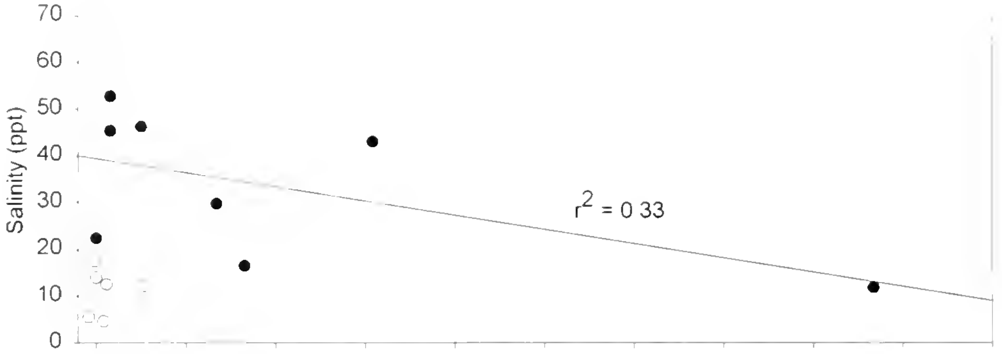
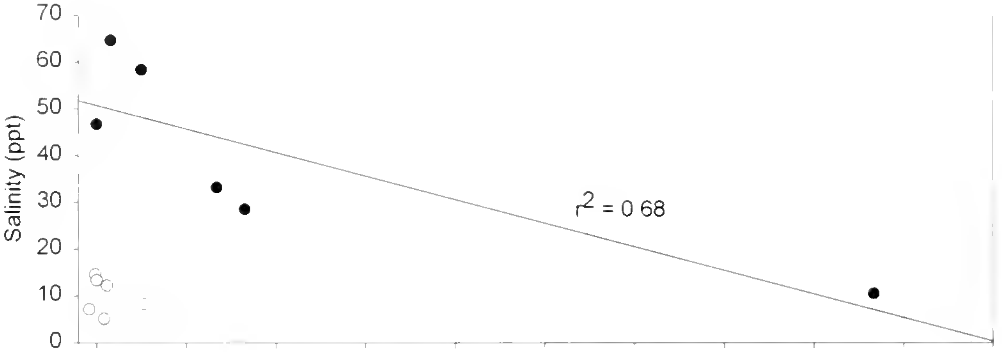


Figure 6-4: Salinity for open water (a) and pore water (b) at each sampling site for each sampling date. Cumulative daily rainfall and inflow into Rincon Bayou also plotted for each period between sampling dates.

(a) Reference Station



(b) Station II



(c) Station III

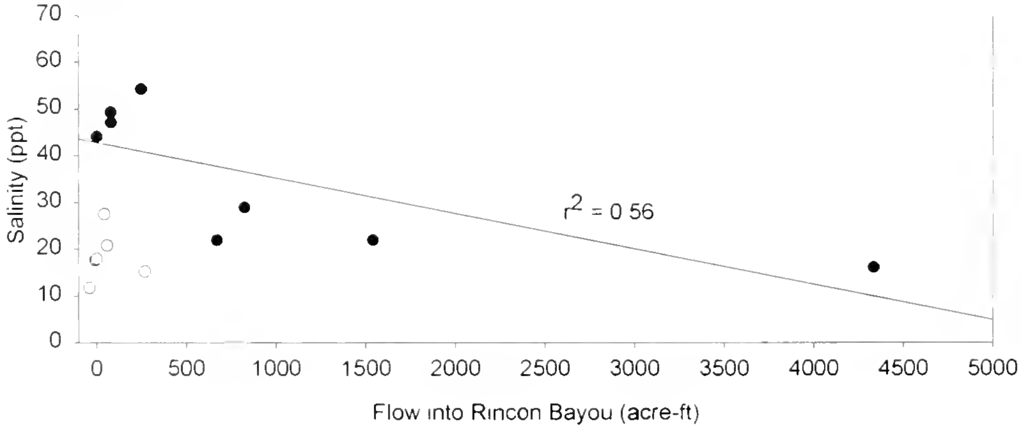


Figure 6-5: Correlation between total flow through Rincon Bayou and open water salinity for each station. Open circles (○) indicate salinity values on sampling dates following heavy precipitation (> 25 cm) with little to no flow (< 617 10^3 m^3, or 500 acre-ft). Closed circles (●) indicate salinity values on all other sampling dates. The separation of salinity values was used to distinguish the effects of freshwater inflow. The linear regressions indicate the correlation between flow and salinity values only for events with large inflow. As flow increased, salinity decreased at the treatment stations (Stations II and III). As expected, a clear correlation was not found at the Reference Station.

Station II ($r^2 = 0.68$) and Station III ($r^2 = 0.56$) and a nonsignificant correlation at the Reference Station ($r^2 = 0.33$). The correlations were based the total precipitation and flow experienced at the stations between sampling periods. However, on two occasions, sampling dates were only two months apart (November 1997/January 1998 and December 1998/January 1999). For these two periods, flow and precipitation for the three months prior to the sampling date were considered.

At the Reference Station, salinity values greater than 35 ppt (seawater concentration) were recorded 22% of the time, while values less than 18 ppt were measured 56% of the time. The highest salinity (53 ppt) occurred in February 1997 during a five-month period with less than 25.2 cm (10 inches) of rain. The lowest values recorded coincide with periods having heavy rainfall. For example, a salinity value of 13 ppt was recorded in June 1997, following three months with over 37.8 cm (15 inches) of rain. However, salinity increased rapidly afterwards to 43 ppt in August 1997. A salinity value of 12 ppt was recorded in December 1998, following four months with over 55.4 cm (22 inches) of rain. In this instance, salinity remained relatively low throughout 1999, most likely because spring rains were abundant, with the highest salinity for the year (23 ppt) being recorded in June 1999.

At Station II, open water salinity values above 35 ppt were recorded on three sampling dates (25% of the samples), with the highest recording being 65 ppt in February 1997. Low values recorded at this station occurred on the same dates as those at the Reference Station. Values after major hydrographic events flooding the Rincon Overflow Channel do not differ by more than 1 ppt from those at the Reference Station but were 5 ppt lower than Station III after the October 1998 and September 1999 events.

Station III had the greatest number of readings higher than 35 ppt (35%). The relatively higher values may be reflective of its closer proximity to Nueces Bay. The highest value (57 ppt) was recorded in May 1996, following six months of less than 5 cm (2 inches) total rainfall.

Pore Water Salinity

Pore water salinity values were typically higher than those in open water (Table 6-2 and Figure 6-4b). At the Reference Station, pore water salinity concentrations ranged between 20 and 87 ppt and were as much as 14 times higher than the open water salinity value measured on the same date. At Station II, values ranged between 8 and 85 ppt and were as much as 16 times higher than the open water value. The range of values at Station III was similar to the other stations (11 to 92 ppt) but was measured to be only as much as 3 times higher than the open water value.

Pore water values did not always decline after a hydrographic event, whether the event was precipitation- or flow-mediated (Figure 6-4b). However, as many of the values are missing, determination of actual decrease proved difficult. Additionally, sampling dates did not always immediately follow times of heavy precipitation or flow events. Consequently, salinity values might have decreased, but unless the sampling date occurred soon after the freshwater input, any pore water response might not have been measured.

On the occasions that values could be recorded, the response was variable. In December 1998, following three months with over 25 cm (10 inches) rainfall, pore water salinity values at the Reference Station decreased by 9 and 26 ppt at two locations (0 and 49 m). However, values at Station II were only reduced at 0 m (the location closest to open water) and only by 6 ppt, despite the flooding of the station during the October 1998 event. In contrast, pore water salinity values decreased at Station II in September 1999 by 36, 58 and 42 ppt at 0, 49 and 99 m locations, respectively. The decrease immediately followed the September 1999 event, which had not yet activated the Rincon Overflow Channel but did see over 15 cm (6 inches) rain in one day. During this event, a tidal surge from the bay flooded the transects, flushing the soils and then retreating after the surge. In this instance, the sampling date was only days following the event. The spring and summer months also had relatively high rainfall compared to the other sampling years. The range of values at the Reference Station following the same event decreased only at 0 m by 6 ppt, but increased at 49 m by 2 ppt and 45 ppt at 99 m.

AMMONIUM

Open Water Ammonium

Concentrations of NH_4^+ at the Reference Station exhibited the greatest variation (0.9 to 14.7 µmoles), with peak values occurring in September 1996 (12.1 µmoles) and June 1999 (14.7 µmoles) (Table 6-3). The increase in September 1996 coincided with a peak at Station II. The June 1999 peak occurred during a period of 4 months with over 30.2 cm (12 inches) of rain.

At Station II, concentrations resembled those at Station III, except for a peak value of 9.4 µmoles in September 1996, 51.6 µmoles in January 1997 and two peaks of 6.4 µmoles in December 1998 and January 1999. The first peak occurred during a period with more than 22.7 cm (9 inches) of rain in two months, and the last two peaks followed the October 1998 event, which flooded the station. Values prior to the event were in the average range for that time of year (2.7 µmoles), but were more than twice as high following the event. The concentration decreased by 60% in the following five months to near 4.0 µmoles, which represented the fall peak range under non-event conditions.

At Station III, concentrations cycled over the study period, with low values (~2.0 to 3.0 µmoles) being observed in the late fall and winter. Values increased from winter to spring and peaked in the late summer or fall (4.0 to 6.0 µmoles). Station III exhibited the smallest range of values, 1.6 to 9.5 µmoles.

Table 6-3: Mean open water ammonium (NH_4^+) and nitrite+nitrate ($NO_2^- + NO_3^-$) concentrations at each station. Values are reported ± SE. ($n = 4$). Samples acquired prior to September 1996 represent only one water sample and therefore do not contain SE. Dashes indicate times when samples could not be taken.

Yr	Mo	Reference Station		Station II		Station III	
		NH_4^+	$NO_2^- + NO_3^-$	NH_4^+	$NO_2^- + NO_3^-$	NH_4^+	$NO_2^- + NO_3^-$
95	Apr	3.7	0.8	5.5	5.3	2.5	2.7
	Jun	4.1	1.2	3.0	20.2	5.6	2.3
	Aug	1.7	1.3	5.4	1.3	2.9	5.6
	Nov	3.1	1.7	1.7	7.1	3.0	2.7
96	Feb	5.0	1.8	-	-	1.6	1.1
	May	-	-	-	-	2.7	0.7
	Sep	12.1 ± 1.00	0.9 ± 0.05	9.4 ± 1.57	1.2 ± 0.08	3.8 ± 0.12	1.8 ± 0.5
	Nov	1.9 ± 0.12	1.2 ± 0.09	1.6 ± 0.11	0.9 ± 0.05	2.3 ± 0.12	1.0 ± 0.07
97	Feb	1.7 ± 0.15	0.8 ± 0.01	1.6 ± 0.14	0.9 ± 0.05	1.7 ± 0.15	0.9 ± 0.04
	Jun	2.3 ± 0.05	0.5 ± 0.03	3.2 ± 0.20	0.7 ± 0.04	2.6 ± 0.08	0.8 ± 0.05
	Aug	3.5 ± 0.17	0.8 ± 0.08	-	-	3.9 ± 0.38	0.8 ± 0.03
	Nov	2.6 ± 0.15	0.5 ± 0.10	3.7 ± 0.17	0.3 ± 0.01	4.1 ± 0.14	0.4 ± 0.02
98	Jan	3.9 ± 0.07	0.5 ± 0.11	51.6 ± 2.22	1.9 ± 0.18	2.9 ± 0.15	0.7 ± 0.17
	Jun	0.9 ± 0.18	0.8 ± 0.03	-	-	1.7 ± 0.11	0.8 ± 0.02
	Oct	5.7 ± 0.17	0.9 ± 0.02	2.7 ± 0.09	0.5 ± 0.03	2.4 ± 0.10	0.5 ± 0.01
	Dec	2.6 ± 0.37	0.7 ± 0.02	6.4 ± 0.44	1.9 ± 0.09	2.1 ± 0.03	0.9 ± 0.03
99	Jan	2.5 ± 0.19	0.9 ± 0.01	6.4 ± 1.50	1.1 ± 0.03	2.3 ± 0.05	1.0 ± 0.01
	Jun	14.7 ± 0.67	0.9 ± 0.04	3.8 ± 0.27	1.1 ± 0.06	5.0 ± 0.23	1.2 ± 0.02
	Sep	2.6 ± 0.06	0.4 ± 0.02	2.8 ± 0.08	0.5 ± 0.01	2.8 ± 0.39	0.5 ± 0.03
	Dec	8.0 ± 0.32	0.9 ± 0.03	4.6 ± 0.10	1.5 ± 0.09	9.5 ± 0.24	1.1 ± 0.05

Pore Water Ammonium

Pore water NH_4^+ concentrations were generally much higher than open water levels, with the highest values recorded being in the summer and lowest values in the late fall and winter (Table 6-4). At the Reference Station, values ranged from 1.9 to 193 µmoles. The highest values were recorded in June 1999 (53 to 193 µmoles). At Station II, values ranged between 4.5 and 197 µmoles. High values (64 to 197 µmoles) were measured over a six-month period from June to December 1999 and coincided with a fourteen-month period with over 125.9 cm (50 inches) of precipitation. The highest values recorded at Station III were also in June through December 1999 (21 to 213 µmoles). At all three stations, values appeared to gradually increase over the study period (Figure 6-6), with similarly high values seen during the second half of 1999.

NITRITE+NITRATE

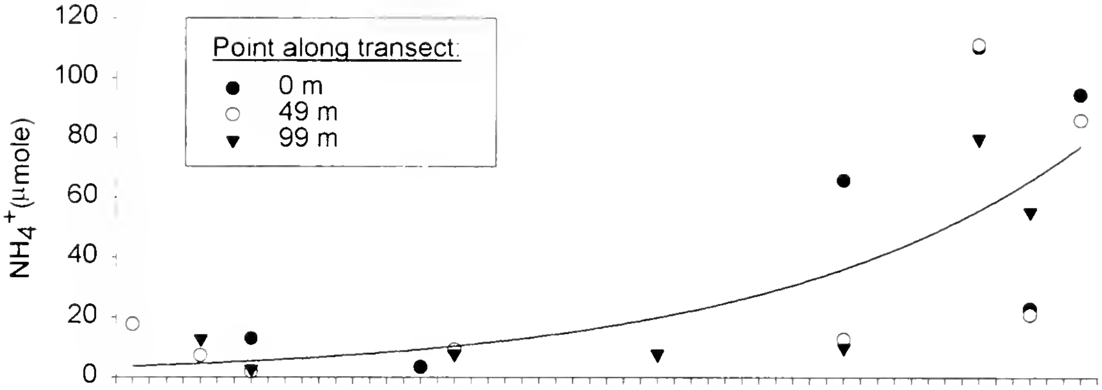
Open Water Nitrite+Nitrate

At the Reference Station, NO_2 + NO_3 concentrations exhibited the smallest range of values (0.4 to 1.8 µmoles), with the highest value being recorded in February 1996 (Table 6-3). The highest overall values were seen at Station III during the first sampling year (1995), with values exceeding 2.3 µmoles at each sampling date during that year and approaching 6 µmoles in August 1995. The range of values for the remainder of the study period was between 0.4 and 1.2 µmoles. The values at Station II were between 0.3 µmoles and 5.3 µmoles, with the highest values recorded in April 1995. An additional small peak occurred in December 1998 (1.9 µmoles).

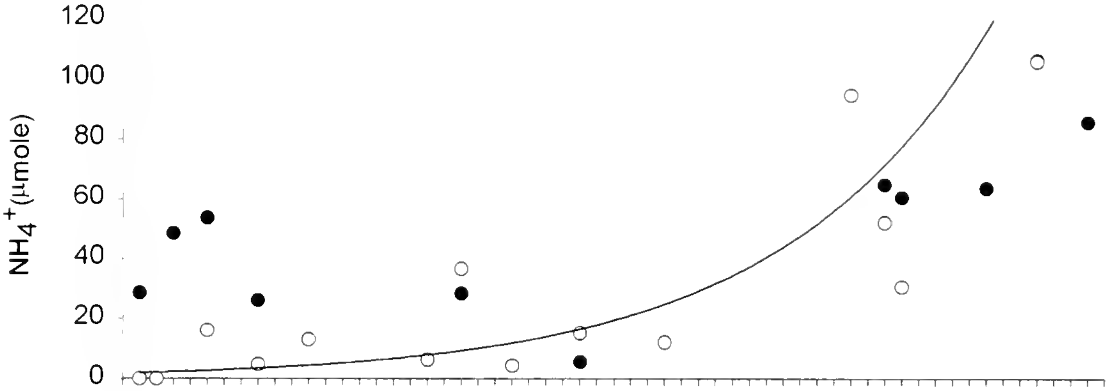
Table 6-4: Mean pore water ammonium (NH_4^+) and nitrite+nitrate (NO_2^- + NO_3^-) concentrations at each station. Pore water samples were taken at three lysimeters located at 0, 49 and 99 m from the water's edge. Two water samples were taken at each lysimeter, and the two values averaged to determine a mean value for that distance. The range of mean values at the three distances is reported. If only one number is listed, then samples were only taken from one well, and dashes represent samples that could not be taken (as a result of sediments being too dry to extract water).

Yr	Mo	Reference Station		Station II		Station III	
		NH_4^+	NO_2^- + NO_3^-	NH_4^+	NO_2^- + NO_3^-	NH_4^+	NO_2^- + NO_3^-
	Apr	11.4	3.5	28.8	1.4	17.7	0.5
	Jun	2.4 to 21.8	8.4 to 38.2	37 to 48.5	2.7 to 14.4	-	-
95	Aug	4.9 to 28.4	2.0 to 3.3	16.2 to 53.7	1.5 to 6.0	7.4 to 12.9	2.8 to 11.9
	Nov	1.9 to 11.4	2.7 to 12.1	4.9 to 22.9	0.1 to 4.8	2.0 to 13	0.2 to 1.0
	Feb	8.6	-	6.1 to 13.2	-	-	-
96	May	-	-	-	-	-	-
	Sep	4.5 to 23.5	2.4 to 31.3	6.4 to 125.4	4.1 to 49.8	3.4	0.5 to 0.7
	Nov	10.9 to 66.6	1.6 to 8.9	24.7 to 36.8	0.8 to 1.2	7.8 to 9.3	0.4 to 0.8
	Feb	10.7	1.3	4.5	25.1	-	-
97	Jun	48.3	0.5	5.6 to 15.3	0.8 to 1.0	-	-
	Aug	-	-	-	-	-	-
	Nov	6.7 to 8	0.9 to 3.6	12.2 to 17.6	1.7 to 2.6	7.9	2.9
	Jan	-	-	-	-	-	-
98	Jun	-	-	-	-	-	-
	Oct	19.9 to 38.2	0.9 to 4	32.8 to 131.7	0.6 to 4.7	10 to 65.9	0.5 to 5.0
	Dec	10.6 to 45.6	1.2 to 10.3	48.7 to 64.7	1 to 2.8	-	-
	Jan	27.2	2.3	30.7-60.5	1.0 to 2.0	-	-
99	Jun	52.9 to 107.4	-	63.7 to 182.8	1.3	79.9 to 111.4	-
	Sep	26.8 to 79.7	0.5 to 1	67.1 to 106.3	0.1 to 0.8	21.1 to 55.5	0.7
	Dec	58.4 to 84.5	-	85.6 to 113.1	-	86.1 to 94.8	-

(a) Reference Station



(b) Station II



(c) Station III

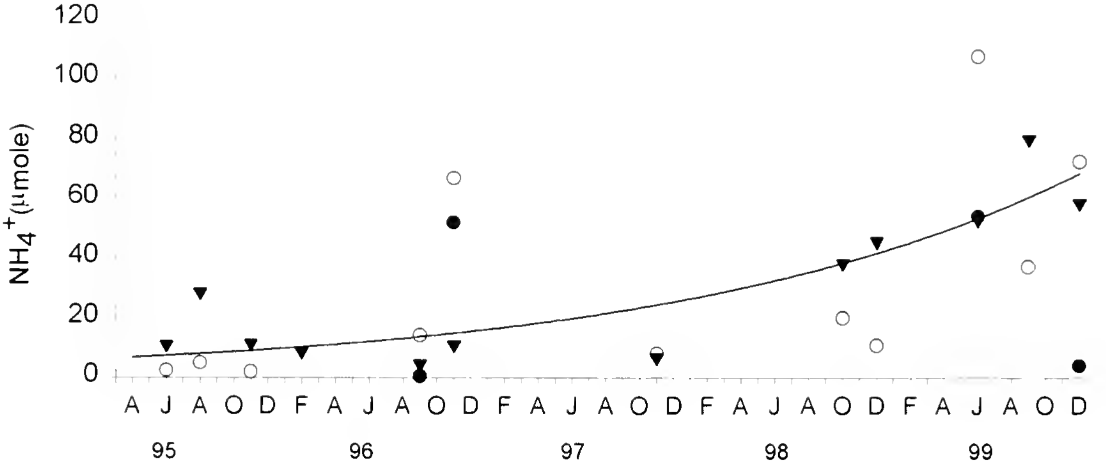


Figure 6-6: Mean pore water ammonium values for each station. Pore water samples were taken at three lysimeters located at 0, 49 and 99 m from the water's edge. Curves represent the best fit curve for the values taken at the 49 m location. The values reported for each distance is the mean of two samples. Occasionally, one or more locations were dry, so some sampling dates do not have measurements or have only one or two measurements.

Pore Water Nitrite+ Nitrate

Pore water $NO_2^- + NO_3^-$ concentrations were typically higher than open water values (Table 6-4). At the Reference Station, values ranged from 0.5 to 38.2 μmoles, and at Stations II and III, concentrations ranged from 0.1 to 49.8 μmoles and 0.4 to 11.9 μmoles, respectively.

LARGE-SCALE WHOLE TRANSECT ANALYSES: INDIVIDUAL SPECIES RESPONSES TO EVENTS

There was considerable variability in the percent cover of each species within and between stations before and after composite hydrographic events (Figures 6-7 through 6-9). At the Reference Station and Station III, vegetation changes appear to be predominantly precipitation-mediated rather than flow generated, while changes at Station II occurred as a result of both flow through the channels and direct precipitation.

Reference Station

Batis maritima – At the Reference Station, total transect percent cover of *Batis maritima* cycled seasonally with peaks generally occurring in the summer and declines in the late fall/early winter (Figure 6-7a). The greatest increase in cover (3.5% to 23%) occurred between February and August 1997. Between February and June, the study area received 52.1 cm (20.7 inches) of rain, or 57% of the total yearly rainfall. At the Reference Station, *B. maritima* exhibited a decrease in cover in June 1998. From April to June 1998, there was little precipitation (< 0.91 cm, or 0.36 inches), unlike other springs during the study period when several inches of rain fell during the same period.

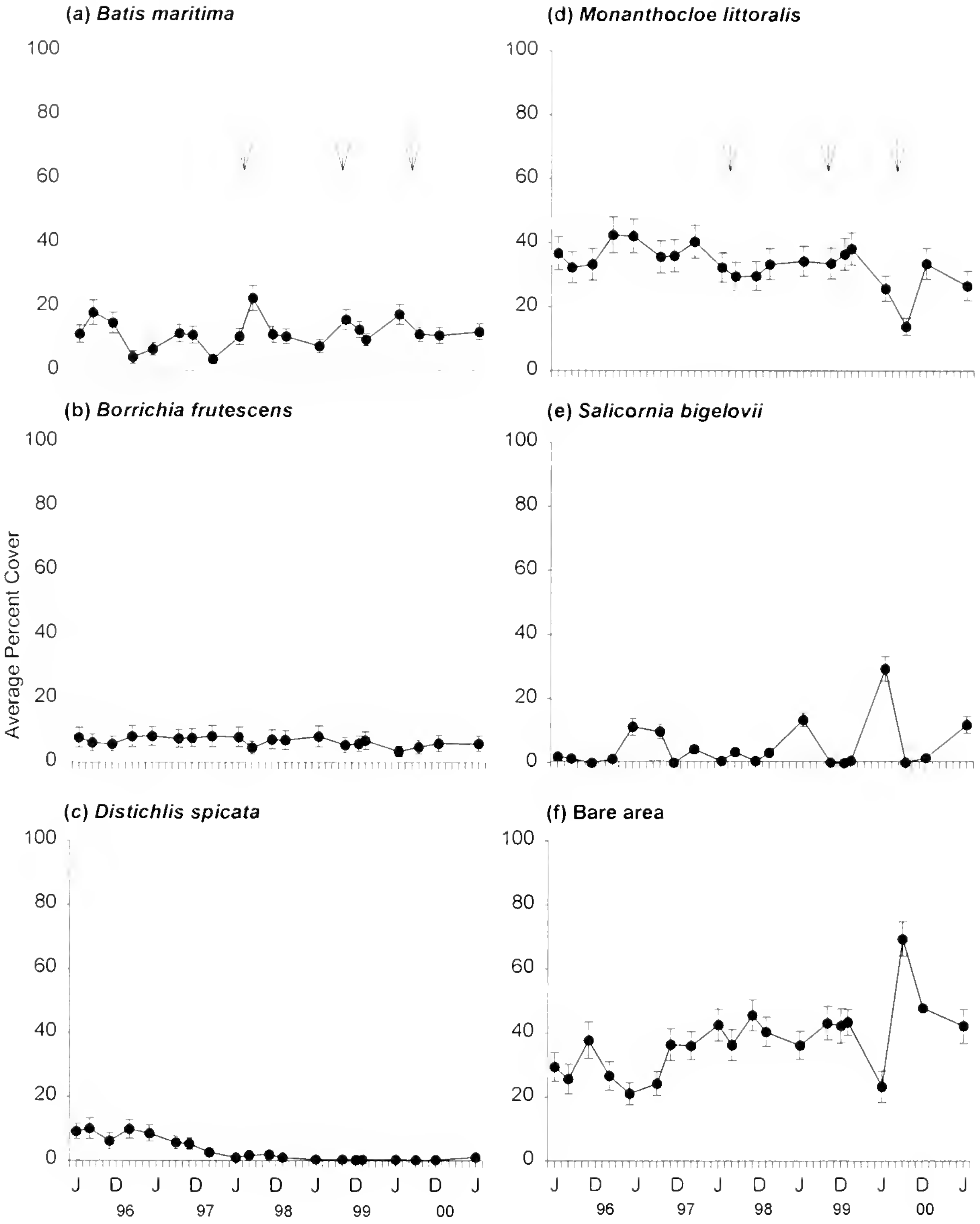
Borrichia frutescens – Percent cover of *Borrichia frutescens* at the Reference Station exhibited an inverse correlation with *Batis maritima* cover (r^2=0.61) (Figure 6-7b). Generally, peaks in *B. frutescens* occurred when *B. maritima* cover was relatively low.

Distichlis spicata – At the Reference Station, cover of *Distichlis spicata* exhibited an overall decrease from 10% in February 1996 to < 1% in June 1997 (Figure 6-7c). Cover remained < 1% for the remaining study period.

Monanthocloe littoralis – At the Reference Station, *Monanthocloe littoralis* cover remained relatively constant throughout the study period (29 to 42%), exclusive of a 23% decline in cover (from 37 to 14%) between January and September 1999 (Figure 6-7d). The initial decline in cover occurred followed six months with about 45 cm (18 inches) rain. The lowest cover measured coincided with the passing of Hurricane Bret (August 1999). The storm released over 15 cm (6 inches) of rain in one day. The transect was also flooded by a tidal surge. *M. littoralis* cover increased 20% (14 to 34%) in the two months following the hurricane, a period with little to no rainfall. Similar, but smaller-scale declines in cover were seen following two or more consecutive months with several inches of rainfall (August to September 1996 and February to June 1997). The decreases in cover were always quickly followed by an increase in growth.

Salicornia bigelovii – At the Reference Station, *Salicornia bigelovii* cover exhibited spring peaks greater than 10% cover occurring in 1996, 1997 and 1998 (Figure 6-7e). The largest peak (30%) in June 1999 was about 20% higher than the other two peaks and occurred following a winter and spring with consistent rainfall (11 out of 14 months received over 5 cm (2 inches) of rain).

Bare Area – On occasion, decreases in bare area corresponded with increases in *Salicornia bigelovii* cover. For example, *S. bigelovii* cover was about 29% in the summer 1999, and bare area cover decreased by about 20% (Figures 6-7e and 6-7f). However, there was no strong correlation between the two parameters (r^2 = 0.27 for *S. bigelovii* cover > 2%). The greatest bare area cover at the Reference Station (69%) occurred in September 1999 following the composite hydrographic event in September 1999, which included the landfall of Hurricane Bret.



(a) *Batis maritima*

(b) *Borrichia frutescens*

(c) *Distichlis spicata*

(d) *Monanthocloe littoralis*

(e) *Salicornia bigelovii*

(f) Bare area

Figure 6-7: Reference Station average total transect percent cover for the five dominant species and bare area on each sampling date. Arrows indicate the dates of composite hydrographic events that caused measurable changes in the vegetation. Error bars represent ±SE (n=65). J = June and D = December.

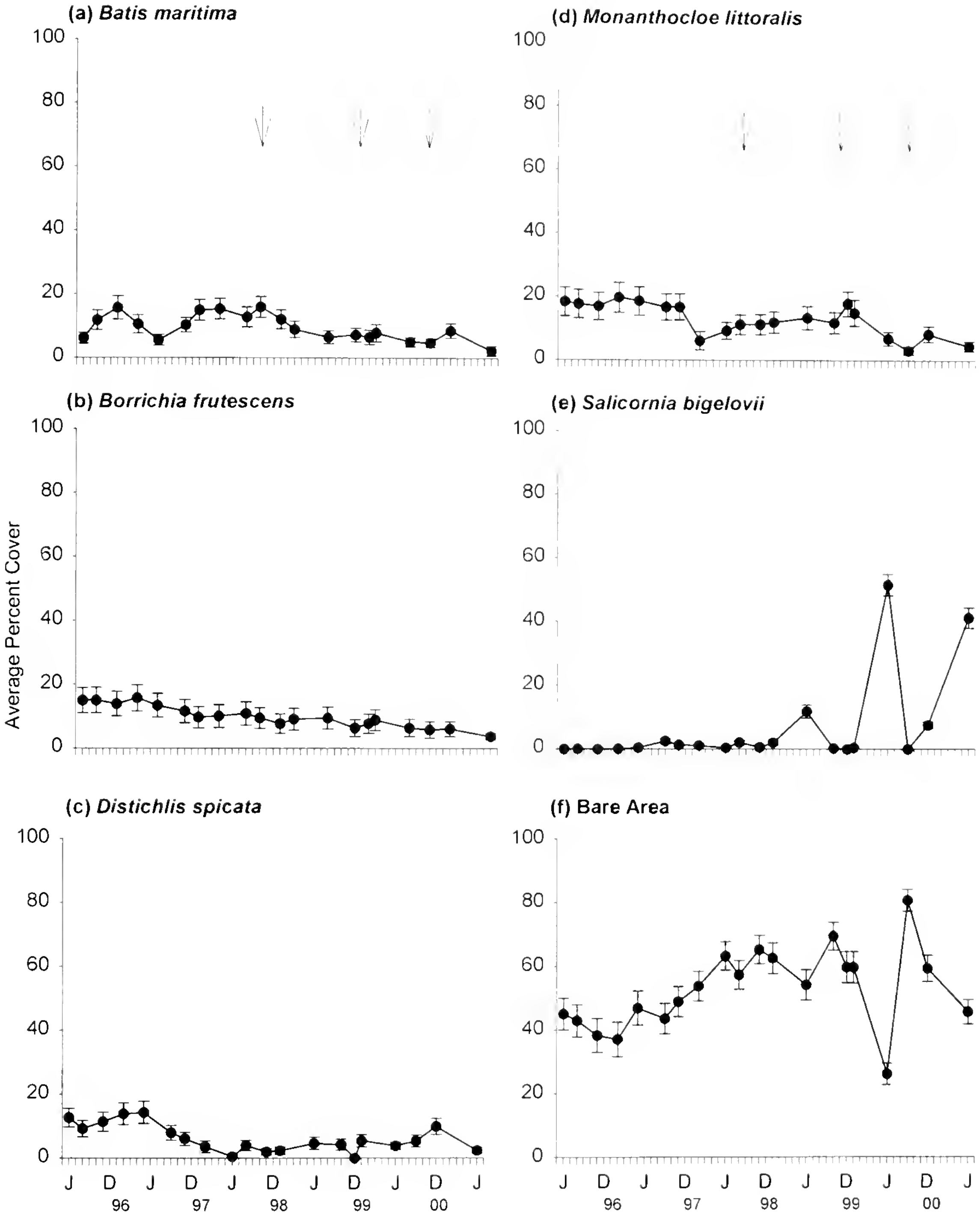


Figure 6-8: Station II average total transect percent cover for the five dominant species and bare area on each sampling date. Arrows indicate the dates of composite hydrographic events that caused measurable changes in the vegetation. Error bars represent ±SE (n=65). J = June and D = December.

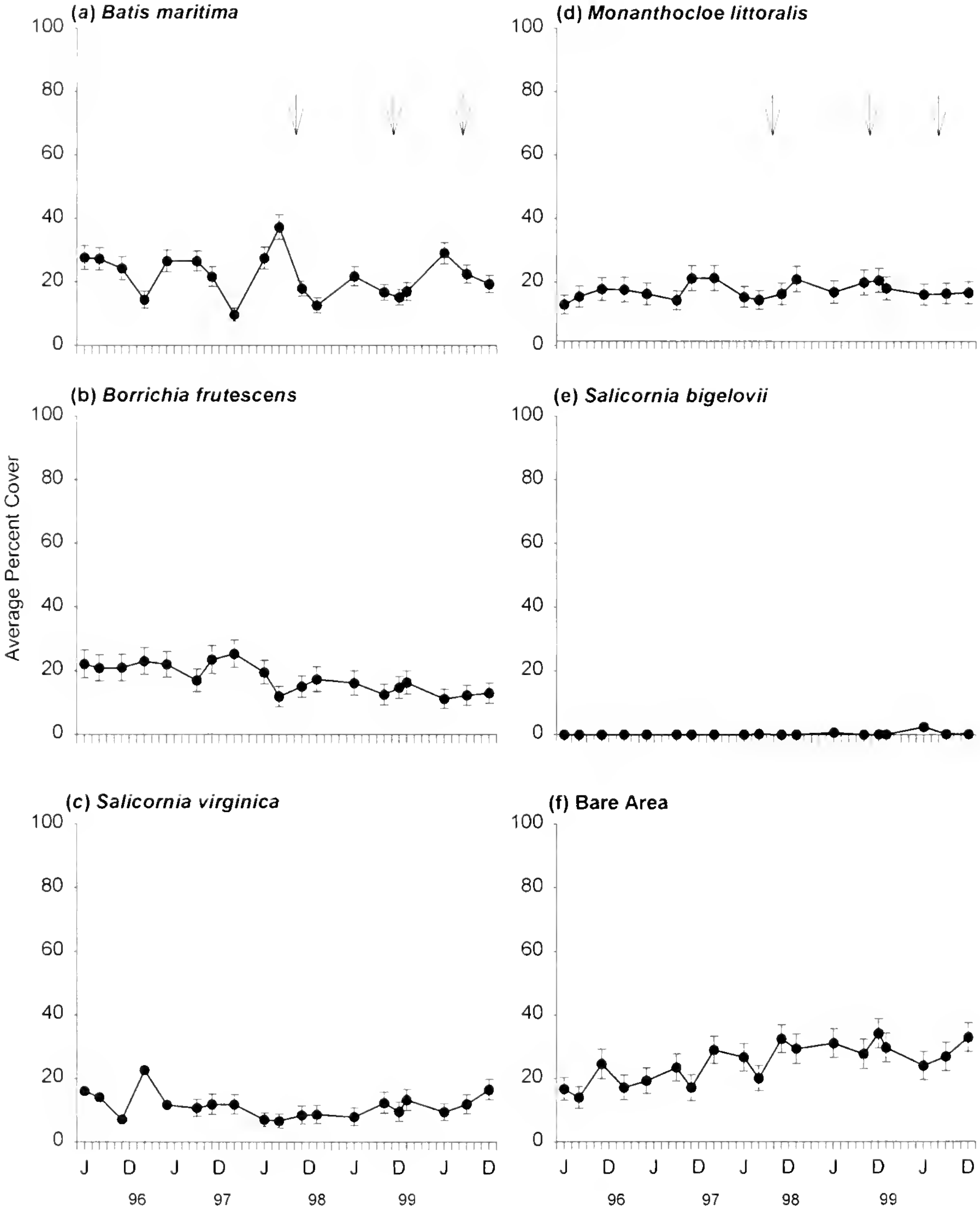


Figure 6-9: Station III average total transect percent cover for the five dominant species and bare area on each sampling date. Arrows indicate the dates of composite hydrographic events that caused measurable changes in the vegetation. Error bars represent ±SE (n=75). J = June and D = December.

Station II

Batis maritima **–** *Batis maritima* percent cover at Station II exhibited a different pattern than the other two stations (Figure 6-8a). Cover of this species peaked at 16% in November 1995 but then decreased by 11% from November 1995 to May 1996. The decrease began following three months (August 1995 through November 1995) during which about 42.8 cm (17 inches) of rain fell. The drop in percent cover was likely the result of direct precipitation, since similar but smaller scale declines were seen at the other two stations during this time. On November 7, 1995, all three transects were flooded with 15.1 to 25.2 cm (6 to 10 inches) of water as a result of about 25.2 cm (10 inches) of rain that fell in one day (October 26, 1995) approximately two weeks earlier.

Batis maritima cover increased 9.5% from May to November 1996. During this time, a positive net flow of over 308 10^3 m^3 (250 acre-ft) passed through Nueces Overflow Channel (Events 11 through 14). However, the diverted water was derived from primarily small exchanges, and the Rincon Overflow Channel was not activated. Furthermore, the majority of the flow was during late October, which was not sufficient to account for significant changes in percent cover. Therefore, the observed increase was more likely correlated to precipitation which occurred during the late summer (*e.g.*, > 22.7 cm (9 inches) fell during August and September). Cover remained near constant for close to a year, then declined by 9.5% from August 1997 to June 1998. The decline occurred immediately following the July 1997 event. During the period between the June and August sampling dates, a total of 9.0 cm (3.55 inches) of rain fell and a positive net flow of 1,902 10^3 m^3 (1,542 acre-ft) passed into Rincon Bayou. During Event 16, Rincon Overflow Channel was activated, and it was suspected that this was also the case with Event 17 (Chapter 3).

Afterwards, cover leveled off and remained relatively stable, until it began to gradually increase in December 1999 near the end of the study period. It should be noted that the major hydrographic events in October 1998 and the precipitation directly falling on the station during the spring and summer of 1999 (> 35 cm, or 14 inches) had no effect on cover. This was most likely a result of cover already being relatively low. An increase in cover began following the September 1999 event, which deposited 15 cm (6 inches) of rain in one day and had a positive net inflow through the Nueces Overflow Channel of 1,012 10^3 m^3 (820 acre-ft) between the September and December sampling dates in 1999. During this period, Event 36 was also suspected to have activated the Rincon Overflow Channel (Chapter 3).

Borrichia frutescens **–** A correlation between *Borrichia frutescens* and *Batis maritima* was not seen at Station II ($r^2 = 0.16$). At Station II, *B. frutescens* cover declined slightly (5%) from the beginning of the study period to the end (Figure 6-8b).

Distichlis spicata **–** At Station II, *Distichlis spicata* cover decreased gradually from May 1996 (14%) to June 1997 (< 1%) and remained relatively low (2 to 5%) for the remainder of the study period (Figure 6-8c). Cover fell to almost 0% following the October 1998 composite hydrographic event but increased in cover from 0% to 10% from December 1998 to December 1999.

Monanthocloe littoralis **–** At Station II, *Monanthocloe littoralis* cover remained relatively constant between June 1995 and November 1996 (about 20%) (Figure 6-8d). Cover declined sharply from November 1996 (17%) to February 1997 (6%). Cover increased (12%) until December 1998 when it dropped continuously to 3% in September 1999. The decrease during the October 1998 event, and the lowest cover recorded (September 1999) and coincided with the flooding of the transect after a tidal surge which occurred due to the passing of Hurricane Bret. This decrease corresponded to decreases seen in *M. littoralis* cover at the Reference Station. Cover then increased by 5% in December 1999, after Event 36, which activated the Rincon Overflow Channel and flooded the transect with fresh water.

Salicornia bigelovii **–** The most significant changes in percent cover were seen in the annual succulent *Salicornia bigelovii*. At Station II, the species was basically non-existent until June 1998, when cover reached near 10% (Figure 6-8e). Cover decreased during the fall months following the plant's annual life cycle (*i.e.*, annual plants complete their life cycle within a year). Cover increased dramatically from < 1% to 52% between January and June 1999. The increase in *S. bigelovii* occurred the summer following the October 1998 composite hydrographic event (*i.e.*, the period between the October 1998 and June 1999 sampling periods), during which a positive net flow of over 4,160 10^3 m^3 (3,372 acre-ft) entered Rincon Bayou. The Rincon Overflow Channel was activated during Event 25, consequently flooding the station. The increase in growth corresponded to a period where 11 out of 14 months received over 5 cm (2 inches) of rain.

The late fall 1998 event significantly lowered open water salinity values at Station II from about 45 ppt (June 1998) to about 11 ppt (December 1998). Open water salinity concentrations were also lowered by precipitation in the fall 1997 (October), which kept early winter salinity values below 15 ppt as well. The only spring without *Salicornia bigelovii* growth was 1997, most likely because a fall event did not occur in 1996 and winter salinity values were relatively high (46 to 58 ppt) compared to the other years.

An increase in cover at Station II during June 1999 coincided with an increase at the Reference Station. However, the increase at Station II was almost twice that of the Reference Station. In June 1998, the percent cover of *S. bigelovii* was almost identical at the reference and Station II (Figures 6-7e and 6-8e). In this instance, late winter salinity concentrations were lowered by rainfall at both stations. Prior to June 1999, winter salinity values at Station II were lowered as a function of freshwater flow through the channels, possibly explaining the almost doubling in *S. bigelovii* cover at Station II compared to the Reference Station that summer and the increase compared to the previous year.

A similar increase in *S. bigelovii* cover was seen in the summer 2000. Cover in June 2000 at Station II was 41%, while cover at the Reference Station was only 12%. Once again, the differences are most likely a result of the hydrographic event that activated the Rincon Overflow Channel in September 1999 (Event 36). The difference in cover between the June 1999 and June 2000 sampling dates at Station II may be indicative of the timing of the flow event. The 1999 event occurred in the late summer, while the 1998 event occurred during the fall and was followed by several months of consistent precipitation.

Bare Area – At Station II, increases (> 2 %) in *Salicornia bigelovii* cover corresponded to decreases in bare area ($r^2 = 0.64$) (Figures 6-8e and 6-8f). During June 1999, *S. bigelovii* cover was about 50% and bare area decreased about 33%, the largest decrease in bare area observed during the study period. Bare area was highest (81%) in September 1999, which was similar to the peak found at the Reference Station (69%).

Station III

***Batis maritima* –** Total transect percent cover of *Batis maritima* exhibited a similar pattern to that seen at the Reference Station (Figure 6-9a). Cover cycled seasonally, and the greatest increase in cover (9.7% to 37%) occurred between February and August 1997. In general, percent cover at Station III varied between 10% and 37% and was greater than the other two stations.

***Borrichia frutescens* –** At Station III, percent total percent cover of *Borrichia frutescens* varied between 10% and 25% (Figure 6-9b). No correlation was seen with *Batis maritima* ($r^2 = 0.05$). Total cover of *B. frutescens* declined gradually from February 1997 (25%) to near 11% in December 1999.

***Salicornia virginica* –** Distichlis spicata was not a dominant species at Station III, so *Salicornia virginica* was analyzed instead because it occurred at Station III (Figure 6-9c). However, this species was rarely found at the other two stations. *S. virginica* cover was greatest in February 1996 (23%) but decreased to 12% in May 1996 and continued to decline to 6.5% in August 1997. The low cover occurred following the July 1997 event. Cover remained relatively low until October 1998, when it began to gradually increase to 16% in December 1999. The increase occurred after the

October 1998 event and continued throughout 1999, which had several months of consistent rainfall.

Monanthocloe littoralis **–** At Station III, *Monanthocloe littoralis* cover remained relatively constant (13% to 21%) over the study period (Figure 6-9d). Cover exhibited only minor decreases in cover in response to the July 1997 event (7% decline) and a 4% decrease after the October 1998 event.

Salicornia bigelovii **–** At Station III, *Salicornia bigelovii* was practically non-existent throughout the study period, with only 1% cover in June 1998 and 3% cover in June 1999 (Figure 6-9e).

Bare Area – Bare area cover at Station III gradually increased 15% from the beginning to the end of the study period, but changes did not appear to be mediated by hydrographic events (Figure 6-9f).

LARGE-SCALE WHOLE TRANSECT ANALYSES: LEAF AREA INDEX

Leaf area index , a non-destructive means of estimating total vegetation foliage density, exhibited considerable temporal and spatial variability within and between sampling transects. Measurements are reported as total transect values. Average LAI values for the transects exhibited seasonal peaks in the summer and declines in the fall and winter (Figure 6-10) and displayed a similar trend at all three stations. However, values at the three stations differed in range and magnitude. At the Reference Station, values range from 0.60 to 1.99 and had an average of 1.42 compared to a range of 0.89 to 1.34 and an average of 1.13 at Station II. Values at Station III were higher than the other two stations, ranging from 1.64 to 2.43, with an average of 2.02. At the three stations, peaks in LAI occurred in September and November 1996, following a two-month period with over 22.5 cm (9 inches) of rain. LAI then declined in February 1997, which was a period with little rainfall. Values increased and peaked in January 1998, another period following a three-month period of over 30 cm (12 inches) rain. The third major peak shared by the three stations was in June 1999, which followed a four-month period with over 30 cm rain. This spring also followed the October 1998 event. The greatest decline in LAI occurred in September 1999 and coincided with a large increase in bare area. The decline occurred several weeks after a tidal surge due to Hurricane Bret flooded the transects and drowned much of the vegetation. In general, large decreases in LAI coincided with increases in bare area.

SMALL-SCALE ANALYSES

Percent Cover

Changes in the percent cover of individual species were evident during sampling periods before and after composite hydrographic events (Table 6-5).

Spring Cover – Analysis of GIS maps created from springtime percent cover at the Reference Station indicated that bare area cover appeared to be greatest following fall periods with little precipitation independent of amount of spring precipitation (Figures 6-11b and 6-11e). *Salicornia bigelovii* increases occurred when fall and spring precipitation were high (Figure 6-11d), and *Monanthocloe littoralis* cover and bare area decreased with increases in *S. bigelovii.* The maps indicate that *S. bigelovii* invaded previously bare areas.

At Station II, maps indicate that bare area was greatest following fall periods with no flow events and/or little precipitation. In June 1997 (Figure 6-12b), bare area was greatest compared to other springs. Prior to this spring, there was little fall rain and no flow. May 1996 and June 1998, springs following falls with heavy rain but no flow event, had less bare area than June 1997 but more than either June 1999 or June 2000. In the falls prior to June 1999 and 2000, there were freshwater diversions and heavy precipitation. *Salicornia bigelovii* cover was greatest in June 1999, having greater than 50% cover over 59% of the transect (Table 6-5). Cover was also high in June 2000, with 49% of the transect having greater than 50% cover. The maps show that *S. bigelovii* invasion occurred in previously bare areas. The maps further indicate that *Batis maritima* cover decreased after flooding events (Figures 6-12c and 6-12d).

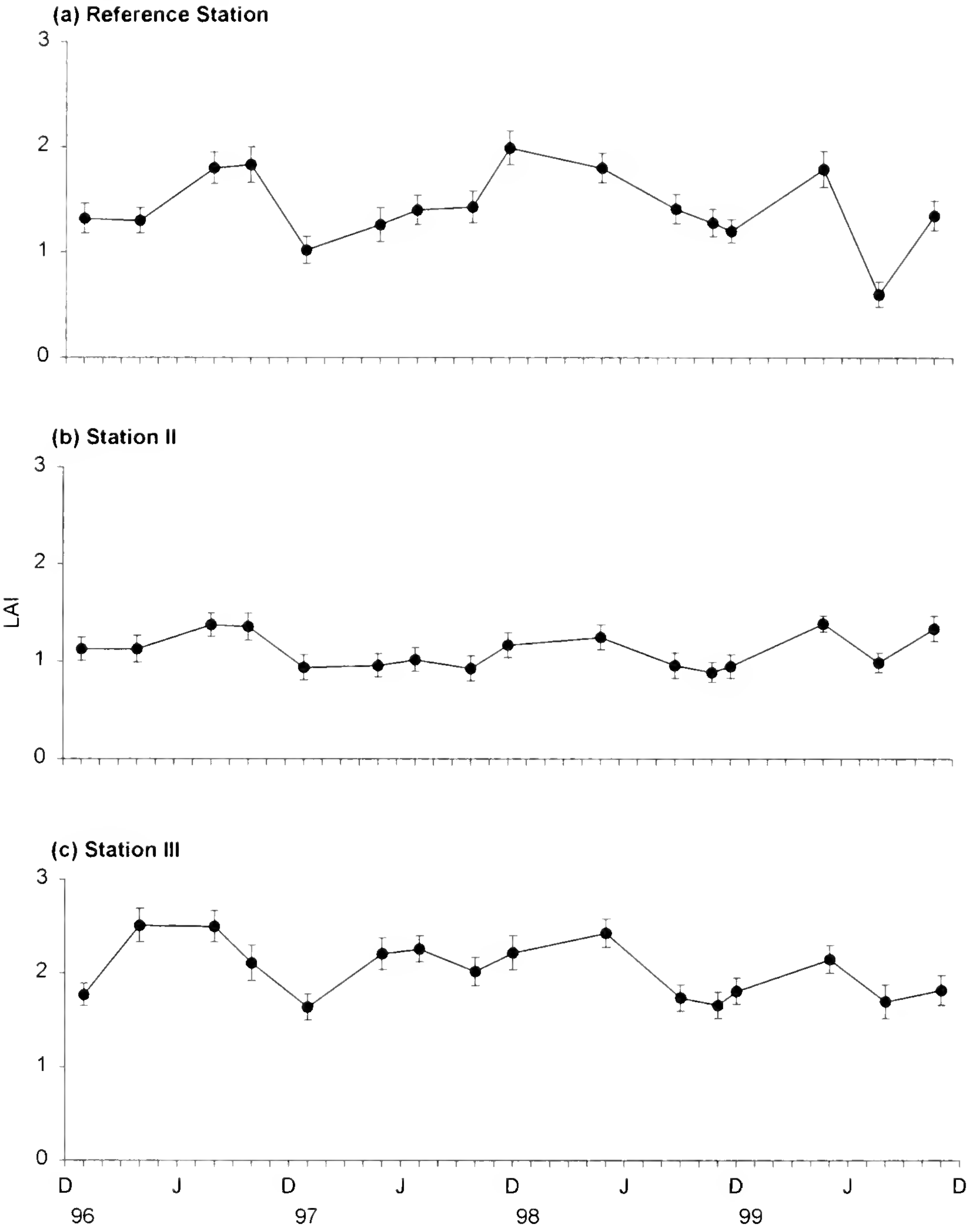


Figure 6-10: Total transect leaf area index (LAI) for each sampling date at each transect. Error bars represent ± SE. J = June and D = December.

Table 6-5: Summary of species percent cover results from GIS analyses. Numerical values represent the percent of transect covered by greater than 50% of a particular species or bare area. Results do not always total 100% because areas not covered by at least 50% of any particular species were not included. Only results from sampling dates prior to or following composite hydrographic events causing measurable changes in the vegetation are included. May 1996 data was included for comparison between the other springtime cover. Hyphens (-) indicate data not taken.

		Percent Transect Covered by > 50 Percent Cover												
		5/96	**6/97**	**8/97**	**11/97**	**1/98**	**6/98**	**10/98**	**12/98**	**1/99**	**6/99**	**9/99**	**12/99**	**6/00**
Reference Station	*Batis maritima*	0.6	1.7	12.1	1.5	1.2	0.7	0.6	0.6	0.5	6.4	0.0	0.0	5.6
	Borrichia frutescens	2.3	2.3	0.5	2.1	2.0	2.4	0.8	1.2	1.8	0.2	0.5	1.4	1.1
	Monanthocloe littoralis	49.4	35.9	34.2	31.9	39.4	41.2	40.8	40.2	43.8	21.3	1.5	33.6	24.6
	Salicornia bigelovii	3.5	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	27.9	0.0	0.0	1.9
	Bare Area	18.4	38.7	33.2	43.6	36.3	31.6	41.9	39.2	44.5	8.0	86.0	45.1	37.7
Station II	*Batis maritima*	1.1	4.7	8.1	4.7	2.6	0.5	1.1	1.3	2.6	0.0	0.1	1.8	0.0
	Borrichia frutescens	4.7	4.3	3.3	2.8	3.5	4.1	1.0	1.5	2.5	1.4	1.2	0.7	0.1
	Monanthocloe littoralis	21.1	5.8	12.6	5.7	9.0	12.5	8.0	14.7	16.2	0.7	0.0	1.3	3.5
	Salicornia bigelovii	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	58.7	0.0	0.0	48.6
	Bare Area	50.9	75.4	64.4	73.3	66.8	62.1	86.3	71.2	67.0	14.1	96.6	85.4	46.2
Station III	*Batis maritima*	12.6	13.7	35.5	2.0	1.8	6.7	3.0	2.9	5.4	12.6	8.1	4.2	-
	Borrichia frutescens	14.2	10.0	3.1	4.8	6.2	6.2	4.3	5.3	5.9	4.2	4.6	4.8	-
	Monanthocloe littoralis	10.9	7.2	7.5	9.0	19.3	10.4	16.3	16.2	12.7	13.1	11.5	9.7	-
	Salicornia virginica	8.6	6.3	8.2	11.2	11.2	11.2	14.0	11.2	18.8	10.8	11.6	11.8	-
	Salicornia bigelovii	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-
	Bare Area	20.9	29.9	20.3	29.4	11.2	33.6	30.9	32.9	29.7	27.1	29.4	33.3	-

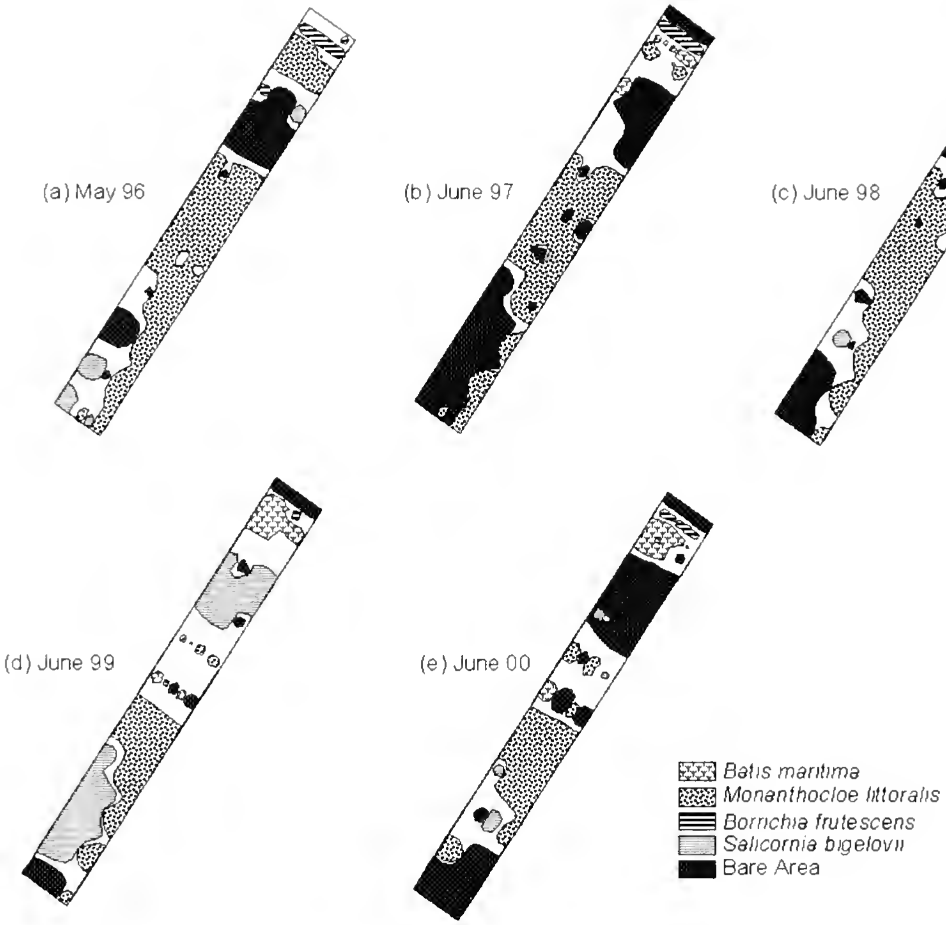


Figure 6-11: Reference Station percent cover maps for the five springtime sampling periods. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species. Springtime cover differed dramatically over the years. May 1996 represents cover following a fall with heavy precipitation (~36 cm) but a spring with little precipitation (~5 cm); June 1997 represents fall with little precipitation (~9 cm) but a spring with heavy precipitation (~43 cm); June 1998 represents fall with heavy precipitation (~33 cm) but a spring with little precipitation (~5 cm); June 1999 represents fall with heavy precipitation (~36 cm) and a spring with heavy precipitation (~18 cm); and June 2000 represents fall with little precipitation (~5 cm) and a spring with little precipitation (~11 cm). Reference Station maps are shown for comparison because this site was not affected by flow diverted by the demonstration project

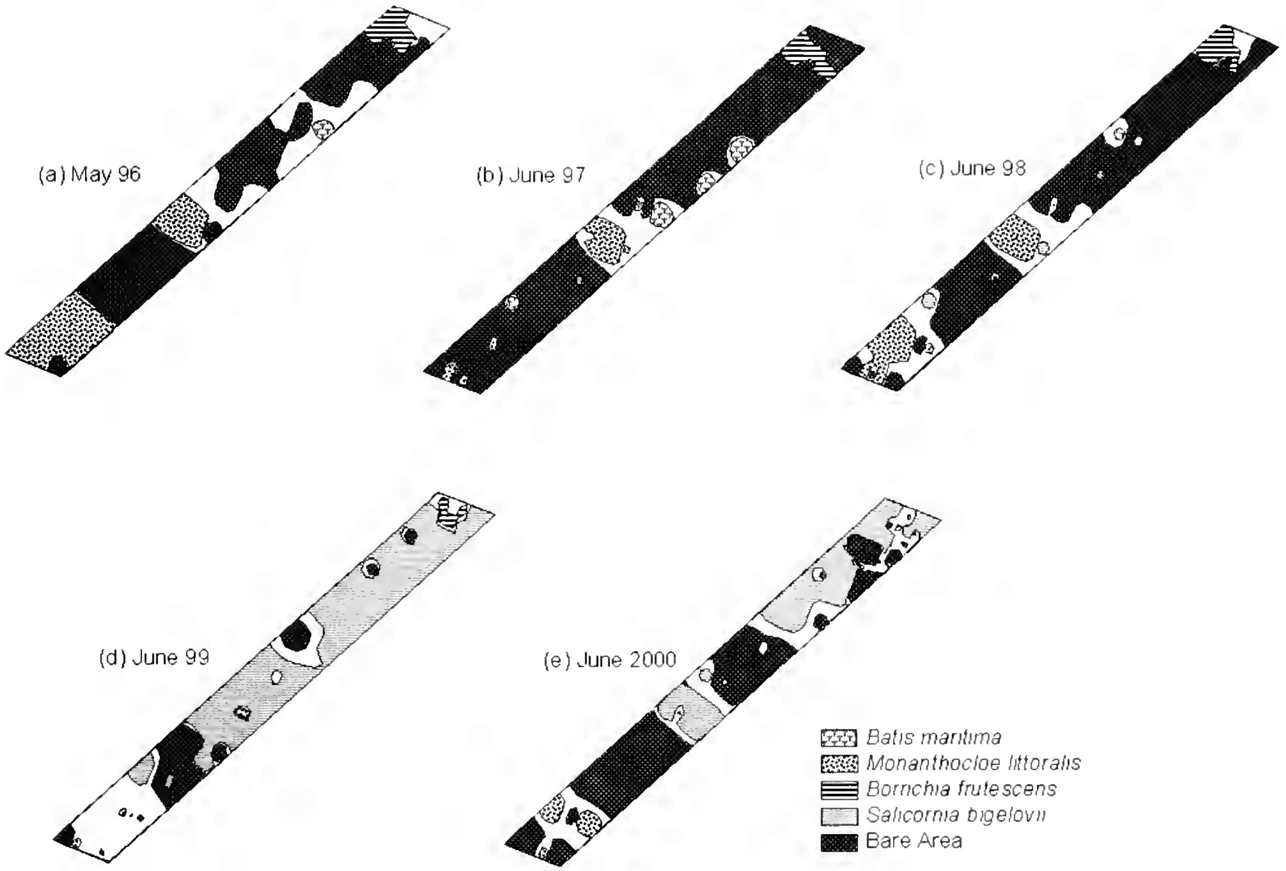


Figure 6-12: Station II percent cover maps for the five springtime sampling periods. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species. Springtime cover differed dramatically over the years. May 1996 represents cover following a fall with heavy precipitation and no flow, June 1997 represents fall with little rain and no flow, June 1998 represents mid-summer flow event and fall with heavy precipitation, June 1999 represents fall with flow event and heavy rains and June 2000 represents late summer flow event and early fall heavy precipitation. Note decreases in bare area and increase in *Salicomia bigelovii* cover in (d) and (e) following late summer and fall flow events.

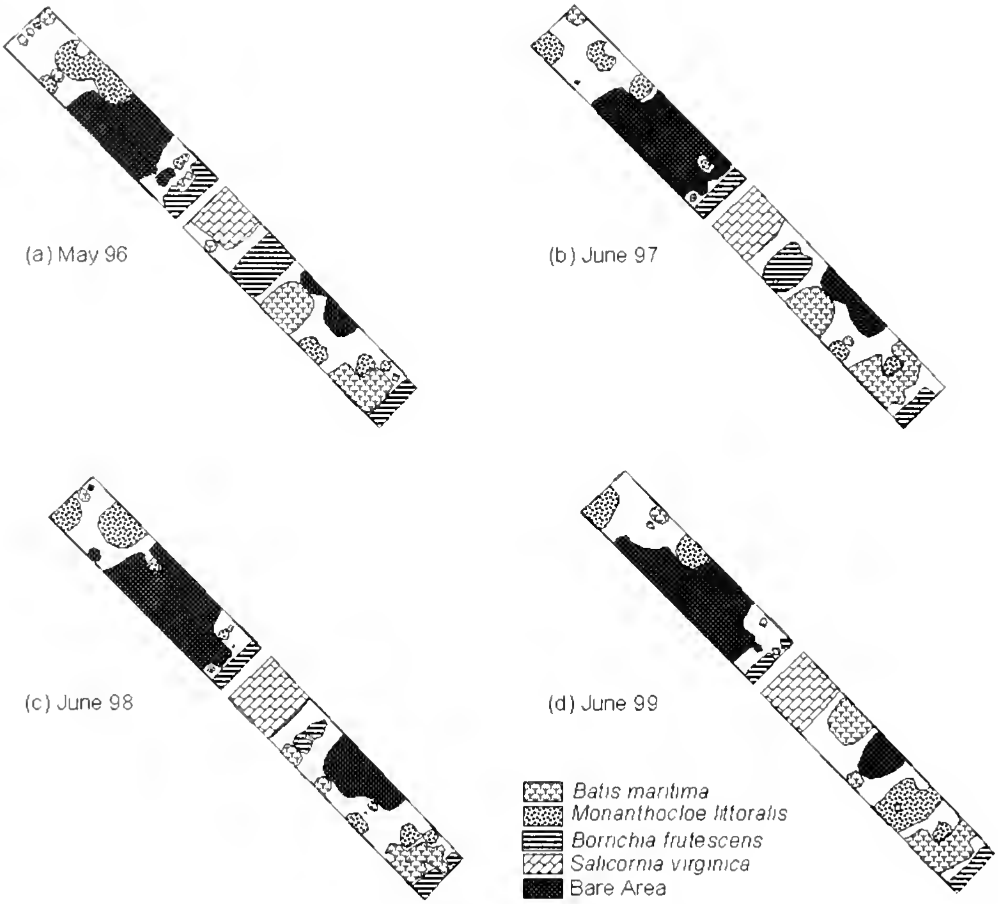


Figure 6-13: Station III percent cover maps for the five springtime sampling periods. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species. Springtime cover differed dramatically over the years. May 1996 represents cover following a fall with heavy precipitation and no flow, June 1997 represents fall with little rain and no flow, June 1998 represents mid-summer flow event and fall with heavy precipitation and June 1999 represents fall with flow event and heavy rains. Note that *Salicornia bigelovii* cover is non-existent in the transect regardless of flow events.

cover maps indicates that both *Batis maritima* and *Borrichia frutescens* decreased in cover in June 1998 and 1999 compared to other springs, while *Monanthocloe littoralis*, *Salicornia virginica* and bare area had increased. The most evident vegetation changes appeared have occurred in the front section of the transect, which was lower and subjected to more influence from freshwater diversions. The maps also indicate that *M. littoralis* was commonly found in the back section of the transect, an area that was rarely flooded. Furthermore, the greatest bare area was found in the back part of the transect, an area that remained relatively constant throughout the spring periods.

July 1997 Composite Event – The July 1997 event resulted in few changes at the Reference Station (Figures 6-14a and 6-14d). Only 8.5 cm (3.4 inches) of rain fell in the study area between the June and August sampling period. The most obvious change was a temporary increase in *Batis maritima* cover from 1.7% in June to 12% in August (Table 6-5). The increase in *B. maritima* corresponded to a 4-fold decrease in *Borrichia frutescens*. However, *B. maritima* cover quickly dropped back to 1.5% in November 1997, and *B. frutescens* increased. Bare area also decreased slightly by 5% between June and August but increased quickly afterwards.

At Station II, the vegetation was inundated by water through the Rincon Overflow Channel and precipitation during the event. Following the event, *Batis maritima* cover increased 3.4% but decreased to its pre-event cover in November 1997 (Figures 6-15a through 6-15c) (Table 6-5). *Monanthocloe littoralis* cover increased by ~7% in August but returned to its pre-flood values in November as well. The increase in these species directly following the event corresponded to an 11% decrease in bare area. Bare area also increased quickly thereafter.

At Station III, *Batis maritima* cover increased 22% in August following the event but dropped dramatically by 34% from August to November (Table 6-5). The increase in *B. maritima* occurred in the front section of the transect, and corresponded to a decrease in *Borrichia frutescens* and a reduction in bare area to almost 0% in that section of the transect (Figures 6-16a and 6-16b). *B. maritima* cover retreated in November, and the *B. frutescens* zone near the back of the front section of the transect began to recover (Figure 6-16c).

October 1998 Composite Event – At the Reference Station, few changes were seen in the transect during the two sampling periods following the event; however, major changes were seen the following spring (Figures 6-17a through 6-17d). GIS analyses indicate that in June 1999, *Salicornia bigelovii* expansion into previously bare areas had occurred. The increase in *S. bigelovii* also corresponded with a decrease in *Monanthocloe littoralis* and an increase in *Batis maritima* cover.

During the October 1998 event, diversions through the Rincon Overflow Channel were significant enough to wash out the road crossing at the north end of the channel, inundating Station II with freshwater. In the sampling periods following the October 1998 event, several significant changes in vegetation percent cover occurred (Figures 6-18a through 6-18d). Bare area decreased gradually from 86% in October 1998 to 14% in June 1999. The decrease in bare area began as an increase in *Monanthocloe littoralis* cover. However, by the following spring, *Salicornia bigelovii* had occupied almost all previously bare area and several parts of the transect previously occupied by *M. littoralis*.

Few changes were seen in the transect at Station III following the October 1998 event (Figure 6-19).

September 1999 Composite Event – At the Reference Station, a major increase in bare area occurred following flooding of the transect due to the tidal surge of Hurricane Bret in August 1999 (Figures 6-19a and 6-19b). Afterwards, 42.5 cm (17 inches) of rain fell between September and December, leading to noticeable vegetation increases and bare area decreases. *Monanthocloe littoralis* cover quickly filled in almost half of the bare area by December 1999 (Figure 6-19c). Bare area continued to decrease in June 2000 and both *Batis maritima* and *Salicornia bigelovii* cover increased (Figure 6-19d).

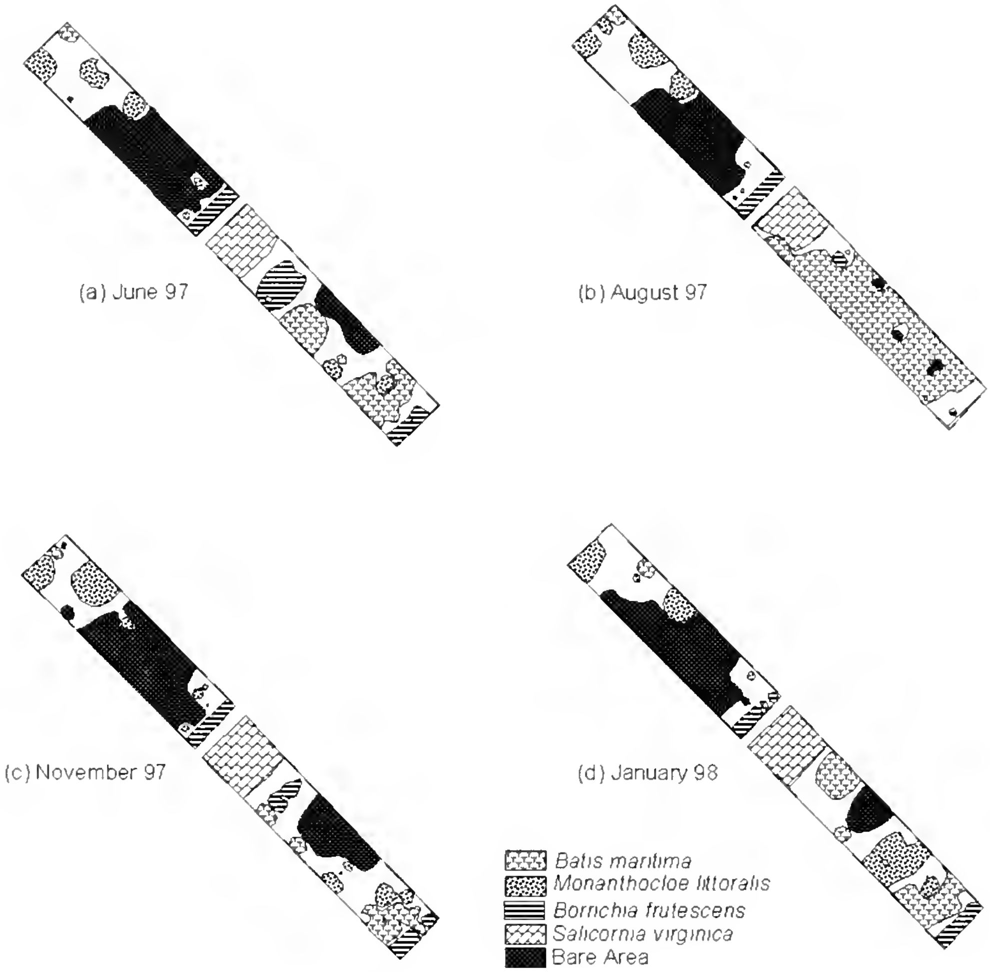


Figure 6-14: Reference Station percent cover maps on the sampling date prior and three sampling dates following the July 1997 composite hydrographic event. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species. Reference Station maps are shown for comparison because this site was not affected by flow diverted by the demonstration project.

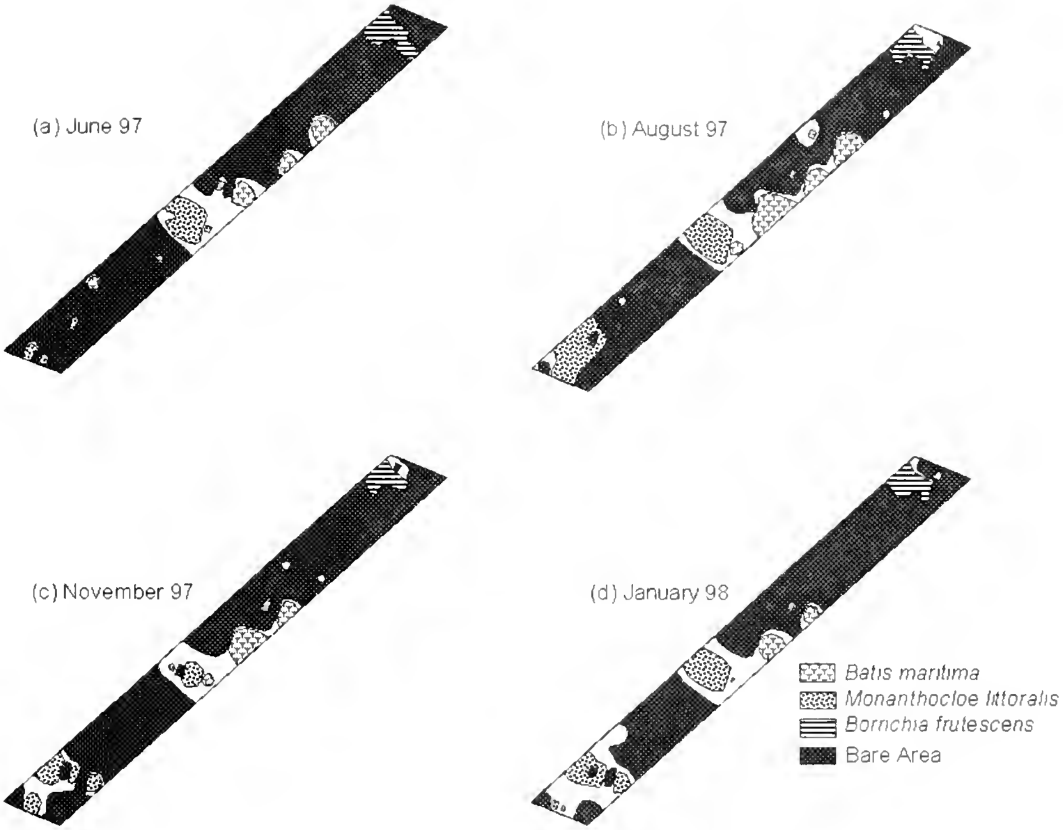


Figure 6-15: Station II percent cover maps on the sampling date prior and three sampling dates following the July 1997 composite hydrographic event. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species. During the event, the Rincon Overflow Channel was activated and Station II was inundated with freshwater. Note increases in *Batis maritima* and *Monanthocloe littoralis* and decreases in bare area in August 1997 following the event.

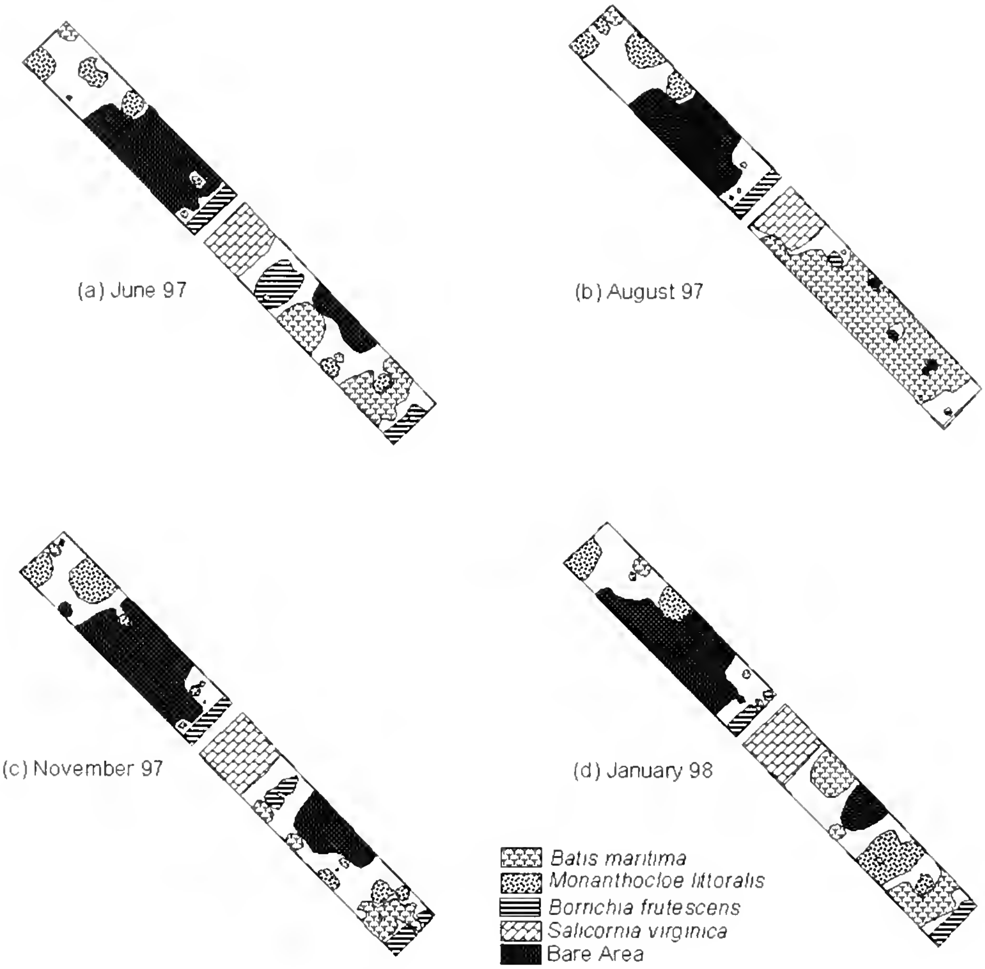


Figure 6-16: Station III percent cover maps on the sampling date prior and three sampling dates following the July 1997 composite hydrographic event. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species. Note increases in *Batis maritima* in August 1997 following the event. Increases in *B. maritima* corresponded to decreases in *Borrichia frutescens* and decreases in bare area.

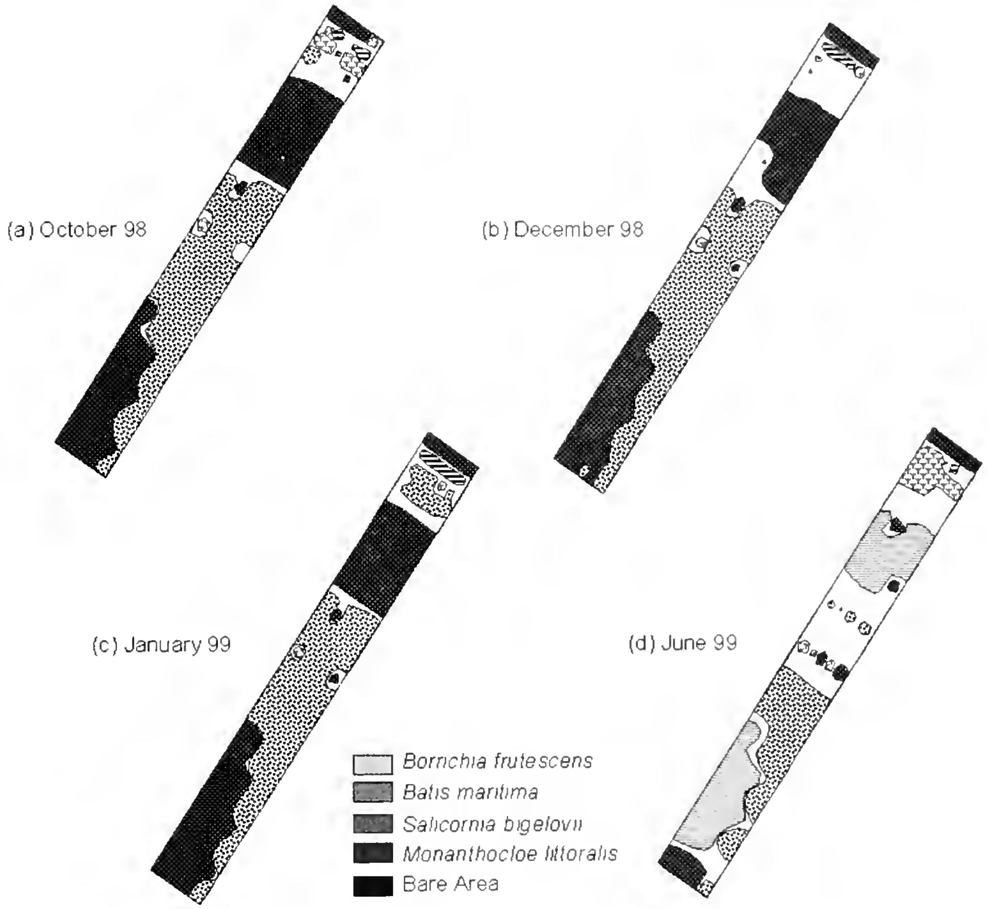


Figure 6-17: Reference Station percent cover maps on the sampling date prior and three sampling dates following the October 1998 composite hydrographic event. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species. Reference Station maps are shown for comparison because this site was not affected by flow diverted by the demonstration project.

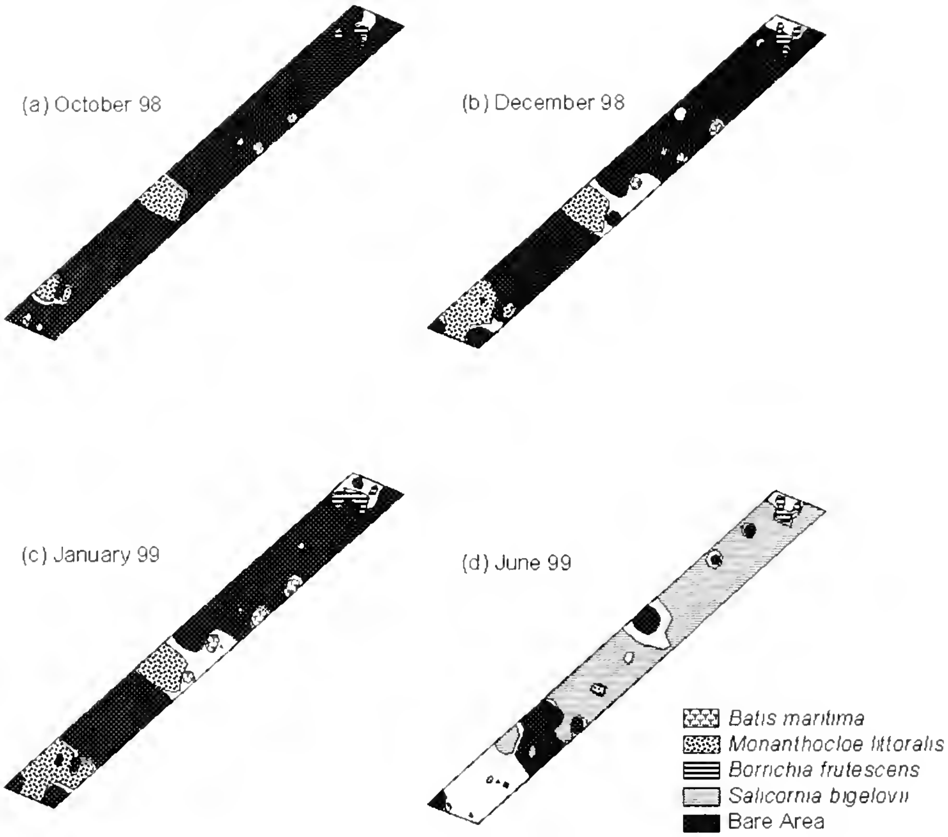


Figure 6-18: Station II percent cover maps on the sampling date prior and three sampling dates following the October 1998 composite hydrographic event. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species. During the event, the Rincon Overflow Channel was activated and Station II was inundated with freshwater. Note the increase in *Salicomia bigelovii* cover and decreases in bare area in the spring (June 1999) following the event.

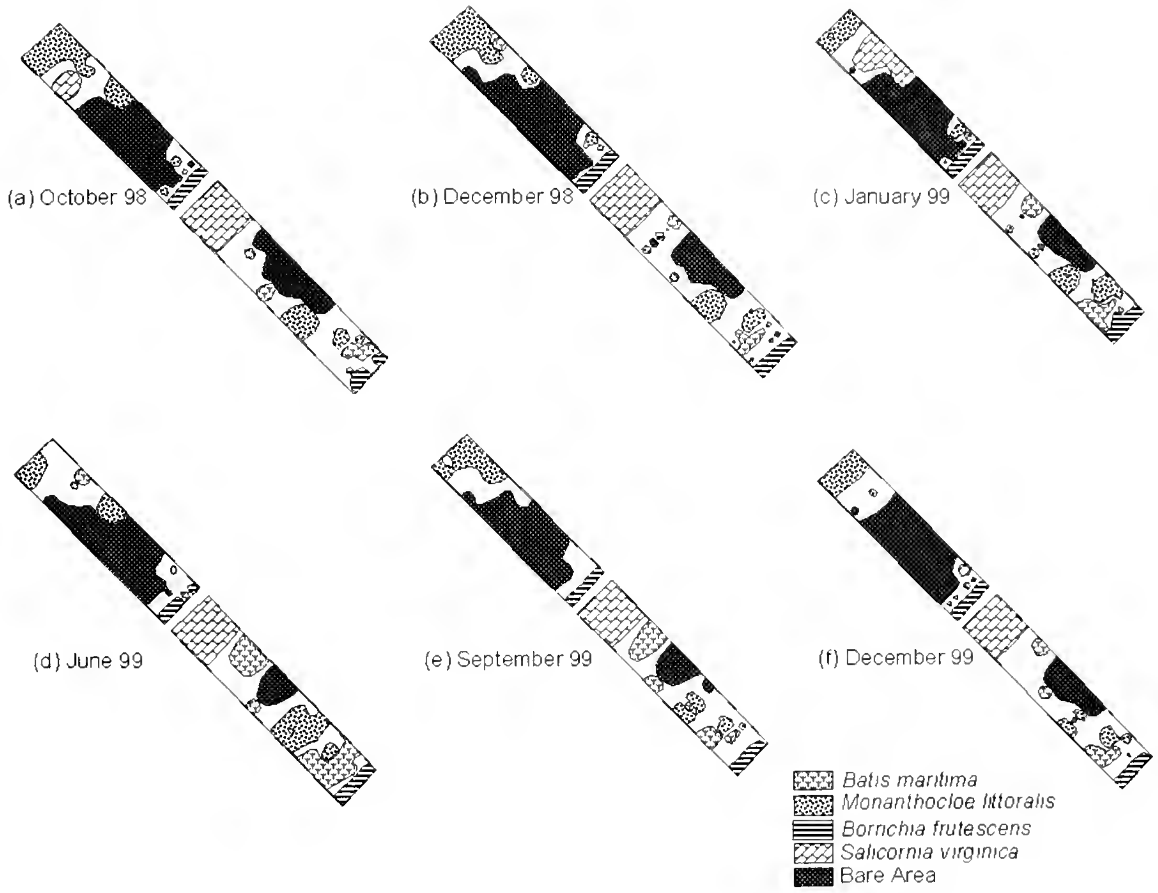


Figure 6-19: Station III percent cover maps on the sampling date prior and three sampling dates following the October 1998 composite hydrographic event. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species. Little change was observed at Station III during this event.

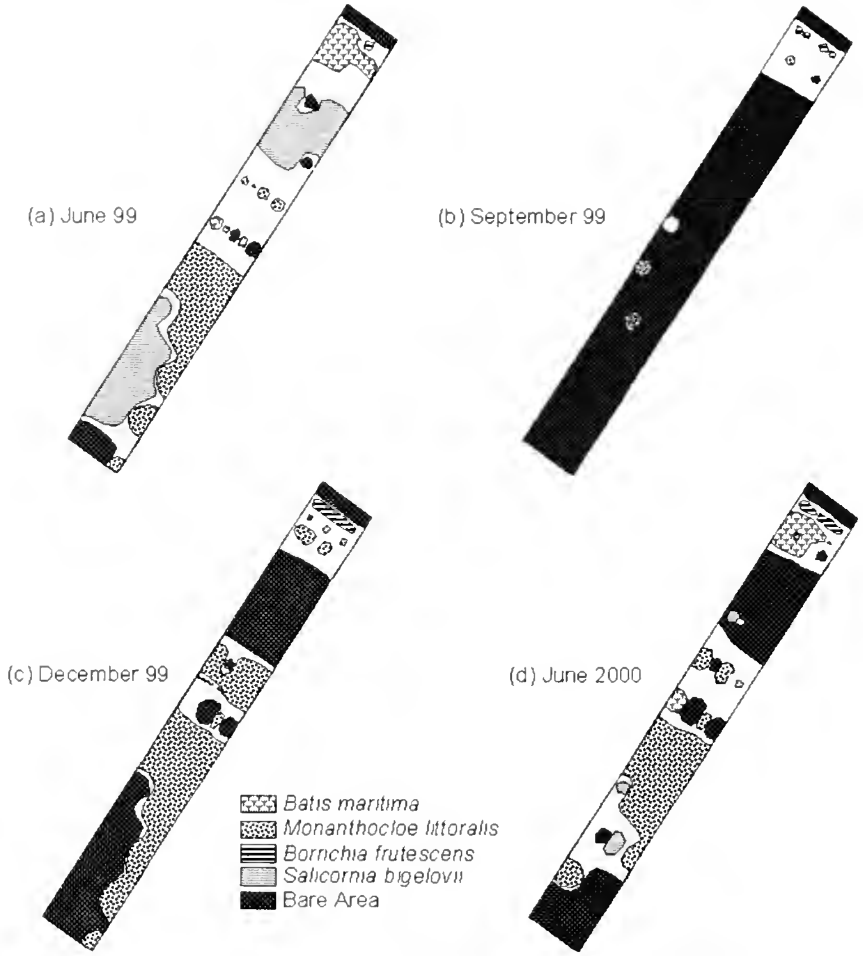


Figure 6-20: Reference Station percent cover maps on the sampling date prior and three sampling dates following the September 1999 composite hydrographic event. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species. Reference Station maps are shown for comparison because this site was not affected by flow diverted by the demonstration project. Note the increase in bare area in September 1999 following the tidal surge of Hurricane Bret.

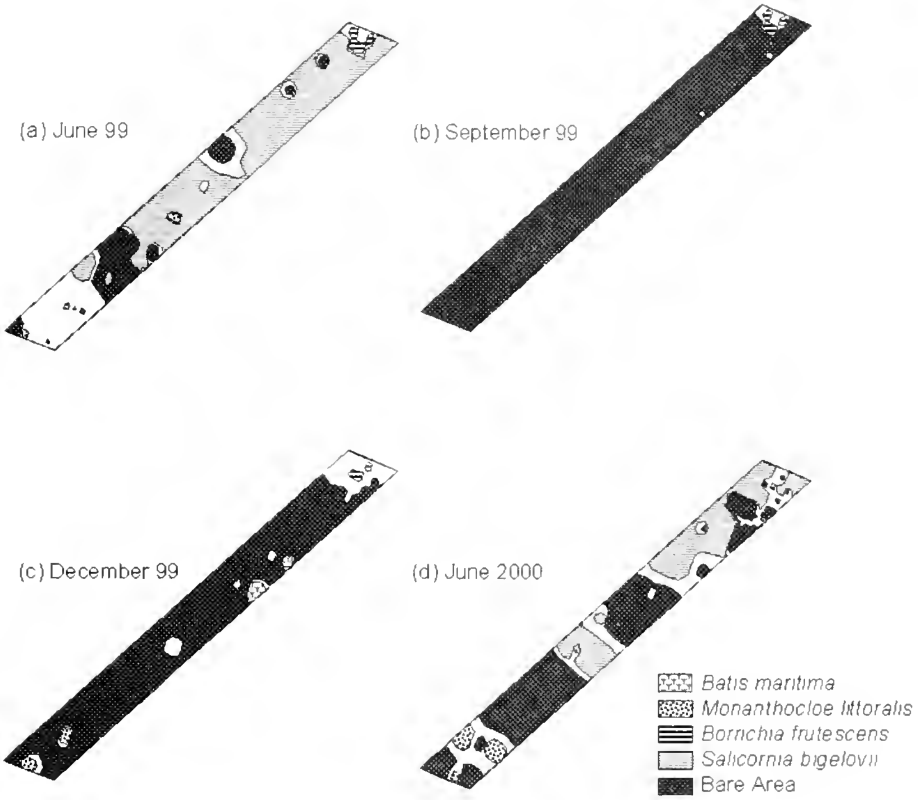


Figure 6-21: Station II percent cover maps on the sampling date prior and three sampling dates following the September 1999 composite hydrographic event. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species. During the event, the Rincon Overflow Channel was activated and Station II was inundated with freshwater. Note the increase in bare area in September 1999 following the tidal surge of Hurricane Bret. This was not a freshwater inundation effect.

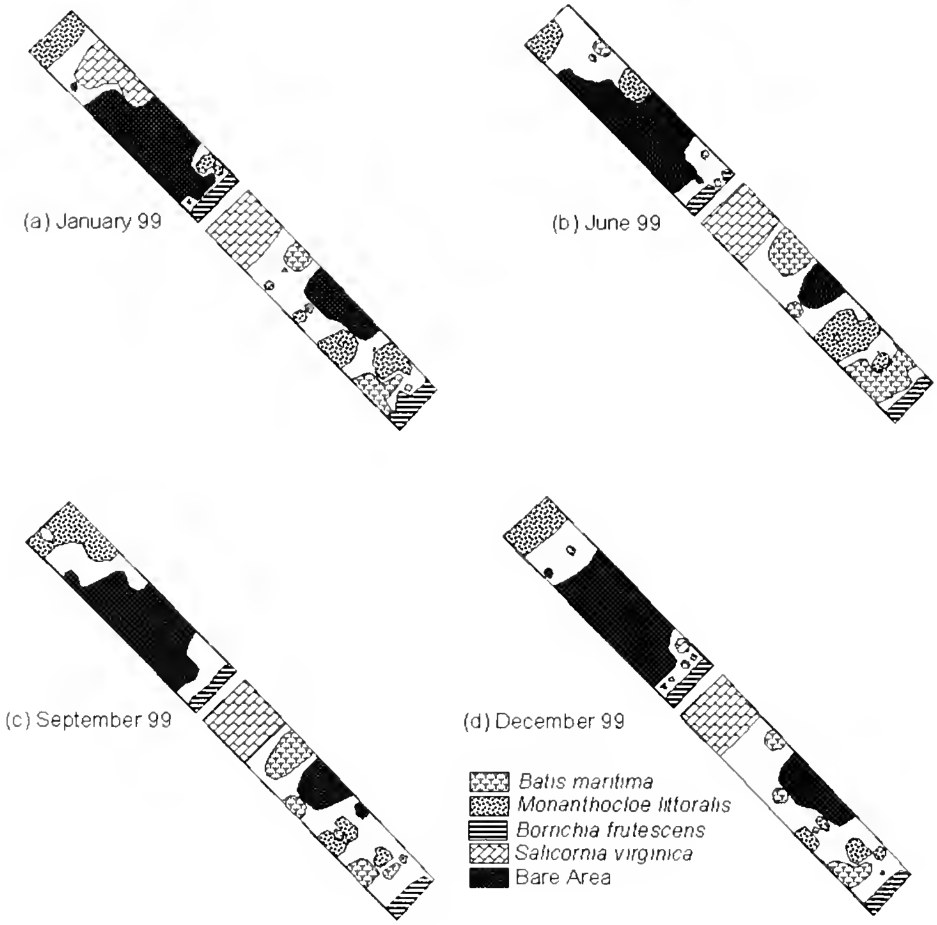


Figure 6-22: Station III percent cover maps on the two sampling dates prior and two sampling dates following the September 1999 composite hydrographic event. Shaded areas for each species represent parts of the transect covered by at least 50% of that species. Areas with no shading (white) were not covered by greater than 50% of any one species.

The tidal surge in August produced similar decreases in vegetation cover at Station II (Figures 6-20a and 6-20b). The transect was then flooded by fresh water through the Rincon Overflow Channel several days later. Bare area had decreased by ~11% in December 1999, following the event. By June 2000, bare area had decreased by ~40% and *Salicornia bigelovii* had invaded ~50% of the transect in areas that were previously bare.

In January 1999, the most significant change was the appearance of *Salicornia virginica* in the back section of the transect (Figure 6-21c). However, the cover had decreased to levels below the 50% mapping level in June 1999. An increase in *Batis maritima* also occurred in the spring following the event (Figure 6-21d). No obvious vegetation changes occurred in the transect at Station III following the tidal surge or the freshwater flow through the channels during the September 1999 event.

Leaf Area Index

Vegetation maps showing the LAI distribution within and between the transects indicate that overall foliage density varied considerably. At the Reference Station, LAI values were highest in January and June 1998 and June and December 1999 (Table 6-6). The high LAI values appear to coincide with high *Monanthocloe littoralis* cover (Figures 6-14d and 6-23e). *M. littoralis* also appears to be responsible for high LAI values in June and October 1998 and December 1999. In June 1999, high LAI values corresponded to high *Batis maritima* cover in addition to *Monanthocloe* cover.

At Station II, LAI values were consistently lower than the other stations (Table 6-6). However, increases in values were seen in August 1997, following the July 1997 event. The increased values occurred in the same area of the transect as the increased *Batis maritima* growth (Figures 6-15b and 6-24c). High LAI values in June 1998 coincide with *Monanthocloe littoralis* and *Borrichia frutescens* cover (Figures 6-12c and 6-24f). In June 1999, the greatest LAI values occurred where *Salicornia bigelovii* cover was high (Figures 6-12d and 6-24j). Low LAI values correspond to high bare areas.

LAI values at Station III were typically higher than the other stations (Table 6-6). The highest values were in the spring (Figure 6-25) and were lowest in areas with little to no vegetation.

BIOMASS

Batis Maritima

Batis maritima biomass showed no obvious seasonal trends or event-mediated responses (Table 6-7). Biomass at all three stations ranged between 643 and 3,878 g/m^2 Lowest values occurred at the Reference Station in May 1996 (1,016 g/m^2) and February 1997 (1,201 g/m^2). The lowest value recorded at Station II was also in May 1996 (643 g/m^2). Low values occurred on the same dates at Station III as well (1,180 and 805 g/m^2, respectively). Simultaneous occurrence of the low values between stations does not appear related to hydrographic conditions. At the Reference Station, biomass values peak in June 1997 (3,208 g/m^2), and gradually declined by more than half to 1,379 g/m^2 in June 1999. *B. maritima* biomass did not exhibit the same trend at the other two stations.

Borrichia Frutescens

Borrichia frutescens has the greatest range of biomass values and the greatest total biomass of the four species sampled (Table 6-7). Values between the stations were within the range of 1,948 to 10,412 g/m^2. At all three stations, the highest values were seen at the beginning of the study period. At the Reference Station and Station II, high values of 8,053 and 8,575 g/m^2, respectively, were measured on May 1996. At Station III, the highest values measured were in February 1996 (10,412 g/m^2) and 1997 (9,848 g/m^2). Biomass gradually decreased over the study period for all three stations.

Table 6-6: Summary of LAI results from small scale GIS analyses. Values represent the percent of the transect covered by each LAI range. Only results from sampling dates prior or following composite hydrographic events causing measurable vegetation changes are included. May 96 data were included for comparison with other springtime values

LAI Range	Leaf Area Index Distribution (%)											
	5/96	**6/97**	**8/97**	**11/97**	**1/98**	**6/98**	**10/98**	**12/98**	**1/99**	**6/99**	**9/99**	**12/99**
Reference Station												
0-1	47.1	40.4	39.8	38.9	2.0	3.1	40.3	44.5	29.6	1.7	87.0	32.8
1-2	39.2	34.1	46.0	49.6	77.1	78.4	45.4	47.7	67.9	80.0	12.7	55.6
2-3	11.8	23.6	13.1	10.6	32.6	15.3	14.3	7.3	2.5	11.3	0.3	11.1
3-4	1.5	1.8	1.0	0.7	6.4	2.7	0	0.5	0	4.1	0	0.6
4-5	0.5	0.1	0.1	0.1	0	0.6	0	0	0	2.9	0	0
5-6	0	0	0	0	0	0	0	0	0	0	0	0
6-7	0	0	0	0	0	0	0	0	0	0	0	0
Station II												
0-1	46.0	58.9	55.2	59.9	52.9	45.4	50.5	81.5	72.0	18.5	91.3	28.5
1-2	41.1	37.0	39.5	38.2	39.3	46.0	45.9	17.2	26.9	75.5	8.7	61.9
2-3	11.6	4.1	5.3	1.6	7.6	7.6	3.7	1.3	0.9	6.0	0	8.5
3-4	1.4	0	0	0.4	1.0	1.0	0	0	0.2	0	0	1.1
4-5	0	0	0	0	0	0	0	0	0	0	0	0
5-6	0	0	0	0	0	0	0	0	0	0	0	0
6-7	0	0	0	0	0	0	0	0	0	0	0	0
Station III												
0-1	9.0	16.0	15.0	20.1	18.1	16.9	27.4	26.6	25.7	21.6	26.4	26.9
1-2	19.7	28.2	21.7	28.1	29.3	15.1	37.4	51.8	30.9	22.8	42.0	32.6
2-3	38.1	36.8	45.6	37.7	28.5	45.6	29.3	18.3	37.7	34.1	24.1	25.9
3-4	25.2	17.3	16.7	13.9	18.8	21.4	5.6	3.2	5.3	19.8	7.0	12.0
4-5	6.0	1.7	1.1	0.2	4.6	0.7	0.4	0.1	0.4	1.6	0.3	2.5
5-6	1.4	0	0	0	0.7	0.2	0	0	0	0	0.1	0.1
6-7	0.5	0	0	0	0	0	0	0	0	0	0	0

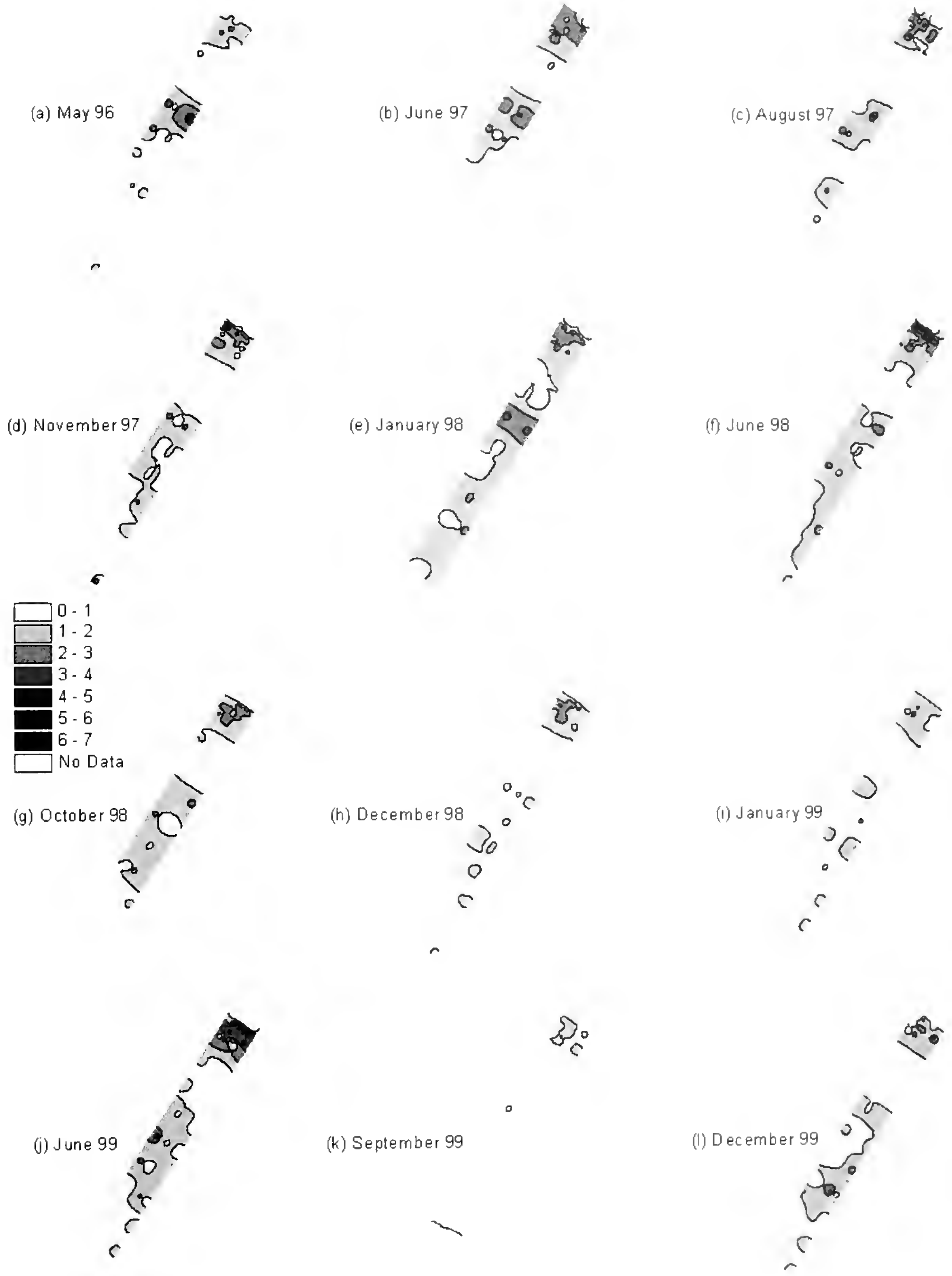


Figure 6-23: Reference Station leaf area index (LAI) from GIS analyses. Results from sampling dates prior to and following the three composite hydrographic events that caused measurable changes in the vegetation are shown. May 1996 is shown for comparison with other springtime sampling dates. Reference Station maps are shown for comparison, because this site was not affected by flow diverted by the demonstration project.

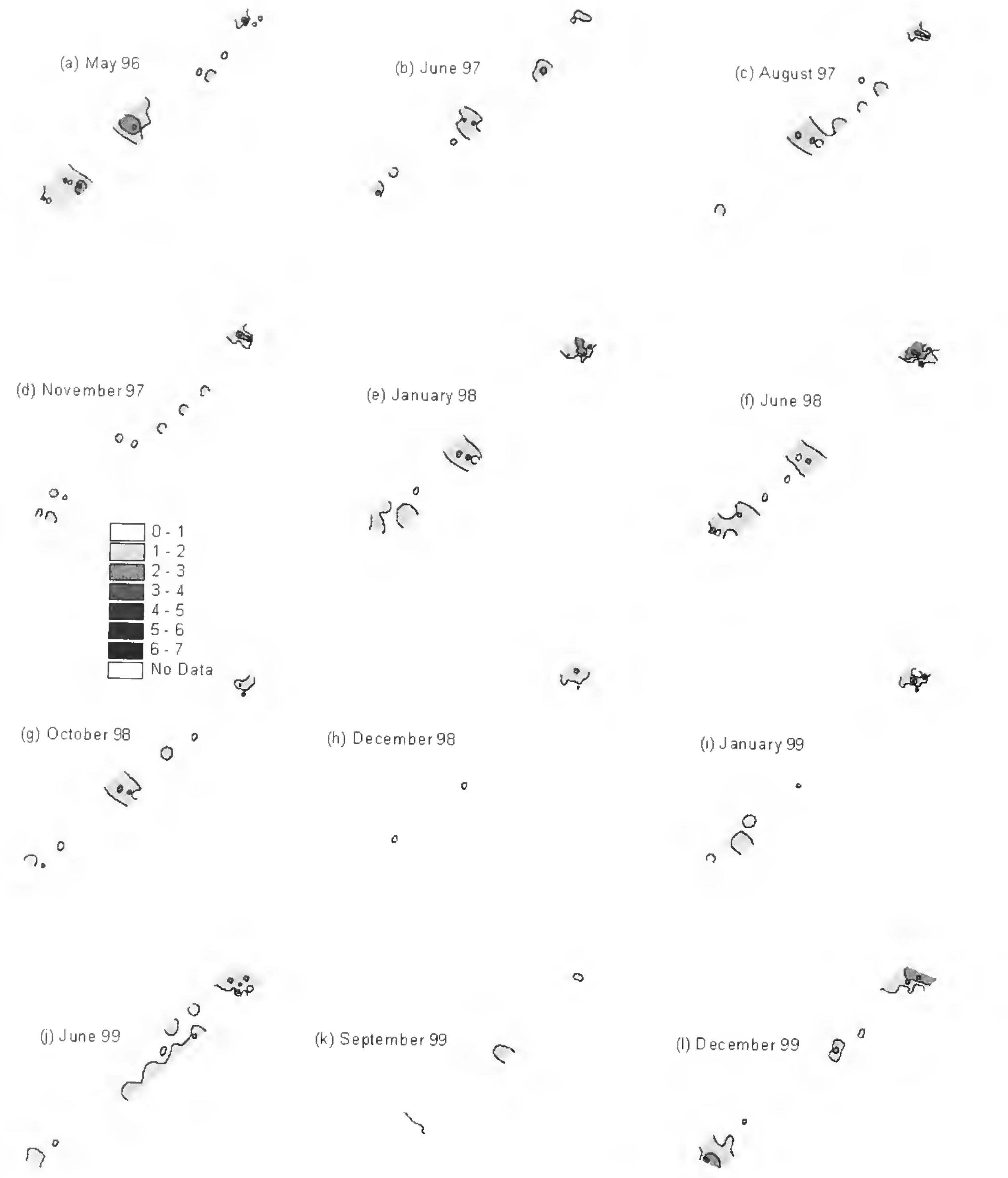


Figure 6-24: Station II leaf area index (LAI) from GIS analyses. Results from sampling dates prior to and following the three composite hydrographic events that caused measurable changes in the vegetation are shown. May 1996 is shown for comparison with other springtime sampling dates. Note increases in LAI in August 1997 following the July 1997 event and increases in June 1999 following the October 1998 event.

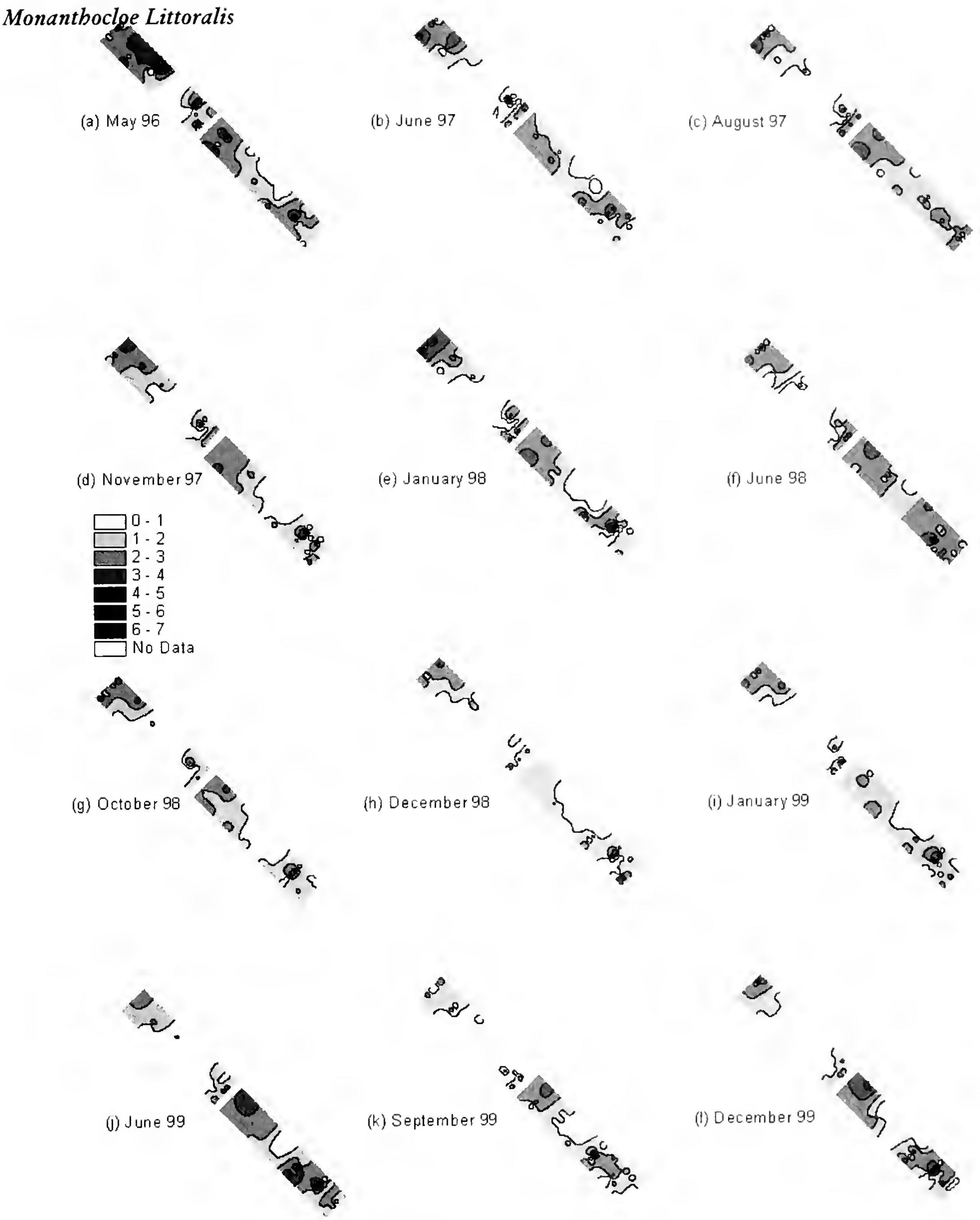


Figure 6-25: Station III leaf area index (LAI) from GIS analyses. Results from sampling dates prior to and following the three composite hydrographic events that caused measurable changes in the vegetation are shown. May 1996 is shown for comparison with other springtime sampling dates. Note increases in LAI in June 1999 following the October 1998 event.

Table 6-7: **Average total biomass values for four halophyte species at the three stations on each sampling date.** Values are ± SE (n=4). Hyphens (-) indicate biomass

	Total Biomass (g/m^2)							
	2/96	**5/96**	**2/97**	**6/97**	**1/98**	**6/98**	**1/99**	**6/99**
Reference								
B. maritima	2,371 ± 429	1,016 ± 186	1,201 ± 302	3,208 ± 261	2,614 ± 465	1,909 ± 392	1,483 ± 315	1,379 ± 209
B. frutescens	4,392 ± 1,001	8,053 ± 681	6,529 ± 899	4,775 ± 652	2,120 ± 464	2,389 ± 434	4,172 ± 624	3,876 ± 608
M. littoralis	3,236 ± 365	2,249 ± 334	1,525 ± 87	3,164 ± 595	2,562 ± 510	1,347 ± 130	1,833 ± 424	1885 ± 193
D. spicata	1,179 ± 459	1,697 ± 264	1,314 ± 294	1,675 ± 237	1,175 ± 125	2,199 ± 384	1,154 ± 146	1,047 ± 36
Station II								
B. maritima	2,069 ± 643	643 ± 116	1,889 ± 223	3,002 ± 418	2,669 ± 327	3,028 ± 392	1,780 ± 334	2,315 ± 629
B. frutescens	4,361 ± 815	8,575 ± 727	5,115 ± 952	2,562 ± 653	2,658 ± 299	2,080 ± 307	4,401 ± 502	2,229 ± 456
M. littoralis	3,351 ± 396	2,499 ± 180	1,772 ± 269	2,927 ± 277	2,031 ± 419	2,024 ± 490	3,379 ± 800	2,213 ± 264
D. spicata	2,668 ± 312	1,255 ± 43	1,076 ± 132	1,917 ± 235	3,557 ± 468	1,444 ± 333	1,322 ± 123	1,573 ± 307
Station III								
B. maritima	2,552 ± 497	1,180 ± 282	805 ± 61	2,272 ± 192	2,634 ± 662	3,878 ± 770	1,750 ± 107	3,161 ± 825
B. frutescens	10,412 ± 2,275	5,560 ± 1054	9,848 ± 2,675	5,904 ± 1,624	3,680 ± 446	5,263 ± 1,106	3,838 ± 844	1,948 ± 565
M. littoralis	3,706 ± 625	2,554 ± 210	1,331 ± 59	2,081 ± 230	2,397 ± 406	2,536 ± 285	1,846 ± 289	883 ± 46
D. spicata	666 ± 105	402 ± 89	-	-	539 ± 51	-	314 ± 51	399 ± 24

Monanthocloe Littoralis

Monanthocloe littoralis biomass values were between 883 and 3,706 g/m^2 for all three stations (Table 6-7). Low values were seen at all three stations in February 1997 (< 1,772 g/m^2). Biomass increased to near 3,000 g/m^2 in June 1997 at the Reference Station and Station II and declined to values between 1,885 and 2,213 g/m^2 in June 1999. At Station III, values increased by 1,205 g/m^2 from February 1997 to June 1998 and decreased again by 1,653 g/m^2 to the lowest value recorded (883 g/m^2) in June 1999.

Distichlis Spicata

Distichlis spicata exhibited the lowest biomass range of all four species sampled (314 to 3,557 g/m^2) (Table 6-7). Values ranged between 1,047 and 2,199 g/m^2 at the Reference Station. At Station II, values were similar to the Reference Station with the exception of one high value recorded in January 1998 (3,557 g/m^2). Values at Station III were considerably lower than the other two stations (314 to 666 g/m^2), and on three sampling dates, coverage of *D. spicata* was so sparse that monospecific stands could not be found for sampling.

ROOT: SHOOT RATIOS

Batis Maritima

R:S ratios of *Batis maritima* were lowest in May 1996 at all three stations (0.16 to 0.22) (Table 6-8). The ratios gradually increased until January 1998 at the Reference Station (0.83) and Station III (1.72) and continued to increase until June 1998 at Station II (1.27). Values decreased gradually at the Reference Station and Station II to values of 0.36 and 0.54, respectively. The ratio peaked again in January 1999 at Station III but then declined to a final recorded value of 0.61. Twenty-two of the twenty-four (98%) ratios measured were between 0.1 and 1.0, indicating that for most of the demonstration period, the plant biomass above the ground was proportionately larger that below the ground.

Borrichia Frutescens

At the Reference Station, R:S ratios were greatest in the summer months and lowest in the winter (Table 6-8). This station also exhibited the greatest range in ratios (0.2 to 0.9). At Station II, values peaked in June 1997 (0.83) and then gradually decreased by 64% to 0.30 at the end of the study period. Values at Station III showed little variation, with the range in values being limited to 0.2 to 0.4. The lowest values measured at all three stations were in February 1997. All values recorded were between 0.2 and 0.9.

Monanthocloe Littoralis

No apparent seasonal trend in the R:S ratios of *Monanthocloe littoralis* could be seen at the three stations, and ratios between stations were variable (Table 6-8). At the Reference Station, values remain relatively constant between 0.1 and 0.6. A gradual decrease in ratios occurred from June 1998 to June 1999. A peak ratio was measured in June 1997 at Station II (1.3), and in June 1998 at Station III (1.1). The peaks did not correspond to changes in freshwater input. Values for all three stations ranged between 0.1 and 1.3.

Distichlis Spicata

R:S ratios at the Reference Station and Station II exhibited similar patterns for *Distichlis spicata*, although the range of values was greatest at Station II (Table 6-8). Peak ratios were recorded in June 1997 and June 1999, following periods of heavy rainfall. Lowest values were measured in June 1998 during a period of little to no rainfall.

Table 6-8: Average (n=4) root:shoot ratios for four halophyte species at the three stations on each sampling date. Values are ± SE. Hyphens (-)

	Root to Shoot Ratios							
	2/96	5/96	2/97	6/97	1/98	6/98	1/99	6/99
Reference								
B. maritima	0.80 ± 0.16	0.16 ± 0.03	0.46 ± 0.15	0.55 ± 0.11	0.83 ± 0.12	0.45 ± 0.21	0.43 ± 0.07	0.36 ± 0.09
B. frutescens	0.57 ± 0.12	0.34 ± 0.06	0.20 ± 0.01	0.93 ± 0.30	0.34 ± 0.05	0.70 ± 0.22	0.30 ± 0.10	0.41 ± 0.12
M. littoralis	0.17 ± 0.03	0.13 ± 0.02	0.62 ± 0.07	0.52 ± 0.11	0.44 ± 0.05	0.60 ± 0.05	0.52 ± 0.18	0.23 ± 0.05
D. spicata	0.47 ± 0.04	0.59 ± 0.04	0.55 ± 0.10	1.02 ± 0.18	0.71 ± 0.09	0.45 ± 0.06	0.82 ± 0.08	1.11 ± 0.28
Station II								
B. maritima	0.76 ± 0.05	0.16 ± 0.02	0.54 ± 0.04	0.48 ± 0.11	0.75 ± 0.08	0.99 ± 0.2	0.95 ± 0.22	0.54 ± 0.15
B. frutescens	0.44 ± 0.08	0.23 ± 0.05	0.15 ± 0.04	0.83 ± 0.10	0.74 ± 0.25	0.50 ± 0.13	0.28 ± 0.05	0.30 ± 0.07
M. littoralis	0.15 ± 0.04	0.15 ± 0.03	0.66 ± 0.10	1.27 ± 0.30	0.50 ± 0.10	0.57 ± 0.13	0.69 ± 0.21	0.35 ± 0.03
D. spicata	0.46 ± 0.02	0.32 ± 0.07	0.77 ± 0.16	1.08 ± 0.15	0.29 ± 0.03	0.22 ± 0.05	0.48 ± 0.05	0.99 ± 0.28
Station III								
B. maritima	0.62 ± 0.08	0.22 ± 0.03	0.35 ± 0.04	0.55 ± 0.12	1.40 ± 0.39	0.47 ± 0.05	1.05 ± 0.19	0.61 ± 0.18
B. frutescens	0.25 ± 0.04	0.52 ± 0.08	0.15 ± 0.03	0.26 ± 0.06	0.39 ± 0.08	0.37 ± 0.08	0.28 ± 0.04	0.36 ± 0.05
M. littoralis	0.34 ± 0.06	0.22 ± 0.02	0.65 ± 0.12	0.74 ± .012	0.59 ± 0.13	1.09 ± 0.25	0.23 ± 0.04	0.38 ± 0.08
D. spicata	0.37 ± 0.10	0.58 ± 0.16	-	-	1.11 ± 0.11	-	1.07 ± 0.16	1.03 ± 0.32

DISCUSSION

SALINITY

In general, open water salinity values appeared to be influenced by precipitation and flow-mediated freshwater inputs. Typically, salinity values were decreased by freshwater inputs and increased by drought periods. The greatest peaks in salinity occurred during dry periods. The extent and duration of the freshwater event determined the degree to which the salinity fell, and the time span over which the salinity remained low. For example, a summer event in 1997 reduced open water salinity levels by 40 ppt at the Reference Station. However, the salinity had increased by 30 ppt only two months following the event. The magnitude of the increase was most likely due to the timing of the event. The event occurred during the summer, and, after the precipitation ceased, air temperatures were high and resulted in rapid evaporation. In contrast, the October 1998 event reduced open water salinity values at the Reference Station from 33 ppt in June 1998 to 11 ppt in December 1998. Salinity levels remained low throughout the winter and spring 1999, most likely because the event occurred during the cooler part of the year, and because there was steady rainfall during the beginning of the year.

Pore water salinity concentrations were almost always higher than open water values. The periods when values were similar were because the transects or part of the transects were flooded with open water. This trend was similar to that described by Hackney and De la Cruz (1978) for a Mississippi tidal marsh. The increased pore water values appear to be due evaporation of water from the soil, as well as lack of dilution from fresh water, as the highest pore water values were seen during drought periods (*e.g.*, 85 to 92 ppt in December 1999, which had 0.25 cm of rain). Changes in pore water salinity concentrations were usually reflected by changes in open water salinity values.

INORGANIC NITROGEN

Open water NH_4^+ and NO_2 + NO_3 values showed only small responses to freshwater inundation. A problem with evaluating the impact of the project on these values was that it must be assumed that instantaneous nitrogen levels measured on different sampling dates were representative of the same body of water. However, in reality, the channel water was not stagnant, and moved continually based on tidal oscillations.

These problems were probably minor in the analysis of vegetation responses as the nitrogen available for plant uptake was found in the soils, which, unlike channel water, did not move. The role of pore water nitrogen in determining the biomass and productivity of salt marsh vegetation has been investigated repeatedly. In general, it has been demonstrated that nitrogen fertilization of marsh plants has significantly increased plant biomass, indicating nitrogen as a limiting nutrient in estuaries. Several investigators have concluded that nitrogen scarcity is responsible for stunting the growth of *Spartina alterniflora* (Broome *et al.* 1975; Gallagher 1975; Valiela and Teal 1974; Valiela *et al.* 1978). Mendelssohn (1979) demonstrated that nitrogen fertilization increased the aerial living standing crop of the short form of *S. alterniflora* from 49% to 172%. De La Cruz *et al.* (1979) found significant increases in the annual aboveground net primary productivity of four tidal marsh communities seven months after ammonium nitrate fertilization.

In this study, pore water NH_4^+ levels increased dramatically from the beginning to the end of the study period. Most increases were seen after the October 1998 composite hydrographic event. The change does not appear to be flow related, as similar increases were measured at all three stations. However, the concentrations were most likely too high to be purely rainfall meditated. The change may have been a result of cyanobacterial mats that formed on the soil surface following the event. Many cyanobacteria species are capable of taking atmospheric nitrogen and fixing it into a biologically available form NH_4^+. These mats remained on the soil surface for over a year (they were at the stations through the December 1999 sampling date but were dried up by June 2000). In general, 1999 was a relatively wet year, and the moisture might have attributed to the survival of the mats. The persistence of the mats for an extended time could explain the unusually high soil NH_4^+ levels. Unfortunately, the high levels were not seen until the end of the study period, and any subsequent positive effects on the vegetation would have taken several months to manifest.

VEGETATION

The most significant vegetation changes seen as a result of hydrographic events through the channels were the germination and establishment of the annual succulent *Salicornia bigelovii.* The relative success of this plant appears to provide relevant information regarding the timing and quantity of fresh water needed to promote sexual (seed) colonization in hypersaline salt marshes. Because the species is an annual and reproduces primarily by seeds, successful establishment can only occur if soil salinity concentrations are reduced to a level that alleviates the osmotically induced seed dormancy.

In salt marsh habitats, the ability of halophytes to reproduce sexually (seeds) is critical for the success of plant populations (Ungar 1991 and Allison 1996). While vegetative growth can expand plant cover in a particular area, seeds are necessary for establishment at locations distant from neighbors. Seeds also allow for reestablishment following disturbance events like flooding, drought or burial that oftentimes result in adult plant mortality. Quick recovery is only possible through seeds, which can withstand the disturbance by remaining dormant and then germinating afterwards.

In this study, the timing of soil salinity reduction was found to be critical. Hydrographic events which lowered soil salinity values during the late fall/early winter allowed the successful germination and establishment of *Salicornia bigelovii* during the spring and summer, independent of whether or not the intermediate seasons were wet or dry. The degree of survival was most likely a function of air temperatures and evaporation rates, which were relatively low in the winter compared to summer and did not increase as rapidly. When summer approached and soil salinity increased, the seedlings were large enough to withstand the increasing salinity concentrations. If an event occurred in the late spring or summer, the seeds might have germinated, but unless the soil salinity was kept suppressed by sequential diluting events, the seedlings would not survive and establishment likely failed.

Flooding events through the Rincon Overflow Channel occurring in the late fall significantly increased the number of established plants seen the following spring compared to the number seen after only a precipitation event. In June 1999, *Salicornia bigelovii* cover at Station II (52%) was 26% greater than that seen at the Reference Station (26%), while cover in June 1998 was approximately the same at the two stations (11 to 13%). Heavy rains occurred during fall 1997 with no flow event, hence the approximately equal cover at the two stations. While in fall 1998, heavy rains and a flow event occurred through the Rincon Overflow Channel, possibly leading to a doubling in cover at Station II compared to the Reference Station. The flooding of Station II was reflected in the soil salinity levels, which were 6 to 20 ppt. These values are 1 to 11 ppt lower than the Reference Station and Station III, respectively, immediately following the flow event.

The lack of a significant difference between *Salicornia bigelovii* cover at Station III between June 1998 and June 1999 indicated that diverted fresh water in the channels might not have affected more than just the lower (adjacent) portions of the transect at Station III. Most likely, during a major event such as the October 1998 event, most flow diverted through the Nueces Overflow Channel backed up at the intersection of the upper and central segments of Rincon Bayou by the private road crossing, and a majority of this volume likely passed through the Rincon Overflow Channel. Some amount of fresh water reached Station III, as open water salinity was 8 to 11 ppt lower than the other two stations following the October 1998 event, but this water likely remained channelized. However, open water salinity values were 8 to 9 ppt and 5 to 6 ppt higher following the July 1997 and September 1999 events, respectively. The higher salinity values, even after major hydrographic events, may be indicative of increased tidal influence, as this station was closer to Nueces Bay. The smaller responses seen in *S. bigelovii* cover at the Reference Station and Station III compared to the response seen at Station II after the 1998 event appear to be precipitation-mediated and limited by a lack of freshwater inundation.

Small scale GIS analyses indicated that the establishment of *Salicornia bigelovii* corresponded to a decrease in bare area at the Reference Station and Station II. At Station II, decreases in bare area were proportional to increases in cover. LAI maps produced from the small scale analyses further supported the increase in vegetation at both the Reference Station and Station II during spring 1998 and 1999. Weilhoefer (1998) and Dunton *et al.* (2000) have previously documented establishment and expansion of vegetation cover and subsequent decrease in bare area after freshwater inundation in the lower Nueces Delta. Decreases in bare area could have direct affects on the functionality of the marsh.

Other studies have noted that halophyte species, which can occupy bare areas following disturbance events through sexual (seed) reproduction, can act to reduce soil salinity concentrations by shading the soil surface and by actively uptaking salts. The reduction in soil salinity eventually allows the establishment of dominant and persistent perennial species (Bertness *et al.* 1992). The establishment of these species is necessary as they provide stable habitat for many for many small organisms, including crabs, molluscs and small terrestrial animals such as rats. The marsh vegetation also serves as habitat and food for a variety of permanent and migratory birds (Henley and Rauschbauer 1981). Successful long-term establishment provides large amounts of plant biomass to the detrital food-web, which can then be utilized by microorganisms and other small animals such as snails (Marples 1966). This is an especially important role of annual plants because all of their annual biomass production eventually becomes detritus. Marsh vegetation contribution to the detrital food-web is essential as it serves as a critical link between primary and secondary trophic levels (Burkholder and Burkholder 1956; Odum and Wilson 1962; Teal 1962). Vegetative occupation of bare space is critical as the vegetation acts to stabilize marsh sediments, thereby sheltering the metropolitan area of Corpus Christi from extensive flood damage and erosion. Without vegetation expansion into bare space, the functionality of the marsh would be compromised.

Batis maritima cover at the Reference Station and Station III changed seasonally, with peak cover in the summer and declines in the winter. This seasonal trend appears to be due to natural variation and corresponds to observations made by Weilhoefer (1998) in the lower Nueces Delta. *B. maritima* is a highly salt tolerant perennial succulent, which may explain its high cover during the summer. The plant expanded in cover during the spring and early summer when soil salinity levels were usually low and was then able to maintain a high cover during the summer months, although active growth may not have occurred during the hot, dry season. The greatest percent cover observed at the three stations, however, was during the summer of 1997, following a spring with over 52.1 cm (20.7 inches) of precipitation. The rain was steady over a five-month period and was not due to a major hydrographic event. No other spring during the study period experienced a similar rainfall pattern. Although *B. maritima* is capable of surviving at elevated salinity concentrations, increases in cover occur when gradual freshwater inputs alleviate soil salinity levels.

After a major composite hydrographic event in July 1997, percent cover of *Batis maritima* temporarily increased in August but then declined at all three stations. After the summer 1997 event, the following fall, winter and spring were relatively dry, potentially keeping cover low at all three stations during June 1998. Cover increased again in June 1999 at the Reference Station and Station III; cover remained low for over two years at Station II. The continual suppression of *B. maritima* growth at Station II might reflect this species intolerance to waterlogging and anaerobic soils. Freshwater-mediated decreases have been noted in a species with similar morphology, *Salicornia virginica* (Zedler and Beare 1986; Weilhoefer 1998). Continual flooding occurred during the fall 1998 and throughout 1999. At Station II, the vegetation began at the mean water line, so, after flooding, fresh water drained slowly. This effect was magnified at Station II after an event activating the Rincon Overflow Channel, as a larger amount of water affected this station as compared to the other stations. It is important to note that *B. maritima* cover began to increase following the composite hydrographic event during the summer of 1999, as the winter months were dry and the waterlogged conditions potentially alleviated. At Station III, the vegetation zone began above the mean water line and so was not flooded as easily by channel water. Furthermore, water from precipitation did not produce standing puddles that could waterlog the soils.

The decrease in cover of *Monanthocloe littoralis* at the Reference Station and Station II following the summer 1999 composite hydrographic event was most likely due to flooding of the transects. During the time of the floods, the transect soils were covered by thick, green cyanobacterial mats. When the waters flooded the transects, the mats were lifted from the soils; when the waters retreated, the mats were left lying on top of most of the vegetation. The thick mats most likely caused decreases in plant cover by passively shading the vegetation, making interception of light necessary for photosynthesis almost impossible. Fortunately, cover of both *Batis maritima* and *M. littoralis* began to quickly recover after the event. In this instance, although flooding initially served as a disturbance resulting in decreases in adult plant cover, the likelihood of long-term successful establishment might not have been affected by the event. However, as noted by Allison (1996), the recovery may depend upon the presence of occasional freshwater inundation.

Biomass values and R:S ratios did not show obvious freshwater mediated responses. Previous studies have suggested that plants living in hypersaline soils invest more energy into below-ground tissues in order to cover a larger area of soil to obtain water (Brugnoli and Bjorkman 1992; Kuhn and Zedler 1997). However, the physiological capacities of the plants that control their salinity tolerance can vary with each species, and some species may allocate different amounts of biomass to the below-ground tissues depending on their individual ability. Additionally, waterlogging of soils may cause below-ground material to die in some plants and not in others, thereby decreasing the R:S ratio. The analyses were further complicated as a need for increased nutrient uptake might also have resulted in the plants increasing their below- ground tissues, especially when increases in nutrients occurred after precipitation or flooding events.

SUMMARY

The increase of fresh water into the channels and tidal flats of the upper Nueces Delta positively impacted the emergent vegetation by decreasing salinity, allowing for annual seed reproduction, decreasing bare area and increasing vegetative expansion of plant cover. Although similar responses were seen at the Reference Station following heavy precipitation, the effects were accentuated at Station II, which was directly impacted by flow through the Rincon Overflow Channel. The project demonstrated the sensitivity of vegetation to salinity levels and indicated that periodic freshwater inundation could alleviate the stressful condition imposed by hypersalinity. Without fresh water flooding, soil salinity concentrations at several locations in the study area would have likely increased to toxic levels and resulted in plant mortality.

CHAPTER SEVEN

Synthesis and Conclusions

"Then what of this river that having arisen
Must find where to pour itself into and
empty?"

❖ Robert Frost, *Too Anxious for Rivers*

The Nueces Delta is one of the most extensive marshes on the Texas Gulf Coast. It is an integral component of the Nueces Estuary, providing economically and ecologically valuable habitat and food for many estuarine and marine plant and animal species. In 1997, the worldwide average economic value of 17 ecological services provide by an estuary was $9,000 per acre per year (Costanza *et al.* 1997). In Texas, the total of only two recognized estuary functions (commercial and recreational value of fisheries) was about $5 billion dollars for the one million acres of estuarine area in the State (Robinson *et al.* 1995), or about $5,000 per acre per year.

The flora and fauna of the Nueces Delta depend upon periodic freshwater inundation events to maintain their ecological functions. However, over the past century, increases in the human population in the Coastal Bend region of Texas has intensified the demand for fresh water to meet agricultural, municipal and industrial needs. From the combined effects of reservoir construction, changes in land use patterns, increased ground water withdrawals and other human activities, the average annual volume of fresh water diverted into the upper Nueces Delta since 1982 has been reduced by over 99% from that before 1958 (Irlbeck and Ward 2000). Over time, this decrease in freshwater inflow has created a non-functioning estuarine ecosystem in the Nueces Delta. The natural freshwater deficit imposed by evaporation has been magnified by decreased riverine inflow, resulting in hypersaline channel waters and soils. As a result, a "reverse estuary" condition has developed where the lowest salinity values are near Nueces Bay and the highest are in the upper delta. While many estuarine species tolerate this hypersaline environment, prolonged periods of salinity stress have limited active growth and reproduction in the Nueces Delta, leading to lower biological productivity and less species diversity.

This demonstration project was designed to increase the opportunity for freshwater flow events from the Nueces River into the upper Nueces Delta assuming that resultant hydrographic changes would beneficially affect the ecology of the upper delta. Reclamation initiated the demonstration project in 1993 with the excavation of two overflow channels and then monitored the changes in hydrography, the water column, benthic communities and vegetation communities.

CHANGES IN HYDROGRAPHY

During the 50-month period when the overflow channels were open, over 8,810 10^3 m^3 (7,142 acre-ft) of water was diverted from the Nueces River into Rincon Bayou. Of this total amount, only about 1,204 10^3 m^3 (976 acre-ft) would have been diverted without the demonstration project features. Therefore, the total volume of freshwater inflow to the upper Nueces Delta was increased by about 732% from what would have occurred without the project.

In addition to increased inflow, the demonstration project features also increased the distribution of fresh water within the tidal flats of the upper delta. On five different occasions during the demonstration period, the tidal flats of the upper marsh were supplied with diverted fresh water. Without the project features, no natural inflow event would have directly freshened these areas.

These changes occurred because the demonstration project features lowered the minimum flooding threshold for the Nueces River from 1.64 m (5.4 ft msl) to about 0 m mean sea level. This change not only allowed more frequent river diversions into Rincon Bayou and the upper delta, but also provided the opportunity for other non-riverine elements like wind and tide to force frequent exchanges between the upper delta and the Nueces River. As a result, near continual (daily) exchange between the river and delta was observed during the demonstration period. Before the project, such interactions were limited to only extremely infrequent river inflow events.

EFFECTS ON SALINITY

The demonstration project greatly lowered short-term salinity concentrations in the upper and central segments of Rincon Bayou, as indicated by results of the hydrographic analysis (Chapter 3) and subsequent biological response analyses (Chapters 4 through 6). The demonstration project also affected the overall (*i.e.*, long-term) salinity gradient of Rincon Bayou. Unpublished long-term salinity data from selected stations in the Nueces Delta and Nueces Bay were obtained from Dr. Terry Whitledge (University of Alaska Fairbanks) and Dr. Paul Montagna (University of Texas Marine Science Institute) (Figure 7-1).). These data covered the period of January 1992 through December 1999 and were made available from projects sponsored by the Texas Water Development Board, City of Corpus Christi, Corpus Christi Bay National Estuary Program and Texas Sea Grant Program. This 8-year interval was divided into two nearly equal periods before and after the Nueces Overflow Channel was completed (October 26, 1995). The before-project period was about 3.8 years long, and the after-project period was about 4.2 years long.

The average salinity at each selected station was calculated for each month. Monthly averages at each station were then averaged for each period before and after the demonstration project to smooth the year-to-year variation and compare means. These values were then plotted along their respective channel segment lengths, beginning at where the Interstate Highway 37 (IH 37) bridge crosses the Nueces River to a point in Nueces Bay just west of White Point (Figure 7-2).

In the upper and central segments of Rincon Bayou, the average salinity gradient changed dramatically after the opening of the Nueces Overflow Channel. During the period before the demonstration project, there was no regular interaction with the Nueces River and salinity concentrations in the delta were highest in upper Rincon Bayou (Figure 7-2a). This condition may

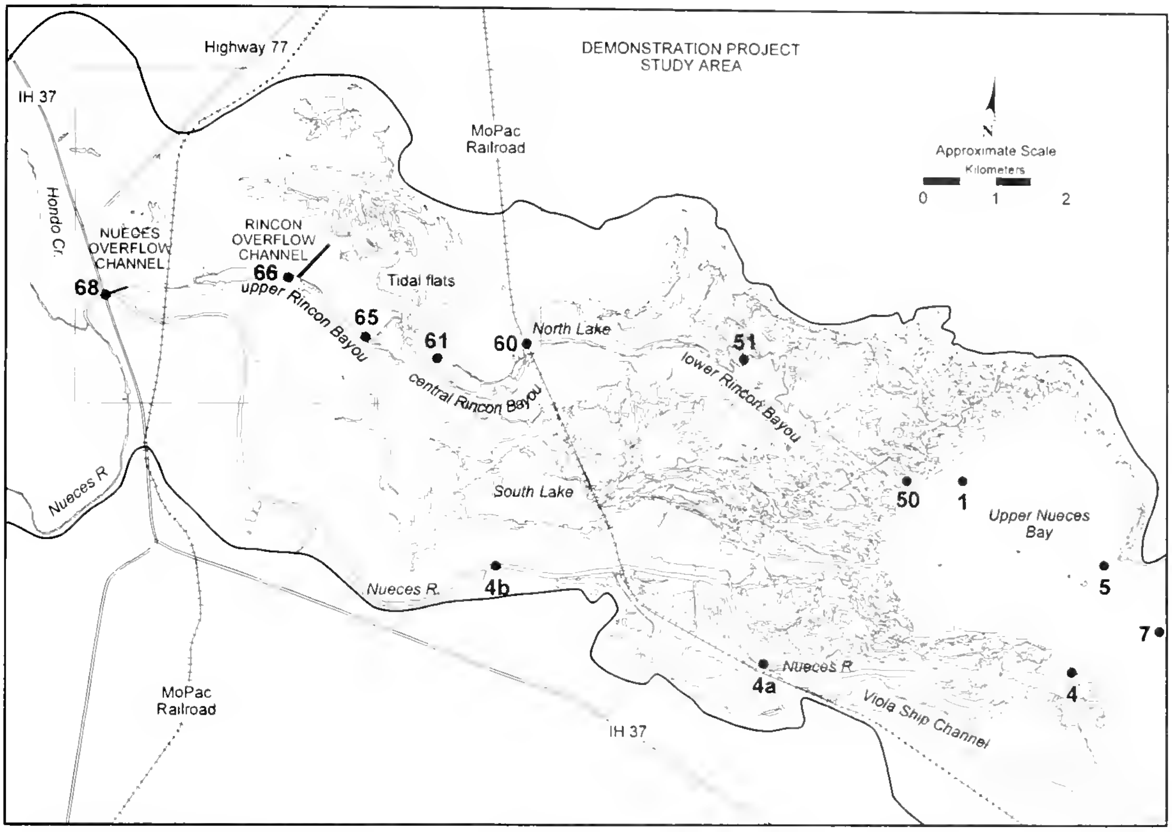


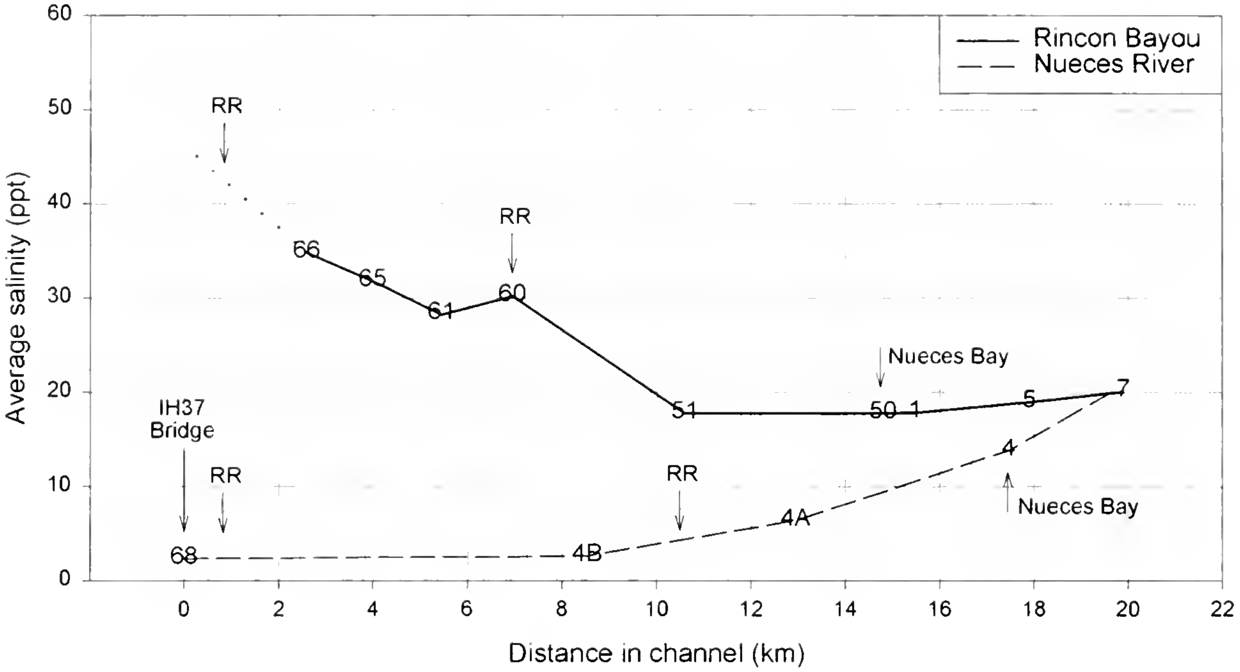
Figure 7-1: Selected stations used for analysis of long-term salinity changes in Rincon Bayou.

be termed a "reverse estuary," because the gradient was opposite what would be expected from a natural (undisturbed) system in which salinity concentrations would be lowest in the upper delta (*e.g.*, at Station 66). For the period after the demonstration project, the salinity gradient reverted to a more natural pattern for much of it's reach, particularly within the upper and middle Rincon Bayou segments (or the first 5 km from the IH 37 bridge) (Figure 7-2b). This change was due to increased diversions of fresh water through the demonstration project features. Without the demonstration project, average salinity concentrations in upper Rincon channel during the second period would have remained strongly hypersaline (likely greater than 50 parts per thousand (ppt) instead of the observed range of 21 to 28 ppt.

As expected, the demonstration project had no obvious effect on the salinity pattern of the Nueces River, nor was it designed to (the project was found to only divert approximately 2% of total river flow during a given hydrographic event (Ward 2000)). During both periods, salinity concentrations in the river channel increased with distance downstream as riverine fresh water (*e.g.*, at Station 68) mixed with salt water from Nueces Bay (*e.g.*, at Station 7) (Figure 7-2).

From comparison of the actual average salinity values in the river and bayou between both periods (*i.e.*, Figures 7-2a and 7-2b), it is apparent that salinity concentrations were generally higher during the after-project period than before the project. For example, in the Nueces River, this difference was about 3 parts-per-thousand (ppt) in the middle of the river (Station 4b) and about 8 ppt in the open bay (Station 7). This observation does not indicate that the demonstration project increased average salinity concentrations in the river but more likely is attributable to a greater freshwater influences on the river from both river flow and precipitation during the period before the project than after (Figure 7-3).

(a) Before the demonstration project (1992 through 1995)



(b) After the demonstration project (1996 through 1999)

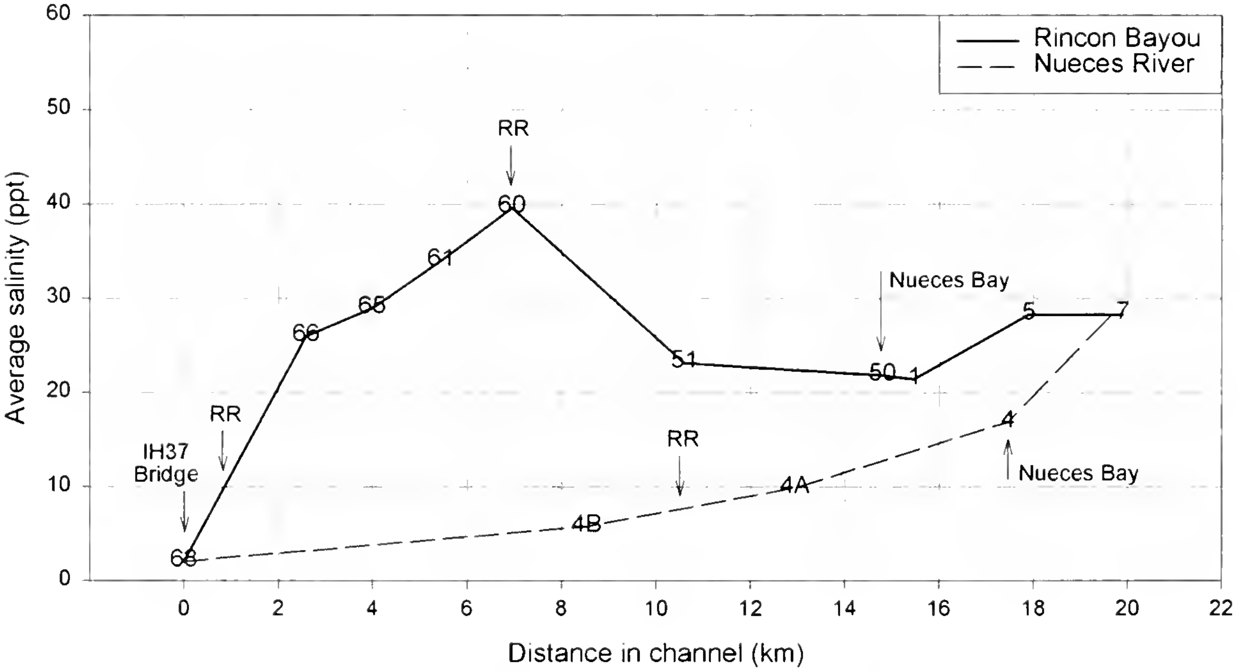
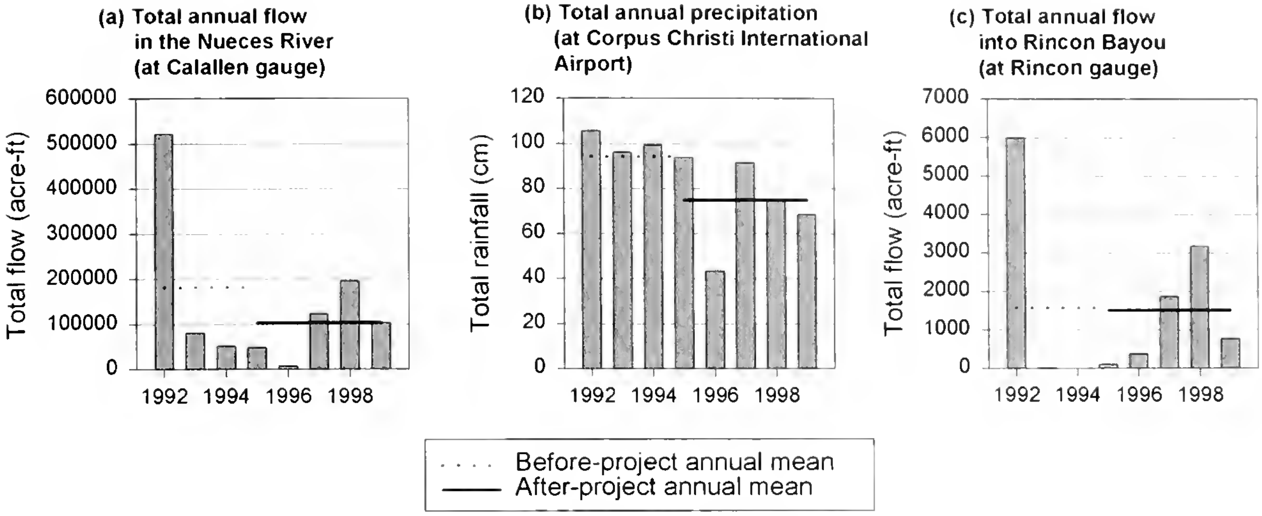


Figure 7-2: Long-term average salinity values for selected stations in the Nueces River and Rincon Bayou before (a) and after (b) implementation of the demonstration project. Station numbers coincide with those in Figure 7-1. Salinity values for the upper-most reach of Rincon Bayou (near Station 67) during the before-project period (a) were unavailable but were estimated by extrapolation to be approximately 45 ppt. RR indicates the point at which each channel is crossed by a railroad.


(a) Total annual flow in the Nueces River (at Calallen gauge)

(b) Total annual precipitation (at Corpus Christi International Airport)

(c) Total annual flow into Rincon Bayou (at Rincon gauge)

Figure 7-3: Total annual cumulations of selected freshwater sources affecting the Nueces Delta during the period 1992 through 1999. Flow in Rincon Bayou for the before-project period was estimated using daily stage data from the Calallen gauge and the methodology described by Irlbeck and Ward (2000). Total flow into Rincon Bayou for the after-project interval of October 26, 1995, through May 15, 1996, was unavailable, but was estimated to be approximately 123 10^3 m^3 (100 acre-ft). The average annual flow in the Nueces River for the first period was 224,581 10^3 m^3 (182,053 acre-ft) but only 127,678 10^3 m^3 (103,500 acre-ft) for the second. The average annual precipitation for the before-project period was 94.2 cm (37.1 in) but only 74.7 cm (29.4 in) for the after-project period. Finally, the annual mean freshwater flow into Rincon Bayou for the first period (1,931 10^3 m^3, or 1,565 acre-ft) was nearly equal to that for the period after (1,854 10^3 m^3, or 1,503 acre-ft).

Note: 1 acre-ft = 1.2336 10^3 m^3

In summary, the effects of the demonstration project on the long-term salinity gradient in Rincon Bayou were measurably significant. In a relatively short period of time (only 4.2 years after the opening of the Nueces Overflow Channel), the "reverse estuary" salinity gradient in the upper delta before the demonstration project reverted to a more natural form, with average salinity concentrations in upper Rincon Bayou becoming the lowest in Nueces Delta.

BIOLOGICAL RESPONSES

The influence of fresh water on the salinity concentrations of the water and soils of the upper Nueces Delta appeared to be the most important parameter affecting the biological response of estuary organisms in the delta.

WATER COLUMN PRODUCTIVITY

The inflow of river water into the upper Nueces Delta imported vital nutrients (nitrogen, phosphorus and silicon) required for plant growth into the channels and ponds of the marsh ecosystem. During the demonstration period, phytoplankton in the water column and on the surface of the sediments rapidly responded to the inputs of riverine nutrients with increased growth rates and accumulation of biomass. In addition, the freshwater inflow also reduced salinity concentrations and lowered the osmotic stress on these organisms. The increased primary production rates were especially prominent during periods when salinity was less than 50 ppt. The assimilation index (*i.e.*, the relative amount of growth per cell) was also generally higher during periods of low salinity, indicating that inherent growth rates were also increased by project diversions.

The species composition of phytoplankton apparently remained dominated by primarily small diatoms during most of the monitoring period. However, several observations of blooms of other phytoplankton were noted immediately after freshwater inflow events. These blooms were typically comprised of single celled blue-green algae (not of the filamentous cyanobacteria of algal mats) normally present in fresh water or very low salinity environments. These blooms were also short-lived, persisting no more than a few days. The presence of these blooms did not occur in the study area prior to the demonstration project except under natural freshening events that occurred every several years. The more frequent presence of these blooms in the upper and central Rincon Bayou were an indication that the water column ecosystem was showing a more typical response to freshwater inflow.

An additional indication of improved conditions for phytoplankton growth during and after freshwater inflow events was shown by an increase in the N:P ratio (dissolved inorganic nitrogen to phosphate ratio), which would provide a relative increase of nitrogen needed for plant growth. These increases following inflow events indicate that relatively smaller amounts of denitrification probably occurred during and following the inflow events.

BENTHIC COMMUNITIES

Benthos consists of two main types of infauna, which have different ecological roles in marine ecosystems and respond to inflow at different spatial and temporal scales. These are the larger macrofauna (organisms greater than 0.5 mm in length) and smaller meiofauna (between 0.063 and 0.05 mm in length). Macrofauna have planktonic larval dispersal and indicate effects of the demonstration project over larger spatial scales and longer temporal scales. Meiofauna have direct benthic development and generation times as short as one month, thus indicate effects over smaller spatial scales and shorter temporal scales.

Diverted fresh water lowered salinity concentrations which triggered bursts of benthic invertebrate productivity as indicated by increases in density and biomass. Salinity levels between 20 and 45 ppt appeared to correspond with high macrofauna biomass ($> 2\ g/m^2$). Macrofaunal abundance also increased with increasing biomass. Meiofaunal biomass and abundance increased when salinity values were between 10 and 40 ppt, with the greatest numbers being seen in the salinity range of 18 to 22 ppt. Biodiversity increased several months (3 to 6) following inflow events, indicating more species were able to utilize the marsh habitat. The macrofauna and meiofauna responded to inflow with similar patterns, indicating both trophic levels of benthos were responding positively to inflow events. Most importantly, the lowest biomass and abundance values occurred during times when there were no flow events. Additionally, strong seasonal increases of biomass occurred during the spring, when salinity concentrations were lowest. In contrast, during summer when salinity values were highest, density and biomass were always lowest.

VEGETATION COMMUNITIES

The most significant changes in the emergent vegetation also coincided with changing salinity regimes caused by flow through the demonstration features or by direct precipitation. During sampling periods with no hydrographic events, soil salinity levels were as high as 80 to 90 ppt, and water column salinity was upwards of 40 to 60 ppt. Following a large hydrographic event, surface and soil salinity concentrations were reduced, with the degree and duration of salinity suppression being a function of the timing and duration of the hydrographic event. Major hydrographic events lowered open water salinity values by over 40 ppt at some stations, and smaller, precipitation-mediated events exhibited smaller decreases.

Hydrographic events that alleviated soil salinity levels during the late fall/early winter allowed the successful germination and establishment of *Salicornia bigelovii* during the spring and summer, independent of whether or not the seasons were wet or dry in regards to precipitation. Because this plant species is an annual succulent that reproduces primarily by seeds, successful establishment seemed to occur only if soil salinity concentrations were reduced at the appropriate time of year to a level that could alleviate osmotically induced seed dormancy.

Most importantly, the establishment of *Salicornia bigelovii* corresponded to a decrease in bare area at all three vegetation sampling stations, with the decreases in bare area being proportional to the increase in *S. bigelovii* cover. Decreases in bare area could have direct affects on the functionality of the marsh. Other studies have noted that halophyte species, which can occupy bare areas following disturbance events through sexual (seed) reproduction, can act to reduce soil salinity concentrations by shading the soil surface and by actively up-taking salts. The reduction in soil salinity can eventually allow the establishment of dominant and persistent perennial species. These plants can then provide stable habitat and food for many small organisms and for a variety of permanent and migratory birds, as well as provide large amounts of plant biomass to the detrital food-web, which boosts productivity of higher trophic levels. Without the expansion of vegetation into bare space, the functionality of that marsh area would be compromised.

The response of *Salicornia bigelovii* also differed after freshwater inflow events when compared to those that were mainly precipitation-mediated. In the late fall 1998, a major flow event flooded the Rincon Overflow Channel and significantly increased the number of plants that emerged the following spring compared to the number seen after a precipitation only event. In June 1999, total *Salicornia bigelovii* cover at Station II was 52%, which was 26% greater than that seen at the Reference Station. In June 1998, prior to the October 1998 composite hydrographic event (*i.e.*, Events 21 through 27), percent cover at the two stations was approximately equal (11% and 13%). The similar amount of cover during the spring 1998 could be explained by heavy rains (> 23 cm, or 9 inches) which occurred during fall of 1997, presumably affecting both stations the same amount, although Station II was also affected by fresh water diverted through the Rincon Overflow Channel.

Peaks in the percent cover of the perennial succulent *Batis maritima* occurred after gradual precipitation inputs, but decreased after major hydrographic events which flooded the station. The decline was most likely due to the species' inability to tolerate waterlogged and anaerobic soils for extended periods. Increases in cover were noted several months following a major event if the soils had time to dry (*i.e.*, no other flooding events occurred).

In summary, freshwater inputs via precipitation or project diversions reduced salinity concentrations in the upper Nueces Delta, and vegetation cover increased as a result. Although large flooding events initially served as a disturbance resulting in decreased adult plant cover, it appears that the likelihood of long-term successful establishment might be enhanced by the increased opportunity of freshwater inflow.

INTEGRATION OF PROJECT EFFECTS

The overall effects of the demonstration project on the ecology of Rincon Bayou and the upper Nueces Delta were positive to the environment (Table 7-1), and were attributable to the re-introduction of fresh water. Prior to the demonstration project, Rincon Bayou was not directly connected with the river (*i.e.*, it was a dead-end channel). Average salinity concentrations were consistently higher in the upper delta than in Nueces Bay. These conditions were alleviated in the upper and central segments of Rincon Bayou by increased freshwater flow through the Nueces Overflow Channel.

The increased opportunity for freshwater inflow also changed nutrient cycling and primary productivity in the upper delta. Generally, nitrogen occurs in the water column in three main forms: ammonia, nitrate and nitrite. Without inflow, the dominant form of nitrogen in the upper delta was ammonia, which was likely derived from the recycling of (decaying) organic matter. Also, water levels were generally low, as shallow as only a few centimeters, and the substrate was covered by mats of filamentous blue-green algae (*i.e.*, cyanobacteria). Although productivity (per unit volume) from these mats was high, the total volume of production was low because the total amount of water was small. Furthermore, cyanobacteria are not food

Table 7-1: Summary of the effects of the demonstration project on the upper Nueces Delta.

ATTRIBUTE	Before	After
Geomorphology	Dead-end	Flow-through with free exchange
Salinity gradient	Higher in the upper delta than in the bay	Lower in the upper delta than in the bay
Nutrient cycling	Recycled nitrogen	New and recycled nitrogen
Primary production	Low in marsh	Higher in marsh
Secondary production	Constrained by dry conditions	Increased by flow events
Habitat utilization	Constrained by dry conditions	Increased during spring and fall

sources for higher trophic levels, indicating that cyanobacteria production was a sink, not a link, in the food chain.

With the re-introduction of fresh water, more oxidized forms of nitrogen were introduced into the delta. Because nitrate and nitrite are the preferred forms of nitrogen by diatoms, these organisms contributed a substantial proportion of the productivity. Flow events resulted in moderate levels of primary production (per unit volume), but the total amount of fixed carbon was very high because the large volumes of water involved when elevations approach a meter or so in depth. Because diatoms were significantly contributing to the total productivity, there was a link with higher trophic levels, and the grazing food chain was stimulated. Increased freshwater inflow lowered salinity concentrations in the soils and waters of the marsh, stimulating plant production as well. Marsh productivity ultimately drives the detrital food chain when the plant material dies and decomposes.

The increased primary production, in both the water column and marsh, resulted in increased secondary productivity in several ways. Grazing organisms could directly utilize the benthic and plankton diatom production. Increased carbon fixation led to higher amounts of detritus and higher amounts of food available to detritivores. A multiplier effect was present because increased marsh vegetation also increased habitat quality and complexity. Marsh areas are important because they provide nursery habitats and for many commercially and recreationally important species, (*e.g.*, shrimp, red fish, and sea trout). Without freshwater flow and concomitant increases in the marsh system, the habitat does not support these estuarine-dependent species. Consequently, the combination of increased food and increased habitat quality and area likely resulted in geometric increases in secondary production.

A CONCEPTUAL MODEL

The data collected during the present study allowed the creation of the conceptual model presented in Figure 7-4 on how Rincon Bayou functions, and, perhaps more importantly, how the upper delta functions with and without freshwater inflow. Rincon Bayou's connection with Nueces Bay allows the exchange of materials and energy flow between the two bodies of water. In addition, nekton (fish and epibenthic shrimp) utilize Rincon Bayou as a nursery habitat when water elevations and salinity conditions are suitable.

The water levels and salinity concentrations in Rincon Bayou are governed by the interactions between tide, rain, evaporation and freshwater inflow (Figure 7-4). These outside forcing elements also drive nutrient concentrations, primarily through tides and inflow. Nutrient concentrations are also governed by biogeochemical processes associated with decomposition of marsh grass, excretion by organisms and recycling of dead organic matter. The nutrients, with sunlight, drive primary production in the water column (phytoplankton), which in turn drives a grazing

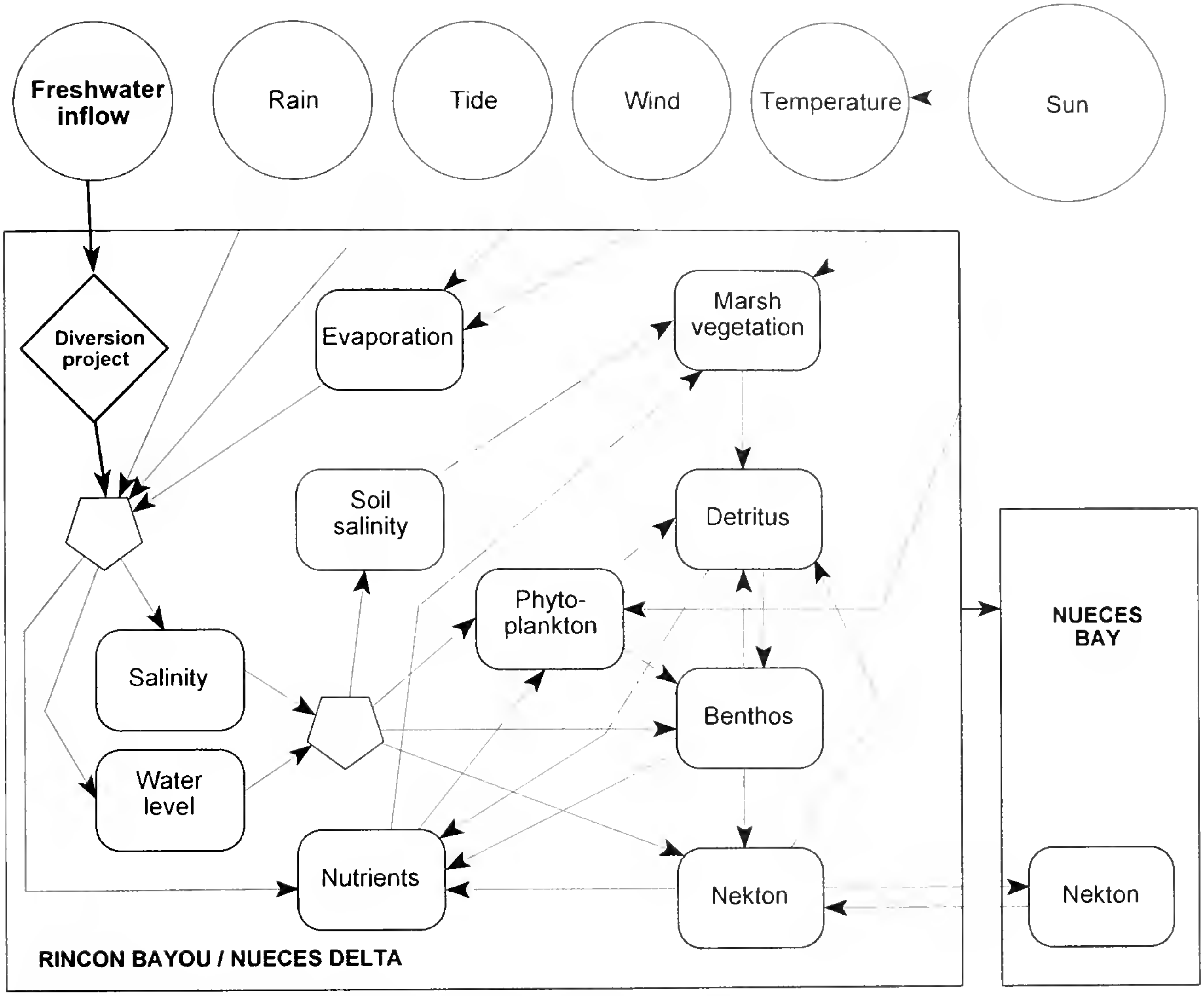


Figure 7-4: Conceptual model of the Nueces Delta ecosystem. Parts of the Nueces Estuary are bounded by shaded rectangles. Circles are forcing functions from outside the system. Rounded rectangles represent standing stocks or energy storage. Arrows represent flow rates of energy and materials. The diamond represents on/off switch. Pentagons represent multipliers.

food chain. Some benthic invertebrates then utilize this marsh and water column detritus, contributing themselves to the detrital food chain. Marsh production is a function of sunlight, nutrients and soil salinity. The soil salinity is affected by water column salinity and elevation. All benthos are strongly affected by salinity because of physiological tolerance to a specific salinity range, or by using salinity gradients as cues for migration and reproduction. Of these elements, fresh water is the most critical for maintaining ecological functions in the upper Nueces Delta. In natural systems, inflow acts as a continuous forcing function. In this conceptual model, a diversion project acts as a "switch" that, when activated, restores some freshwater inflow to the system.

This conceptual model demonstrates an improved understanding of the mechanisms controlling production in the upper Nueces Delta. These mechanisms indicate the importance of the demonstration project in restoring functionality to the marsh-dominated ecosystem. Without fresh water from river diversions, salinity concentrations increase, average water levels decrease, and production of primary and secondary producers declines. A loss of functionality in the Nueces Delta affects Nueces Bay because of the reduced transport of exported materials and the loss of habitat needed by migratory and nursery-dependent species that utilize the delta. Therefore, without freshwater inflow, the delta is not a functioning component of the greater Nueces Estuary ecosystem.

SUMMARY

Since 1982, the average annual amount of freshwater inflow to the upper delta has decreased by over 99% compared to the period before 1958 (Irlbeck and Ward 2000). This dramatic change indicates the large degree to which human activity has altered the delta ecosystem in a relatively short period of time (*i.e.*, less than a quarter century). Nevertheless, the demonstration project successfully increased the amount of fresh water diverted into the upper Nueces Delta by six or seven times that which would have occurred without the project. Although this amount of restored inflow was relatively small (only about 2% of the annual average before 1958) when compared to historical volumes, it returned a significant degree of ecological function to the Nueces Delta and Nueces Estuary ecosystems. Prior to the demonstration project, persistently high salinity concentrations severely inhibited the function of the delta, and its natural contribution to the greater estuary ecosystem was limited to infrequent periods when natural flow events occurred. With the restored regular interaction between the river and Rincon Bayou, fresh water and nutrients were more consistently introduced into the upper delta, stimulating critical chemical and biological processes. As a result, habitat in the delta component of the Nueces Estuary improved in both quality and quantity, and foraging opportunities for many estuarine species were increased.

CHAPTER EIGHT

Future Opportunities

"In nature there are neither rewards nor punishments – there are consequences."

❖ R.G. Ingersoll

The Rincon Bayou Demonstration Project was a short-term initiative undertaken to answer two fundamental questions about the Nueces Delta ecosystem. First, "Was there an opportunity to meaningfully increase the amount of fresh water diverted into the upper delta?", and second, "Would the biological resources in the delta measurably respond to increased fresh water in a favorable way?" The demonstration project answered the first question with a definitive "Yes." Data indicate that project features increased the total amount of diverted fresh water by 732% during the demonstration period (Chapter 3). In the long-term, had the demonstration project features been in place since 1982, the average annual amount of freshwater diversion into the upper delta would have been increased by 633% (Irlbeck and Ward 2000). Project results also answered the second question with an equally definitive "Yes". Because of the freshwater diversions made by the demonstration project, the "reverse estuary" salinity gradient that had previously characterized Rincon Bayou and the upper delta reverted to a more natural pattern (Chapter 7). Primary productivity in the water column was stimulated (Chapter 4), and the abundance, diversity and distribution of both benthic and emergent vegetation communities increased as a result of additional fresh water (Chapters 5 and 6). In summary, the demonstration project was more successful than had been anticipated, both in the amount of fresh water diverted and in the biological responses observed.

Because of limitations in program authority and landowner agreements, the Rincon Bayou Demonstration Project was conducted as only an investigation of the potential for restoration of natural estuary function. Based upon project results, actual function can be restored. The next step in restoring freshwater flow to the upper Nueces Delta should be the implementation of a long-term (permanent) diversion project. In the context of this future scenario, the authors of this report present several opportunities for enhanced project design and future ecological studies. These recommendations were developed based upon observations gained from the results of the demonstration project.

OPPORTUNITIES FOR A PERMANENT DIVERSION PROJECT

From analysis of the hydrographic data collected during the demonstration period, a permanent diversion project could be designed that would produce hydrographic benefits exceeding those of the demonstration project. During the demonstration period, the primary limitations of the total volume of freshwater diverted during a given hydrographic event were restrictions imposed by channel capacity and channel obstructions. Widening some reaches of Rincon Bayou in the upper delta that have significant restrictions in channel capacity (*e.g.*, the reach between the Nueces Overflow Channel and the low water crossing at the head of Rincon Bayou) would result in a greater available cross-sectional area and lower frictional resistance.

Also, if existing channel obstructions (*e.g.*, the private road crossing separating the upper and central Rincon Bayou segments, and the remaining fill material in the north end of the Rincon Overflow Channel) were removed, diversion rates during events would improve (Bureau of Reclamation 2000). Also, the amount of water passing out of the delta back into the river through the diversion channel(s) at the end of a given hydrographic event would likely be reduced. Each of these two recommendations would increase the potential for freshwater diversions beyond that provided by the demonstration project design.

As with the short-term demonstration, a long-term diversion project would have to address the issue of voluntary landowner participation. This factor prevented the continuation of the demonstration project. Although key landowners were willing to consider easements that would have allowed project features to remain in perpetuity, a price agreeable to all parties was not able to be negotiated.

OPPORTUNITIES FOR FURTHER ECOLOGICAL STUDY

SELECTION AND MONITORING OF INDICATOR SPECIES

The use of one (or a few individual) species to reflect the overall condition of an ecosystem is not a new concept. For such indicator species to be useful in applied research, they should have the following characteristics: 1) they should direct attention to qualities of their environment, 2) they should give an indication that some environmental characteristic is present, 3) they should express a generalization about their environment, 4) their study should suggest a cause, outcome or remedy, and 5) they should show a need for action (Soule 1988). During the demonstration period, benthic organisms were useful as indicators of ecosystem productivity, particularly in regards to the effects of freshwater inflow.

Benthos

Future monitoring of delta productivity should consider the use of indicator benthic invertebrates. These organisms are useful indicators because they are relatively long-lived and sessile, so they integrate the effects of freshwater inflow over appropriate temporal and spatial scales. Changes in benthic biomass and abundance indicate changes in secondary productivity, and changes in benthic biodiversity are an important indicator of habitat quality. Although the demonstration project focused primarily on infauna (*i.e.*, animals living within sediments), an important aspect of improving inflow conditions in the Nueces Delta is restoring habitat functionality. This issue could be assessed using epifauna (*i.e.*, animals living on or near the sediment surface) as well. Abundances of epifaunal organisms (*e.g.*, shrimp, crabs, mollusks and benthic feeding fish) would indicate habitat utilization.

Because these organisms are highly seasonal, monthly sampling of epifauna would likely be required.

Vegetation

Certain vegetation species have also proved to be useful indicators of the timing and quantity of freshwater inundation needed to promote sexual reproduction and plant expansion in hypersaline marshes. Annual species like *Salicornia bigelovii*, for which successful establishment can only occur if soil salinity concentrations are reduced to a level that alleviates the osmotically induced seed dormancy, could provide relevant information regarding the timing and quantity of fresh water needed to promote sexual (seed) colonization in hypersaline salt marshes. Because this species occurs only after significant freshwater inundation events during the fall and early winter, spring-time biomass samples may be useful in indicating relative plant productivity between the stations.

During the demonstration project, seasonal changes in emergent vegetation cover and biomass were measured and correlated to overall delta productivity in response to freshwater inflow. However, several changes in the sampling procedure could significantly contribute to future monitoring. These changes include the addition of shorter and more closely spaced transects, more detailed sampling of pore water salinity concentrations and focus on the colonization of opportunistic species following major precipitation and inflow events. Primarily, additional vegetation transects should be established in several places located directly on Rincon Bayou. While sampling in the tidal flats near the Rincon Overflow Channel (*i.e.*, Station II) indicated changes after major flow events, vegetational changes directly along the upper portions of Rincon Bayou likely occurred after freshwater flow through the Nueces Overflow Channel during relatively smaller positive-flow events. A useful approach would be to sample four transects all on Rincon Bayou, with the first transect being located close to the Nueces Overflow Channel and the fourth transect being near Nueces Bay. Shorter transects with closer sampling lines may provide a more detailed picture of vegetation changes (*e.g.*, 50-m long transects with sampling lines spaced 2-m apart). Most importantly, every effort should be taken to ensure that salinity measurements are acquired on each sampling date. Ideally, pore water salinity measurements would be taken at 10-m intervals (if a shorter transect were used) rather than 50-m intervals, as accurate and complete salinity measurements are key to understanding the effects of fresh water and consequent changes in vegetation.

MODELING

The demonstration monitoring program documented changes in biological productivity and species composition in relation to the alteration of the freshwater inflow regime. There is an opportunity to integrate the various data components of this study to determine: 1) how the marsh would have responded during the demonstration period without project diversions, and 2) how the marsh ecology would respond to different freshwater inflow conditions Considerably more data would need to be collected to provide these answers through field studies.

A numerical model could be developed to calculate productivity changes in response to prescribed inflow events. One such modeling concept (*e.g.*, the conceptual model presented in Chapter 7) has already been outlined. Once developed, this model could be used to simulate productivity in Nueces Delta with and without the demonstration project by using the existing monitoring data to calibrate the model. The change in productivity with and without freshwater inflow would allow calculation of the percent change due to the observed restored flow volume. This change would be a direct estimate of the benefits of the demonstration project. Furthermore, the modeling of other fresh water input scenarios could be used to estimate the benefits of particular permanent diversion project designs.

A numerical model would also improve the understanding of how the marsh functions under various conditions. Model sensitivity studies could determine transition points within the ecosystem, as well as how to maximize benefits with adjustments in the timing and amount of freshwater inflow.

Additionally, this model, with adequate built-in generality, could be applied to other estuary systems with similar characteristics and freshwater allocation issues.

OPPORTUNITIES FOR INTEGRATION WITH BAY AND ESTUARY RELEASE SCHEDULES

At present, the City of Corpus Christi is required to make pass-through releases of water from the reservoir system on a monthly basis for bay and estuary needs. Because of the high flooding threshold of north bank of the Nueces River, none of this water directly reaches the upper delta. Only with the demonstration project, which allowed for a regular (*i.e.*, daily) exchange of small volumes of water between the river and Rincon Bayou, was released water able to (occasionally) freshen the upper delta. Information gained from the demonstration project indicates that fresh water passing through Rincon Bayou provides a more direct benefit to the estuary ecosystem than water by-passing the Nueces Delta and flowing directly into Nueces Bay. Therefore, this finding suggests an opportunity for integrating a permanent diversion project with reservoir operations.

Demonstration data suggest that the Nueces Estuary would benefit more if freshwater releases could be made in such a way as to trigger positive-flow events into Rincon Bayou and the upper delta. It was observed during the demonstration period that flow events coincident with elevated water levels in Nueces Bay caused a greater proportion of fresh water to be diverted into the upper delta (Ward 2000). Ward (1997) and Chew (1964) have indicated that seasonal secular excursions in the Gulf of Mexico, which are well reflected in water level variations in the upper delta, are likely during the spring and autumn, although with varying magnitudes and durations. There was also an observed seasonality to the ecology of the Nueces Delta. Animal recruitment and marsh plant growth occurred in spring, and nursery habitat utilization in fall. Therefore, given the combined probability of higher water levels in Nueces Bay and increased ecological benefits to living resources during the spring and fall seasons of the year, larger, quarterly (or possibly semi-annual) releases from the reservoir system could be more directly beneficial to the delta ecosystem than smaller, monthly releases.

There are also theoretical reasons why bigger, less frequent inflow events would be more beneficial. An emerging paradigm suggests that large "pulsed," or punctuated, events will favor large phytoplankton that can out-compete small phytoplankton for nutrients when they are present at elevated concentrations (Suttle *et al.* 1988). Therefore, a pulsed nutrient supply will select for larger phytoplankton, which can out-compete smaller phytoplankton (Turpin and Harrison 1980; Suttle *et al.* 1987). This results in a food-web based on large-size phytoplankton, which is much more efficient in transferring nutrients and energy to higher trophic levels than is a food-web which is based on pico- or nano-plankton. For example, a simple model based on empirical data indicates that distributing nitrogen in pulses rather than at a low homogeneous concentration results in 1.5 times more carbon in large zooplankton than would occur if the nutrients were present at a low homogeneous concentration (Suttle *et al.* 1990). The results for phosphate are even more dramatic, where there would be 3.6 times more carbon in large zooplankton under a pulsed delivery regime. These results suggest that releasing water in large pulses rather than in a continuous manner may deliver more necessary resources to fish and other larger consumers in Nueces Estuary.

OPPORTUNITIES FOR ADAPTIVE MANAGEMENT

Incorporating demonstration project features into a permanent diversion project, modifying reservoir operations, and continuing to study resultant biological responses in the Nueces Delta would present a unique opportunity for one of the most comprehensive studies of ecological benefits accrued by adaptive management. Were such an endeavor to be undertaken, four fundamental questions should be addressed:

1) Which delivery schedule provides more benefit to estuary productivity: pulsed or continuous? Included in this question would be a determination of the release volume necessary to trigger a delta diversion event.

2) How far downstream in Rincon Bayou do beneficial effects accrue? That is, the idea that there is a functional linkage between the marsh, delta, and bay should be tested explicitly.

3) Does export from the marsh benefit the bay, and how much water is necessary for this benefit to accrue? There is little doubt of an existing linkage between the marsh and the bay, but it is not clear what volume of fresh water is necessary to maintain a functional linkage.

4) What are the specific trophic linkages between marsh, planktonic, and benthic production, and how do these resources affect production of commercially and recreationally important species (*e.g.*, shrimp, fish and wildlife).

The minimum freshwater flow necessary for maintaining the ecological integrity of bay and estuary ecosystems is an emerging issue in water resources management, nation-wide. The complexity of this issue is further magnified in estuary systems that are supported by a semi-arid watershed and located adjacent to a large metropolitan area. Therefore, the Nueces Delta and Estuary is an ideal place to develop definitive answers to the question of how to most effectively allocate limited freshwater resources.

Figure 8-1: View of the lower Nueces Delta with the City of Corpus Christi in the background.

Photo courtesy of the Bureau of Reclamation.

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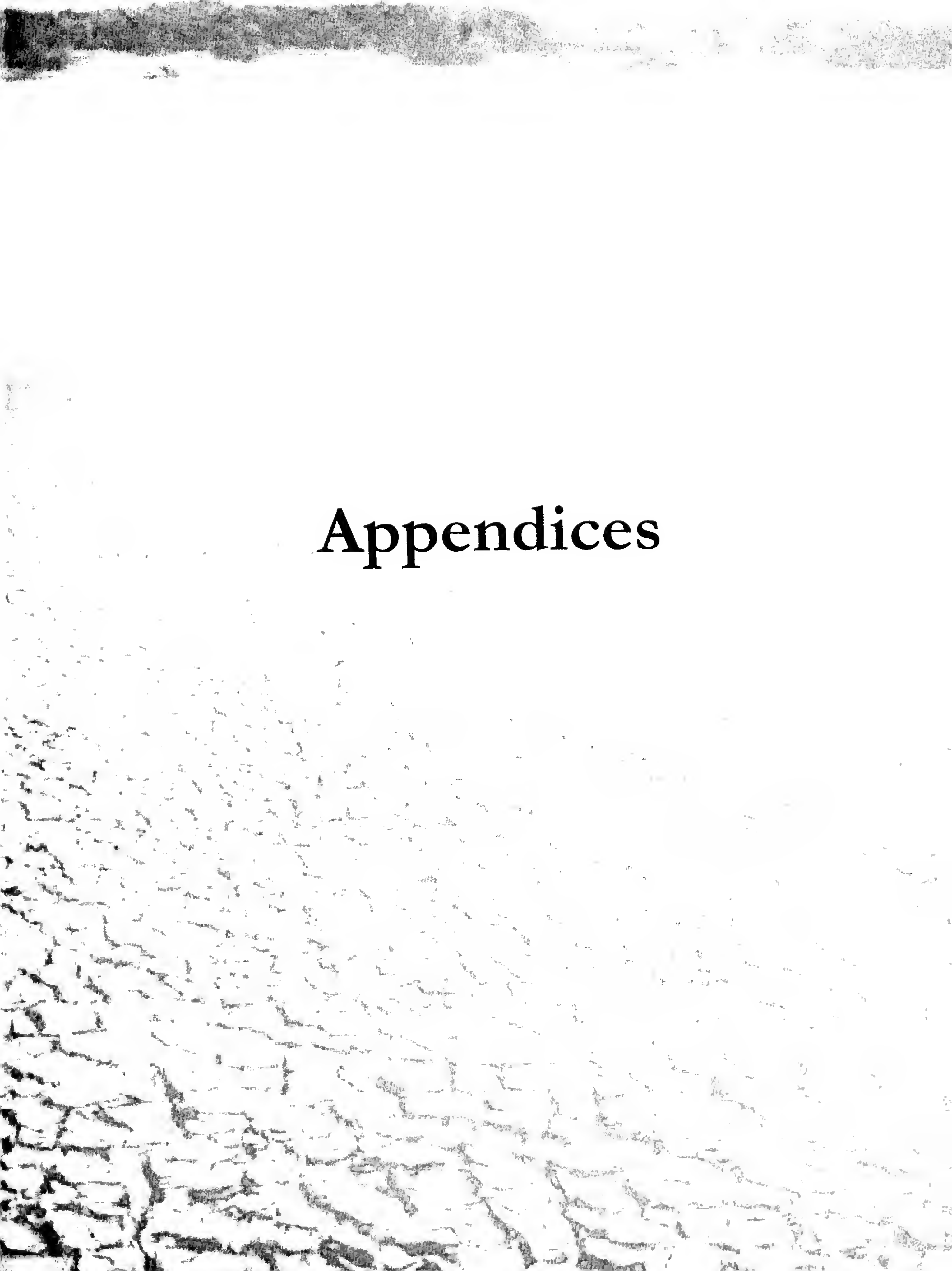

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Technical Notes on the Rincon Gauge and Data

Michael J. Irlbeck U.S. Bureau of Reclamation
Darwin Ockerman United States Geological Survey

INTRODUCTION

On May 16, 1996, as part of the Bureau of Reclamation's (Reclamation) Rincon Bayou Demonstration Project, the U.S. Geological Survey (USGS) installed a stream flow gauging station on the head-water channel of Rincon Bayou (Station 08211503, Rincon Bayou Channel Near Calallen, Texas) located just downstream from the Nueces River Overflow Channel (Figure 1). The purpose of this gauge was to record daily stage and discharge through the overflow channel, and direct precipitation at the site during the demonstration period. Data from the Rincon Gauge was available from the date of its installation (May 16, 1996) through December 31, 1999.

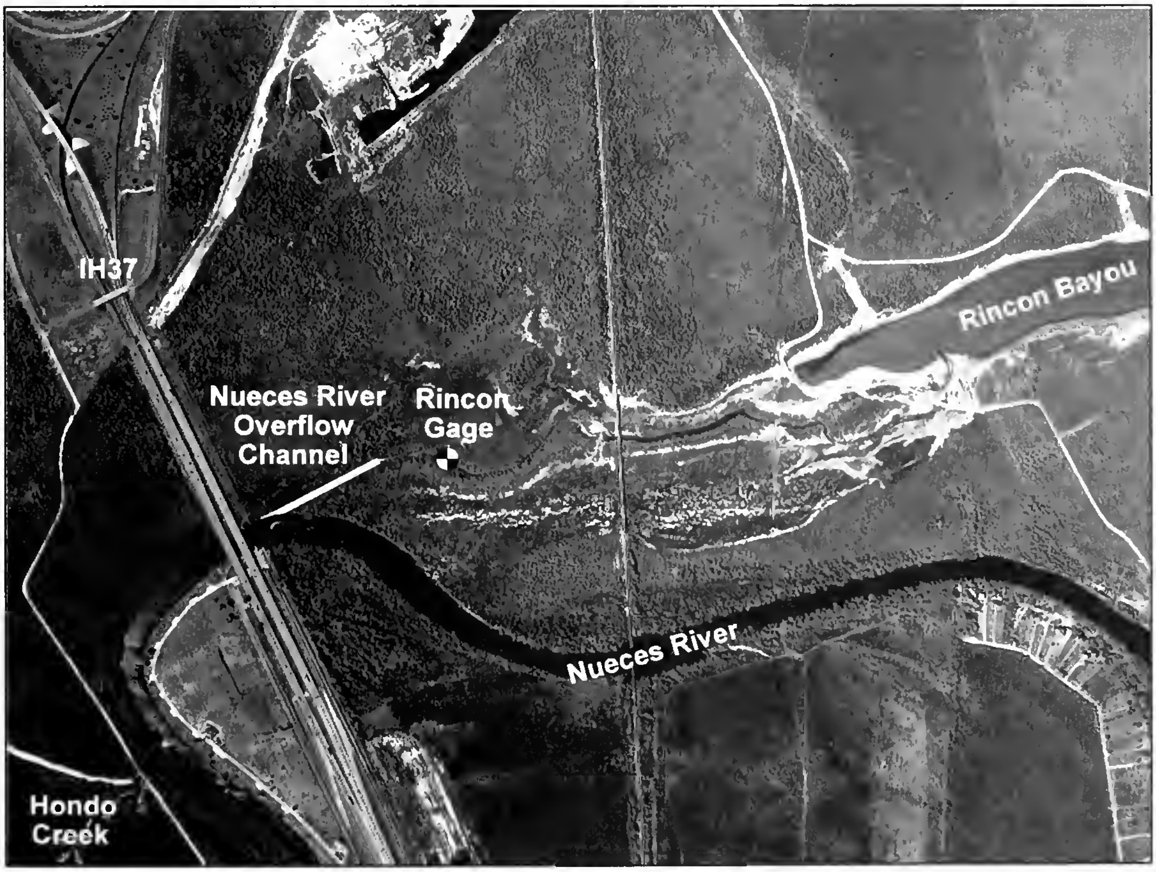


Figure 1: Location of the Rincon gauge.

INSTRUMENTATION

All data from the gauge was measured in 15-minute intervals, stored by a data collection platform (DCP), and transmitted to USGS offices via GOES (Geosyn-chronous Operational Environmental Satellite) in near real time (Figure 2). Water level in the channel was measured by a pressure transducer, and the gauged water level (*i.e.*, gauge height) was referenced to mean sea level. Datum of the gauge is at mean sea level. Flow velocity was measured by an acoustic velocity meter deployed near the center of the channel (Figure 3). The acoustic meter had a resolution of 0.01 feet per second and measured both positive and negative flow in the channel. Rainfall was measured by a tipping bucket rain gauge. Discharge in the channel was computed as the product of the flow cross-sectional area and the mean channel velocity.

Figure 2: View of the Data Collection Platform, Rincon gauge.

Figure 3: View of the gauging instrumentation, Rincon gauge.

At this site, there is no well-defined relation between water level (stage) and discharge due to the effect of tide. The cross-sectional area of flow in the channel is a function of water level in the channel. The relation between water level and cross-sectional area was therefore determined from a cross-section elevation survey. Furthermore, the acoustic velocity meter measures flow velocity at a single point in the channel. Because the measured velocity is not necessarily the mean velocity in the channel, manual discharge measurements were made to determine discharge and mean channel velocity. These measurements of mean channel velocity were related to acoustic velocity measurements by a rating developed from the manual discharge measurements. When actual measured discharge (during calibration measurements) were compared with discharge values determined from calibrated gauge readings, the potential error for flows above 1 cfs were usually within about 10 percent.

SUMMARY OF DATA

Originally, the Nueces Overflow Channel was designed to have a controlling bottom elevation of 2.0 ft msl. However, days after construction of the channel was completed in late October 1995, the Corpus Christi area received 10-12 inches of local rainfall in a 2-day period. The resulting runoff and river discharge scoured the newly cut channel to a new controlling bottom elevation at about mean sea level. The effect of this change was that, in addition to freshwater discharge events through the overflow channel, there was also now the opportunity for regular tidal exchange between the river and the upper delta, even when there was little or no flow coming down the Nueces River. As a result, flow in the channel regularly occurred in both directions during the study period. Positive flow from the Nueces River into Rincon Bayou typically occurred during periods of high discharge in the Nueces River or during rising tide events which pushed water up the river and through the overflow channel. Negative flow from Rincon Bayou into the Nueces River typically occurred when the water level in the upper delta was relatively high immediately after river discharge events or during falling tide conditions.

STAGE

As discussed above, the Rincon gauge is tidally influenced. The stage data recorded by the gauge therefore indicate influences by both freshwater flow events (*i.e.*, stage events driven by discharge in the Nueces River) and saltwater inundation events (*i.e.*, stage events driven by tidal or other hydro-meteorological activity). This dual relationship can be best shown by comparing stage values between the Rincon gauge and the Calallen gauge (Station 08211500, Nueces River at Calallen) (Figure 4). Although there is a strong correlation between the two gauges, the variance in daily stage at the Rincon gauge is about 1.5 to 2.0 ft for any given stage value at Calallen. This variance is the result of tidal influences on the upper delta and the Nueces River below Calallen, which is present regardless of flow in the river.

The maximum stage recorded at the Rincon gauge during a large discharge event in the Nueces River was 7.38 ft msl on October 21, 1998. The maximum stage recorded during a tidal event not influenced by the Nueces River was 5.35 ft msl on August 23, 1999, which was associated with the initial storm surge of Hurricane Bret. A summary of the stage data collected during the study period is displayed in Figure 5 (monthly) and Table 1 (daily).

Table 1: Summary of Daily Stage Data (ft msl), Rincon Gauge. May 16, 1996 - December 31, 1999.

Stage	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	1.62	2.31	2.89	3.30	3.10	5.63	5.34	4.52	5.72	7.25	3.49	1.96
Minimum	1.03	0.97	0.97	1.11	1.32	1.25	1.00	1.08	1.25	1.18	1.05	0.97
Average	1.25	1.43	1.65	1.89	1.80	1.83	1.90	1.59	2.18	2.55	1.79	1.26

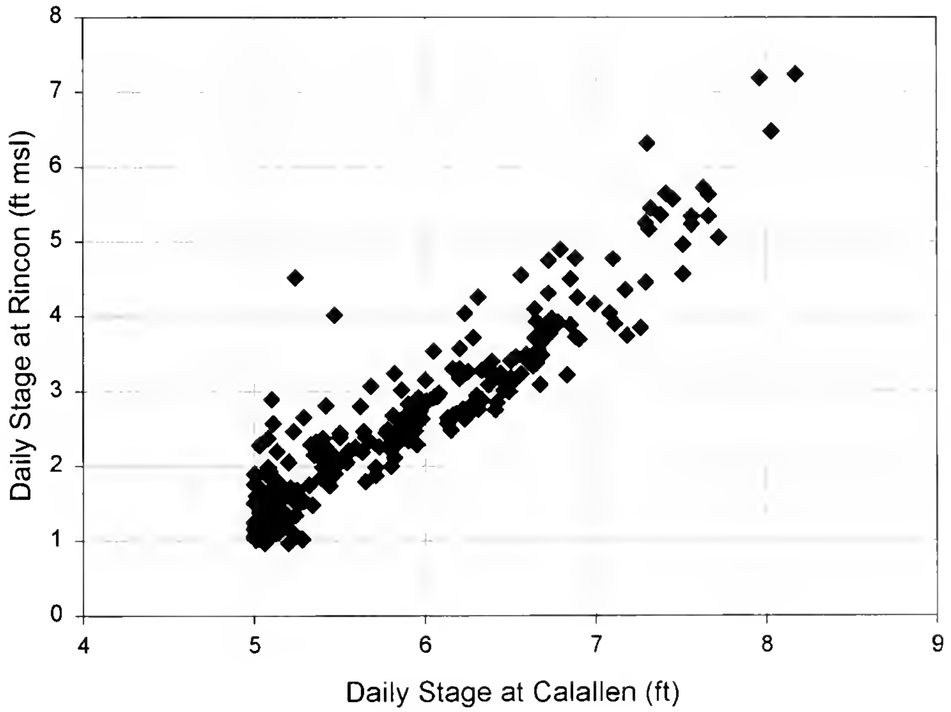


Figure 4: Plot of daily stage values from the Calallen and Rincon gauges. May 16, 1996, through December 31, 1999.

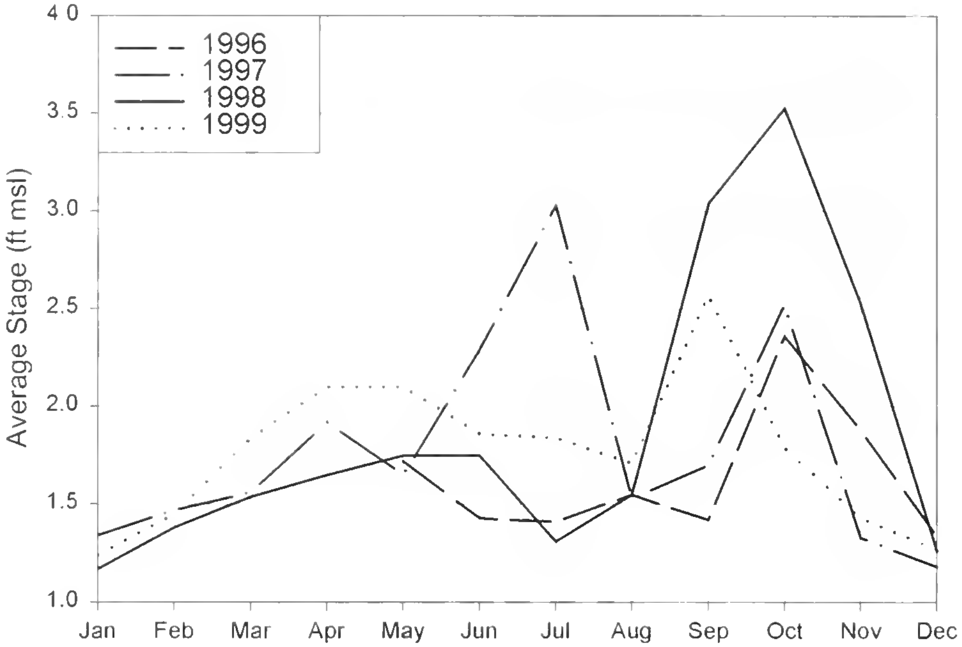


Figure 5: Average monthly stage, Rincon Gauge. May 16, 1996 - December 31, 1999.

DISCHARGE

As with stage, discharge past the Rincon gauge (either positive or negative) was determined by either freshwater flow in the Nueces River or tidal events in the bays, or both. Freshwater flow events were typically infrequent, of high magnitude and positive (i.e. into the delta), while tidally-driven discharge events were more frequent, of lesser magnitude and both positive and negative in direction. However, such a clear distinction between factors affecting discharge through the overflow channel is over simplified. This is because tidal conditions in the lower river and delta consistently exerted a strong influence on the rate of discharge, even during moderate flow events in the Nueces River. For example, daily flow in the Nueces River did not meaningfully contribute to discharge through the Nueces River Overflow Channel when below about 650 cfs, and did not become the dominant factor until river flow exceeded approximately 1,400 cfs (Figure 6). For flow values in the Nueces River below 1,400 cfs, the tide condition at the point of diversion was the dominant factor in determining both the direction and rate of discharge through the overflow channel.

The largest daily discharge event associated with freshwater flow in the river was 274 cfs on October 21, 1998. The largest daily discharge event associated with a tidal event essentially independent of the Nueces River occurred on August 23, 1999, and was approximately 90 cfs. This discharge event was also associated with the initial storm surge of Hurricane Bret. A summary of the discharge data collected during the study period is displayed in Figure 7 (monthly) and Table 2 (daily).

Table 2: Summary of Daily Discharge Data (cfs), Rincon Gauge. May 16, 1996 - December 31, 1999.

Discharge	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	2	9	21	36	29	121	99	90	177	274	22	3
Minimum	0	-2	-9	-13	-14	-12	-69	-42	-60	-66	-16	-1
Average	0.1	0.2	0.4	0.6	-0.4	2.8	3.6	0.0	6.2	11.2	1.0	0.0

PRECIPITATION

Precipitation in the study area was sporadic, but generally coincided with the spring (March through May) and late summer/fall (August through November) seasons. The summer month of July and the winter months of December and January were consistently dry. A summary of the precipitation data collected during the study period is displayed in Figure 8 (monthly) and Table 3 (daily). Specific precipitation events are considered in context with the discussions of significant discharge events.

Table 3: Summary of Daily Rainfall Data (inches), Rincon Gauge. May 16, 1996 - December 31, 1999.

Rainfall	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	0.35	1.49	2.79	2.44	1.65	1.70	0.81	3.38	2.15	4.72	1.39	0.89
Average	0.02	0.06	0.10	0.08	0.06	0.09	0.03	0.15	0.10	0.17	0.06	0.02

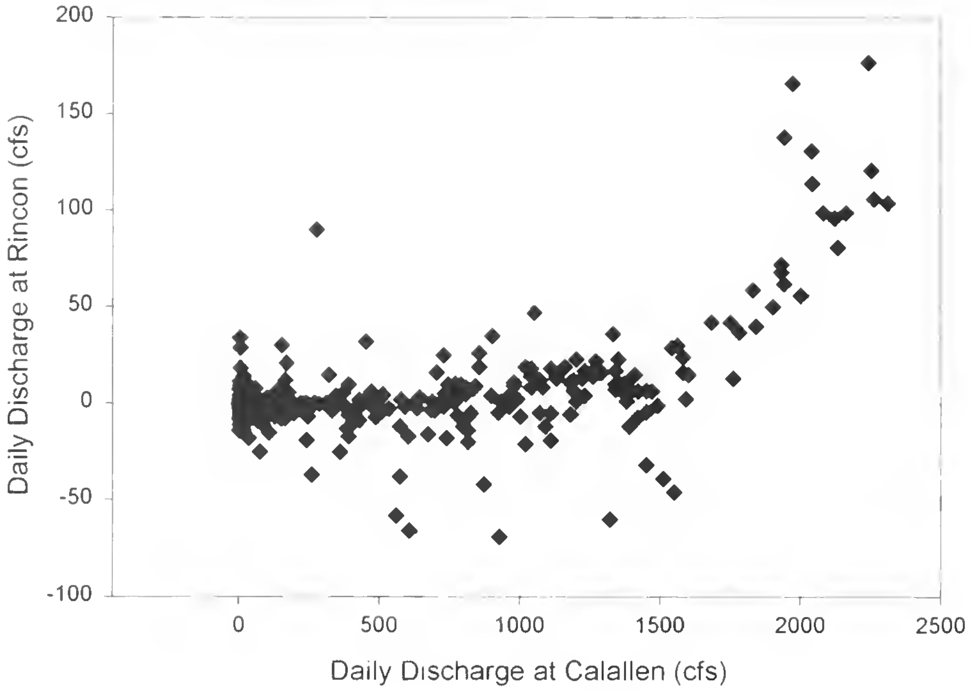


Figure 6: Plot of daily discharge values from the Calallen and Rincon gauges. May 16, 1996, through December 31, 1999. Flow in the Nueces River did not become the dominant factor determining the rate of discharge through the Nueces River Overflow Channel until it exceeded approximately 1,400 cfs.

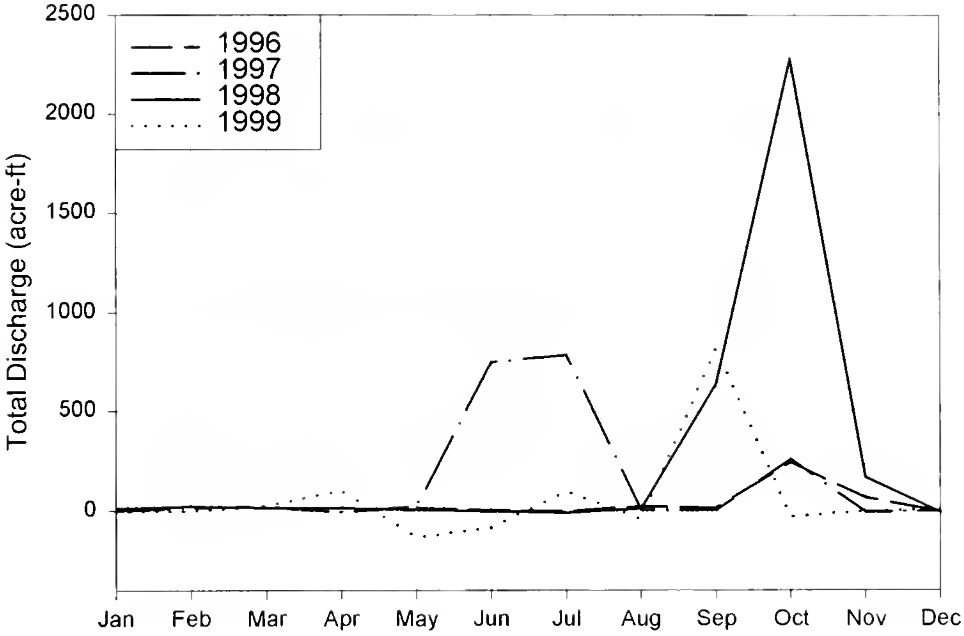


Figure 7: Total monthly discharge, Rincon Gauge. May 16, 1996 - December 31, 1999.

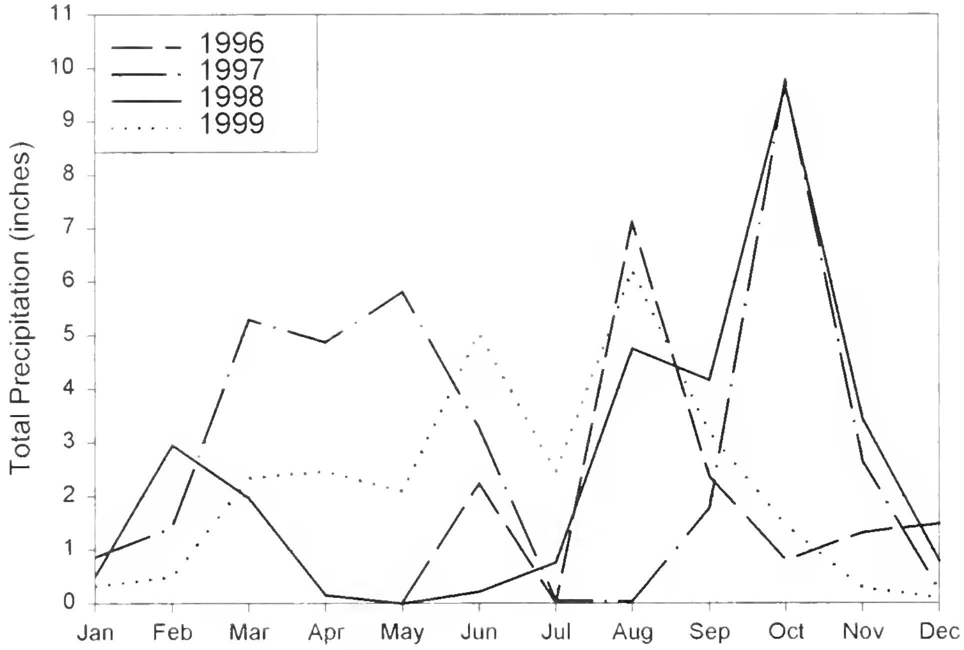


Figure 8: Total monthly rainfall, Rincon Gauge. May 16, 1996 - December 31, 1999.

APPENDIX B

Hydrography of the Nueces Delta and Estuary: 1992-1999

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

BACKGROUND

Three time scales are of pertinence to the evaluation of hydrographic data in the Nueces Estuary: intratidal, intertidal, and event-duration. The intratidal (or intradiurnal) time scale represents short-term behavior at an hourly resolution, the intertidal (or interdiurnal) time scale represents day-to-day variations of hydrographic parameters averaged over 24 hours, and the event-duration scale extends over the time period encompassing all responses to a specific hydrographic event, and can range from several days to many weeks.

DATA SOURCES

Hydrographic data for this analysis were obtained from a variety of sources, including the Texas Coastal Ocean Observing Network (TCOON) marine monitoring system of Texas A&M University-Corpus Christi Conrad Blucher Institute (CBI), the weather station network administered by the National Weather Service (NWS), and the national stream flow gauging program conducted by the United States Geological Survey (USGS) (Table 1).

Table 1: Summary of hydrographic data sources.

DATA SOURCE	Parameter	Measurement Location	Data Type
Nueces River at Calallen, USGS	Estimated daily flow	Nueces River	Data recorded at 15-minute intervals
TCOON system, CBI	Water level Wind direction and velocity Salinity	Nueces and Corpus Christi bays	Data recorded as 6-minute averaged values
Corpus Christi Bay, NWS	Daily precipitation	Corpus Christi International Airport	Data archived as daily values
Rincon Bayou near Calallen, USGS	Water level Current velocity Calculated flow	upper Rincon Bayou	Data recorded at 15-minute intervals
	Daily precipitation		Data archived as daily values

Data obtained from the TCOON system included salinity and water level. For each of these parameters, hourly measurements were obtained from the CBI data archive, and for the analysis reported here, subjected to 24-hour averaging to obtain daily mean values. The salinity data used were from the CBI SALT03 gauge, which is situated due south of White Point in the center of the bay, about equidistant from the mouth of Rincon Bayou and the mouth of the Nueces River, and therefore responds to flow from both conveyances. Salinity concentrations are measured by robot conductivity sensor and converted to salinity, reported in parts per thousand (ppt).

Water level in Nueces Bay was that measured at CBI's White Point gauge, nearer the mouth of Rincon Bayou. While there is no doubt some slope to the water surface in Nueces Bay is in response to meteorology, tides and river hydrographs, this is negligible in comparison to the temporal excursions in water level in the river and marsh. Therefore, stage data from the White Point gauge was regarded as an acceptable indication of the general coincident elevation of Nueces Bay.

The USGS gauges from which data were obtained included the Nueces River at Calallen (Station 08211500) (Calallen gauge) and Rincon Bayou near Calallen (Station 08211503) (Rincon gauge). Flow data were obtained from both gauges, and stage and precipitation data were also obtained from the Rincon gauge. There are significant limitations to the accuracy of the flow data from the Calallen gauge at higher values for two primary reasons. First of all, the gauge ceases to represent the total flow of the Nueces River above about 56.63 m^3/s (2,000 cfs) due to activation of additional flow channels in the floodplain. Second, no reliable field observations of discharge values are available above 77.87 m^3/s (2,750 cfs), so all daily flow values in excess of 77.87 m^3/s (of which there were 3 in the record under review) were estimated by extrapolation.

INTRATIDAL (hour to hour) ANALYSIS

The Nueces Estuary and Delta systems are greatly affected by intratidal processes, including diurnal heating and cooling, tidal inflows and outflows, and short term responses to meteorological forcing, such as sea breezes, convective storms, and frontal passages. Analysis of such short-term behavior provides insight into the dynamics of the study area and the cause-and-effect relations between hydro-meteorological events and the hydrographic response of the Nueces Delta. Most of the variation on this time scale is oscillatory, and therefore obscures the longer period behavior. Intratidal-scale data are best depicted through continuous animated display.

TIME SERIES DISPLAY OF DAILY-MEAN HYDROLOGICAL AND HYDROGRAPHIC DATA

In the process of compiling data on the hydrographic elements of the Rincon Bayou Demonstration Project to support analysis of the various ecological aspects, it was noted that several of the Principal Investigators have data available from the Nueces Delta area dating back to the early 1990's, which might be of potential value as baseline information in assessing the response of the region to the diversion project. Therefore, the compiled data set included as much information that was available for the past decade.

Prior to late-1993, virtually the only extant data is salinity and inflow measured at Calallen. In 1993, reliable records from Conrad Blucher Institute (CBI) tide gauges and anemometers become available. By the date of the breaching of the Nueces Overflow Channel on 26 October 1995, fairly continuous data from the region is available. Only the USGS gauge in the Rincon channel itself is lacking, this not becoming operational until 15 May 1996.

The Nueces Delta in general is subjected to intradaily variations, in response to tides, wind events, water mass replacement, convective storms and other such short-term phenomena. Analysis of such short-term behavior provides insight into the dynamics of the region and the cause-and-effect relations between hydro-meteorological events and the hydrographic response of the Nueces marsh area. It is unlikely, however, that the ecological components respond on such short time scales. In any event, the biological and chemical observations that have been made in this project have been performed on longer time intervals. It is desirable to similarly depict the longer term, daily to weekly variations in the hydrographic environment to facilitate interpretation of the biological response.

For this purpose, daily means have been computed for all of the hydrographic variables. For purposes of effective presentation, a computer display of this daily data has been constructed. Operation of the program "BAION," which should be installed and operated on a PC-type machine, is described below.

PROGRAM OPERATION

Two files were developed:

BAION.exe
IRLBECK.dai

These should be copied into the same directory on your hard drive. The first is the actual program (i.e., executable), and the second is a flat-ASCII data file read by the program. Double-click on the BAION icon (or click on the "START" button on your WINDOWS toolbar, then "RUN...", then enter the path name for BAION in the dialog box). The MS-DOS window will appear displaying the BAION starting banner.

At this point, the program will display a figure showing a circle embedded in a square. You may see an ellipse embedded in a rectangle. If so, you will need to adjust the display of your monitor, by using the controls on the rim of the monitor frame. (Many machines will retain these adjustments in memory, and automatically implement them whenever the same program is activated.) Program operation will resume when you press any key.

The computer will ask for a starting date for the display. For now, you can simply press ENTER, and the display will start at the beginning of the record. Later, you can enter a specific date by using the format YYDDD. You will be prompted for any changes to the plotting scales for the display (answer "no" for now) and then you'll be prompted for assurance that the display should continue (answer "yes"). (The program is rather insecure, and needs frequent encouragement.)

Now the data display will (hopefully) begin. All controls on the program are effected by the keyboard. The bottom line of the display panel summarizes the controls available to the user:

S - slows the rate of the display by inserting a delay between plotted points, can be pressed successive times to further slow the display (but see also "P")
A - accelerates the rate of display by decreasing the time delay between plotted points
P - "pause" or "point" display, holds the present display; each time "P" is pressed an additional point is displayed
R - resumes the default display rate, can be used to cancel the effect of "P"
X - refreshes the axes on the wind panel
L - allows the user to re-scale displays while in progress
Q - terminates the present display

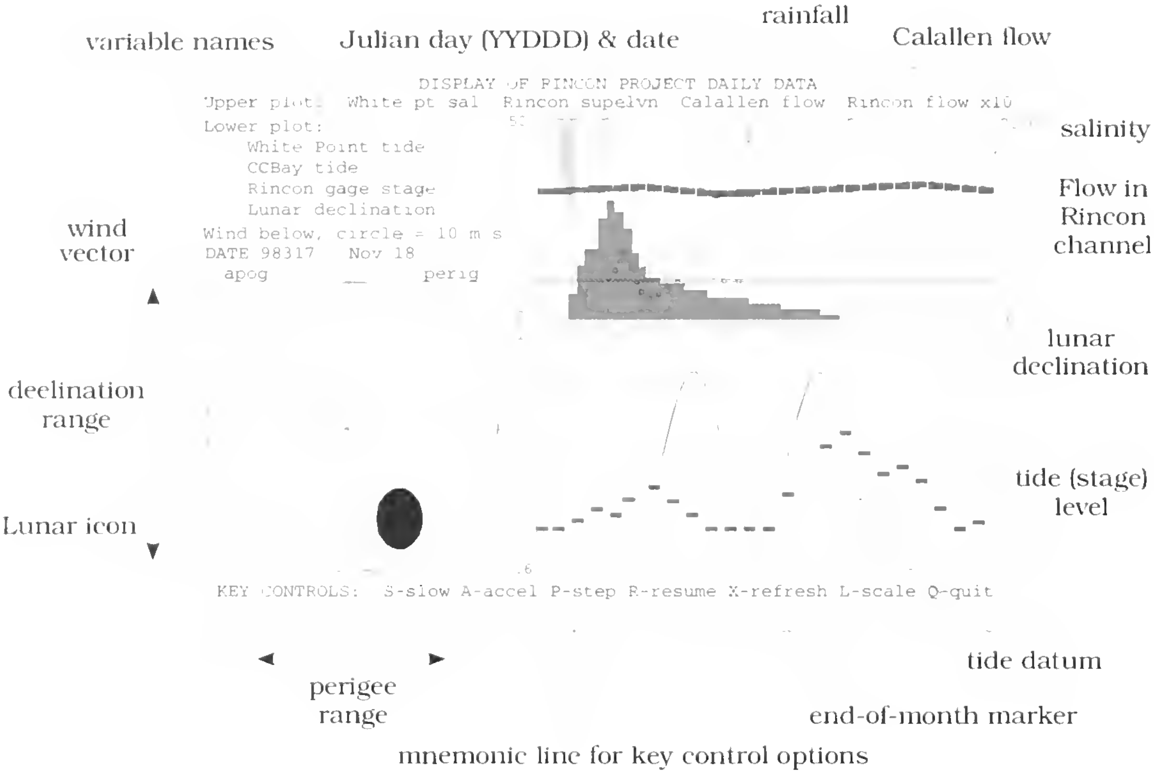
There are three panels in which various data are shown (Figure 1). The panel at the lower left indicates meteorological and astronomical controls. The daily-averaged *vector-mean* wind velocity is shown as a line element terminated by a small circle. (Arrowheads are too hard to plot.) The length of the line segment is proportional to the speed of the wind (the circle indicates 10 m/s) and the orientation of the segment is the direction *to which* the wind is flowing. In the example of Figure 1, the wind blows from SE to NW.

Data from two locations in the region are shown. The yellow vector is representative of the north shore of Corpus Christi Bay. This is primarily the record from the CBI Ingleside anemometer, which is the earliest such record from the project region, beginning in late June 1992. Unfortunately, the data record terminates in December 1996. For the remainder of the period of display (through 31 December 1999), data from the Port Aransas anemometer is used. The combined record is therefore referred to as "North Bay." In July 1994, a red vector is added to the wind display: this is the data record from the Naval Air Station, characterizing the south shore of Corpus Christi Bay. There are frequent gaps in both anemometer records, so the redundancy of two data sources is useful. (These also display the differing responses of the wind depending upon whether it blows over land or water.)

The lower left panel also shows the lunar controls, depicting lunar aspect as a moving icon. The appearance of the icon shows phase of the moon (in Figure 1, the crescent). The vertical (y-) component of the position of the icon is the declination of the moon, and the horizontal (x-) component is an index of the proximity of the moon to the earth, the line marked "apog" corresponding to greatest distance ("apogee") and the line marked "perig" to smallest distance ("perigee"). The 12.4 and 24.8-hr tidal components are virtually eliminated by the 24-hr averaging to which this data has been subjected. The lunar controls on tide are not, therefore, so obvious as when intradaily data are shown, but the lunar declination does account for some of the 15-day oscillation.

Two other panels are shown on the right two-thirds of the screen. The lower of these displays water levels. There are three sites displayed: the CBI White Point tide gauge, the water level of Corpus Christi Bay, and the water level at the Rincon diversion USGS gauge. Corpus Christi Bay is the tide record from the CBI Aquarium gauge, with older records filled in from the CBI Ingleside gauges, *viz.*

Ingleside	92119 - 93268
State Aquarium	93269 - 99365



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                    DISPLAY OF RINCON PROJECT DAILY DATA
Upper plot:  White pt sal  Rincon supelvn  Calallen flow  Rincon flow x10
Lower plot:
    White Point tide
    CCBay tide
    Rincon gage stage
    Lunar declination
Wind below, circle = 10 m s
DATE 98317   Nov 18
  apog              perig

  KEY CONTROLS:  S-slow A-accel P-step R-resume X-refresh L-scale Q-quit
```

Figure 1: Display Screen for BAION.

All three stage records are referenced to the same ("arbitrary") consistent datum. (Also, the 24-hr mean values of the Rincon stage had to be re-computed to reference these to GMT, which is the averaging period for all of the other hydrographic data.) On this same panel, lunar declination is plotted as a faint blue cover. Although declination is indicated by the vertical position of the lunar icon on the left panel, it can be hard to follow in relation to the water level, requiring one eyeball to be fixed on the lower left panel while the other follows one of the traces in the right panel. The vertical lines demarcate months.

The upper panel displays "hydrography", including the salinity variation in upper Nueces Bay, the super-elevation of Rincon gauge over White Point, and the measured discharge in the Rincon diversion channel (starting in May 1996), as well as Calallen flow and regional rainfall. The Rincon discharge is generally about 10% of the flow at Calallen, so it is scaled tenfold to be plotted on the same axis (scale on the right side of panel). The salinity data is from CBI SALT03 gauge, which turns out to be situated due south of White Point, but in the center of the bay about equidistant from the mouth of the Rincon and the mouth of the Nueces. It therefore responds to flows in both conveyances.

Daily rainfall is plotted as a light blue bar, positive downward from the top of the panel. This is a composite data set, consisting of the measurement at the USGS gauge back to May 1996, and the Corpus Christi airport measurement prior to this. The Calallen flow is plotted as a bar graph at the "back" of the panel. This slows down the display, because more time is required to "paint" the record, but this strikes me as a clearer depiction of flow conditions. (Note the jazzy shadows of the data points when a trace crosses a flood hydrograph.)

One problem with the record of super-elevation is that both the White Point and the USGS Rincon gauge peg at low water. The Rincon gauges is especially problematic. For these data, any day with more than 25% of the data (5 measurements) at the low pegged value was deleted from the record. For those days with 5 or less such pegged values, a daily mean was computed using the peg values. (To omit them would overestimate the mean stage.) Approximately 16% of the data at the Rincon gauge proved to be pegged values. Fortunately these were confined to winter or summer low flows, in the absence of significant river flow, so there should be little effect on the use of the data in the biological analyses. However, no super-elevation can be computed when one of the two stage values is missing, so these peg values become gaps in the super-elevation data stream.

COMMENTS ON THE DATA

Upon starting the display at the beginning of the data period, *viz.* 1992, one is immediately struck by the substantial flow hydrographs in the Nueces River. A series of large hydrographs begin in February and continue through June, holding salinity concentrations to virtually fresh throughout this period and the early summer. The Interim Order mandated releases begin in September 1992, and are manifested as the small pulses of inflow occurring near the end of each month. The 1992 fall high water occurs in early October. During this period, the lunar declination is near its maximum attainable value, and only one front of any consequence occurs in the fall, the remainder of the period being dominated by onshore flow from the Gulf.

In late June 1993, a substantial rainfall event over a three day period occurred. Simultaneously, a spike in water levels of over 0.5 m is registered synchronously in Nueces and Corpus Christi Bays. The cumulative rainfall in the event totaled 0.23 m as measured at Corpus Christi. Evidently, such a large volume of rainfall can account for at least part of the observed excursion in water level. A few days later the associated hydrograph on the Nueces reached Calallen and delivered a cumulative 3.3 Mm^3 of inflow. Spread over the 500 km^2 of combined surface area of Corpus Christi and Nueces Bays, this would amount to less than a cm of additional water depth. Indeed, the water-level data from July show no discernible response to the Nueces inflow.

The moral of this comparison is that hydrograph events on the river could be expected to have little impact on the elevation of water in the bay, whereas sudden diluvial rainstorms may have, if the rainfall area encompasses a substantial portion of the bay area. Several such spikes can be seen in the water level histories that correspond to intense rainfalls. On the other hand, the Calallen flow hydrographs create a greater response in the salinity than a rainfall event. The former in fact is a water-mass displacement process, while the latter is a dilution of the rainfall depth throughout the water depth.

The summer 1993 water-level history is a good example of the summer seasonal low water, due to the absence of other hydrographic factors from late June through August. In this same year, the subsequent fall high water is a rather minimal event. The 1994 fall high water is more typical of this annual event.

The only significant hydrographic events occurring during the period after opening of the Nueces Overflow Channel but before the operation of the USGS Rincon gauge are found in October 1995, the month during which the channel was opened. A low but fairly steady flow over Calallen occurred during October but abated the day before the channel was opened. Irlbeck observed that the level of water in the Nueces did not acquire the threshold to force flow through the overflow channel. On 28 October, two days after the channel was opened, an intense rainfall event (over 20 cm in one day) created sufficient local flow to scour down the channel (see Chapter 3 in the draft report). Although a spike in bay water level occurs, the effect on salinity is negligible. For the next several months, only a few minor rainfall events appear in the record, and the bay salinity climbs, nearly monotonically, into the hyper-saline range.

Finally, it should be noted that there are other pathways for flow to enter Rincon marsh, viz. the series of low points in the north levee of the Nueces River. Only when stage in the river becomes sufficiently high does flow begin to pass these other openings. Based upon HEC-2 hydraulic model runs (Bureau of Reclamation 2000), a relation has been developed between the flow in the Rincon channel and the total flow entering Rincon marsh by all of the available routes. The results of this modeling analysis are summarized in the following figure showing the proportion of total flow into the marsh represented by the Rincon channel. For small river stages, this is clearly 100% (Figure 2). Then the proportion rolls off in a sigmoid-like shape approaching a level of about 5%. Considering the sources of error in all of this, the total flow into Rincon marsh can be approximately related to that in the Rincon channel as follows:

$$\text{Combined Q (cfs)} = \begin{array}{lr} \text{Rincon Q} & \text{Rincon Q} < 200 \text{ cfs} \\ 0.8\ (\text{Rincon Q} - 200)\ \text{Rincon Q} & 200 < \text{Rincon Q} < 450 \text{ cfs} \\ 20\ (\text{Rincon Q}) & \text{Rincon Q} > 450 \text{ cfs} \end{array}$$

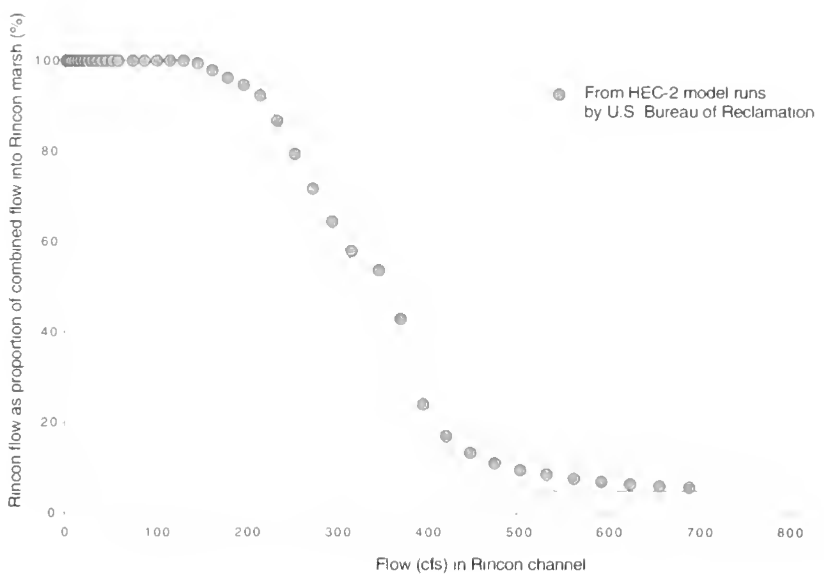

Figure 2: Proportion of combined flow into upper Nueces delta carried by Rincon channel. Source of HEC-2 model run is Bureau of Reclamation (2000).

INTERTIDAL (day to day) ANALYSIS

The depiction of hydrographic time history in the Nueces delta on an intertidal time scale is based upon compiling the data sources and computing their integrated values for each day (24-hour period UCT) within the period of record. (The astronomical tidal period is actually 24.8 hrs, but an average over 24 hours eliminates almost all of the variability it contributes.) The term "integrated" means either averaged or accumulated, whichever is more meaningful for the parameter under consideration. The depiction is best presented either graphically or in tabular summary of the hydrographic variables.

EVENT-DURATION ANALYSIS

The intertidal (day to day) analysis covered the period of January 1992 through December 1999. After inspection of the entire period of record on both intertidal and intratidal scales, criteria were formulated to identify an "event" based upon the separate hydrographic behaviors of each of the key response parameters. These response variables included stage (in Nueces Bay, in Rincon Bayou and a super-elevation of the two), flow (in the Nueces River and in Rincon Bayou), and salinity (in Nueces Bay) (Table 2). It should be emphasized that these criteria were ultimately arbitrary, but were utilized to ensure an objective selection of candidate events for analysis.

It is noteworthy that precipitation was not treated as a separate hydrographic variable, though it was certainly an important hydrographic element in understanding the response of the delta ecology. The reason for its exclusion as a defining parameter was that it provides no information *per se* on the response of the Nueces Estuary or Delta. A similar argument was made for excluding wind as a defining criterion.

Once these criteria were established, the daily data for the period of study was manually inspected. Individual occurrences within the record which met at least one of the six criteria were identified as an "event". Then, for each event, the 24-hour mean data for all hydrographic variables during the event were separated and transferred for individual analysis. The duration period for each event was at least that for which the defining

Table 2: Criteria used to define hydrographic events in the data record by response variables.

RESPONSE PARAMETER	Location	Defining Criteria of a Hydrographic Event
Flow	Nueces River	A 24-hour mean (daily) flow in the Nueces River at Calallen exceeding 14.2 m^3/s (500 cfs).
	Rincon Bayou	A 24-hour mean (daily) flow in Rincon Bayou, either positive or negative, exceeding 0.28 m^3/s (10 cfs).
Stage	Nueces Bay	A 24-hour mean (daily) stage in the water elevation of Nueces Bay exceeding 0.30 m (1.0 ft). [Referenced to the consistent CBI datum from Ward (1997), established by "empirical leveling".]
	Rincon Bayou	A 24-hour mean (daily) stage in the water elevation of Rincon Bayou exceeding 0.61 m (2.0 ft). [Relative to Rincon gauge datum, which is 422 cm above the consistent datum for CBI gauges.]
	Super-elevation	The sum of Rincon Bayou minus Nueces Bay daily stage values exceeding 0.15 m (0.5 ft). [Referenced to common datum.]
Salinity	Nueces Bay	Change in salinity concentrations of Nueces Bay exceeding 5 ppt over a five day period.

criterion was satisfied, though often a longer event period was chosen to be sure that the complete response of the bay or delta was included in the analysis. When several hydrographic events overlapped (*i.e.*, when several variables each satisfied criteria separately and simultaneously), the event duration was at least the period from the first occurrence of the criterion threshold for the earliest parameter to at least the last such threshold for the latest parameter.

The greatest difficulty in separating such events was met when a time series of events occurred in which the response of one parameter overlapped that of the next. For example, a series of river hydrographs might occur, each of which raises Rincon stage or Calallen flow above the threshold defining an event, and a new surge of inflow occurs before the recession of the preceding has subsided. Separating these into individual events was rather arbitrary, and from the estuarine response point of view, such a sequence might acceptably be considered one long event rather than a sequence of separate events.

The parameters compiled for each event include the following: event number, date, duration, rainfall, flow, stage and salinity.

EVENT PARAMETERS

Event Number

For purposes of tracking and reference, each discrete event in the record was assigned an event label. Each event occurring from October 1, 1994, through December 31, 1999 (the duration of the demonstration project), was numbered sequentially in time, beginning with 1. Events occurring before the demonstration period were labeled with sequential letters, beginning with A.

Date and Duration

The span of each event was specified by its starting date. In some cases, the ending date of one event was the starting day of the next, which indicates that a subjective separation had been assumed in the record for purposes of analysis. This arbitrary division may or may not have been capable of differentiation in the actual environment, which may have responded as if the two events were a single "merged" event.

Rainfall

For the period of October 1, 1994, through May 15, 1996 (*i.e.*, prior to the activation of the Rincon gauge), local daily precipitation obtained from Corpus Christi airport, which evidenced a correlation with the USGS gauge on Rincon Bayou near Calallen (Station 08211503) (Rincon gauge) of 0.81 for the 3 years of coincident data. After May 15, 1996, daily precipitation was obtained by the Rincon gauge.

Flow (Nueces River)

Daily values for flow in the Nueces River were obtained from the U.S. Geological Survey (USGS) on the Nueces River at Calallen (Station 08211500) (Calallen gauge). Because no reliable field observations of discharge values were available above 77.87 m^3/s (2,750 cfs), all daily flow values in excess of 77.87 m^3/s were estimated by extrapolation (Irlbeck and Ockerman 2000).

Flow (Rincon Bayou)

For dates before the opening of the Nueces Overflow Channel (October 26, 1995), daily flow data into Rincon Bayou from the Nueces River were estimated from daily stage values recorded at the Calallen gauge using the method described by Irlbeck and Ward (2000). No daily data were available from the period of October 26, 1995, through May 15, 1996, when the Rincon gauge was installed. From that date through the end of the record, flow data reported for Rincon Bayou was the total net daily flow gauged at the Rincon gauge.

It is important to note that, during the demonstration period, the Nueces River did not exceed the natural flooding threshold for the delta, which is 1.71 m (5.60 ft) (Bureau of Reclamation 2000), except for on three occasions. This means that, except for these four events (Events 16, 18, 25 and 36), the only water exchanged between the Nueces River and Rincon Bayou passed through the Nueces Overflow Channel. During the three excepted events, an additional amount of water entered Rincon Bayou naturally via the low depressions along the bank of the river, and was estimated using the hydraulic model developed by Reclamation (2000).

Stage

Water level data for the Nueces Bay and Rincon Bayou were obtained from the Texas Coastal Ocean Observing Network (TCOON) marine monitoring system of Texas A&M University-Corpus Christi Conrad Blucher Institute (CBI) and the USGS Rincon gauge, respectively. The super-elevation of water levels, determined by subtracting the Nueces Bay stage from the Rincon Bayou value, was used to determine the predominant influence on stage in upper Rincon Bayou. On an instantaneous basis, the super-elevation is the direct force for discharge through the Nueces Overflow Channel.

Salinity

Salinity data were obtained from the CBI SALT03 gauge of the TCOON system.

OBSERVATIONS

Freshwater Flow

A principal objective of this demonstration project was to increase the opportunity for partial diversion of flow events in the Nueces River through the Nueces Overflow Channel into Rincon Bayou and the upper delta. The project would thereby periodically increase water levels and inundate regions of the upper marsh, while at the same time reduce salinity concentrations, all of which were considered to be ecologically beneficial. Since the purpose of the demonstration project was to divert a portion of a flood hydrograph on the Nueces through the diversion channel, a logical inquiry was the proportion of such a flood so diverted. The bulk event data can be used to address this question.

Upon examination of the relation between the total flow volume in the Nueces River (for events which met the criteria) and in the Nueces Overflow Channel, it became obvious that there was a general association between the two. The volume diverted increased generally with the flow in the river, and the actual proportion of the flow amount diverted was on the order of 2 percent of that in the river (Figure 3). But this relation, such as it was, evidenced considerable scatter. In further analysis, the data was segregated by water level in Rincon Bayou at 0.3-m (1-ft) intervals. Within each class of water levels, the volume transported through the Nueces Overflow Channel proved to be substantially independent of the volume in the Nueces River. This was somewhat surprising.

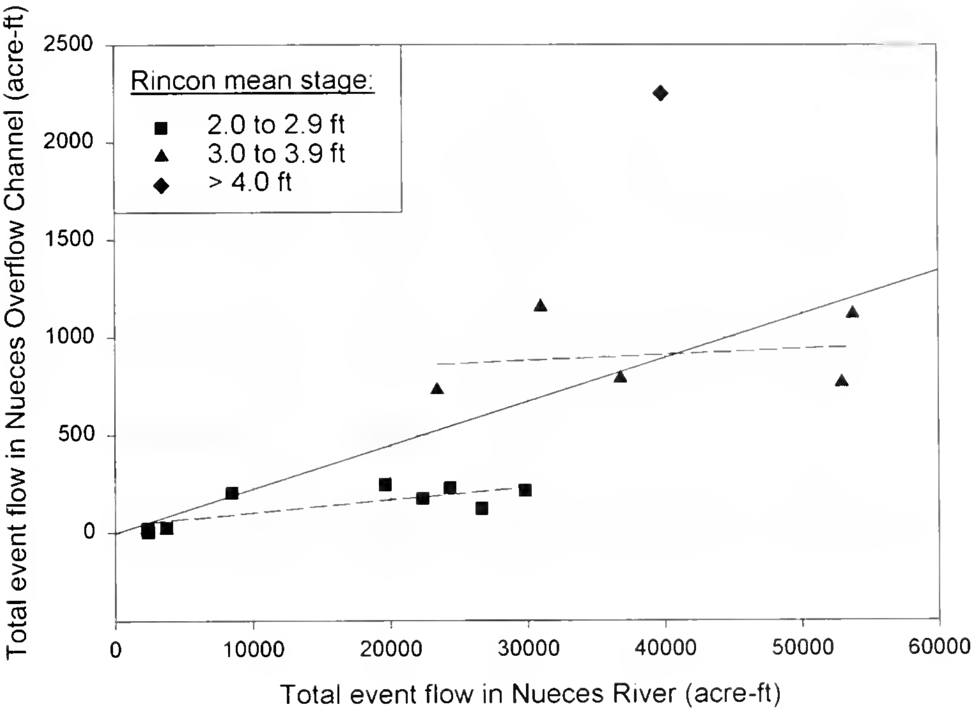

Figure 3: Total flow volume carried in the Nueces River versus total flow volume diverted through the Nueces Overflow Channel. Only events that met criteria for a flow event in the Nueces River were used. The values plotted for Rincon flow volume are the total net exchange, or the integrated positive values.

Note: 1 ft = 0.3046 m, 1 acre-ft = 1.2336 10^3 m^3

That the relation between Nueces River event volume and the volume transported through the Nueces Overflow Channel should depend upon water level was not unexpected, based upon hydraulic considerations. Unlike a river channel system in which the head gradient and the water level (stage) are closely related, there is no direct relation between water level and flow in the Nueces River below Calallen Diversion Dam because of the corrupting effect of tidal and meteorological water-level variations. The Nueces River hydraulic head is superposed on whatever water level is present in Nueces Bay. However, this water level does affect how the river head can drive flow through the overflow channel, because the deeper the water, the greater the cross-section area of the channel and upper delta, and the lower the frictional resistance. Therefore, a given hydraulic head in the Nueces River drives a greater flow through the diversion channel when the Nueces Bay water levels are higher.

The surprising aspect of Figure 3 was the apparent constancy of the volume diverted versus river flow volume for a given class of water levels. For this there are two possible explications. The first is that this observation was an artifact due to the way that a hydrographic "event" was defined (which includes the entire period in which all of the variables respond, then return to their pre-event values or, in the case of salinity, to a stable value). Thus the duration over which Nueces River flow was computed is generally longer than the duration of the flow event in the diversion channel. The rebuttal to this thought is that there is flow in the Nueces River that occurs when there is not flow in the overflow channel, so it was legitimate to integrate over the full hydrograph in the river channel. The second is that this observation was a manifestation of the phenomenon of hydraulic capacity, suggesting that the Nueces Overflow Channel and upper Rincon Bayou very quickly reach their hydraulic capacity shortly after a flood event begins. The result is that the volume diverted through the overflow channel becomes substantially constant, even as flow in the Nueces River increases. The present writers are inclined to this second view. If this constancy of volume is a valid inference, it would imply that the 2% proportion of flow in the Nueces River diverted into Rincon Bayou is itself an artifact of data points corresponding to different Nueces Bay water levels.

Water Level

As with river flow, there was also a proportional increase in total flow through the Nueces Overflow Channel with an increase in super-elevation of stage. A similar sorting by water levels also occurred when the event-duration data for flow volume in Rincon Bayou was plotted against the event mean super-elevation (Figure 4). In this figure, all 28 events were plotted, not just those events which met the criteria, as was done in Figure 3 Again it was observed that the larger flow volumes were associated with greater depths, independent of the magnitude of the super-elevation. Therefore, a given hydraulic head gradient drives a greater flow if the water is deeper.

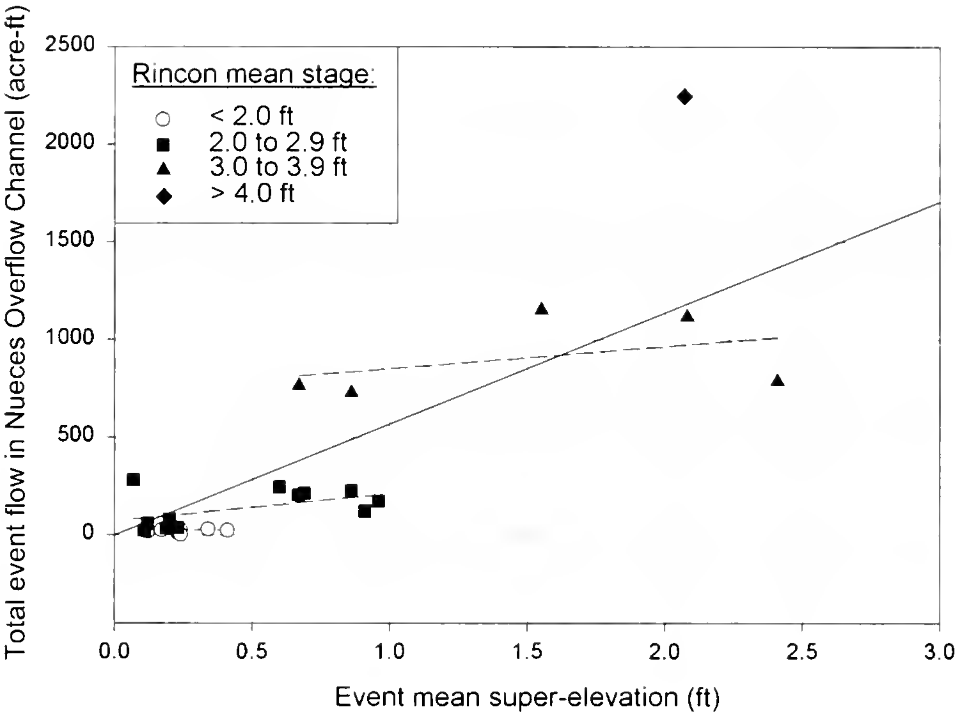

Figure 4: Flow volume diverted through the Nueces Overflow Channel for all events versus event-mean super-elevation.

Note: 1 ft = 0.3046 m, 1 acre-ft = 1.2336 10^3 m^3

Salinity

Upon examination of the relation between salinity response of Nueces Bay before and after the opening of the Nueces Overflow Channel, all hydrographic events occurring from 1992 through 1999 were considered, rather than just those occurring after the initiation of the demonstration project. The incremental percentage salinity responses (%chg) of each event was plotted against the total event flow volume in the Nueces River (Figure 5). Data for events during which the starting salinity was less than 5 ppt were not included due to "noise" in the salinity measurements themselves. Several inferences immediately followed an inspection of this figure.

First, for total event flows greater than 12,336 10^3 m^3 (10,000 acre-ft), there was no obvious difference between the fractional salinity response of events occurring before the opening of the overflow channel and those after it. That is, the same general relation of diminishing percent salinity response with increasing event flow in the

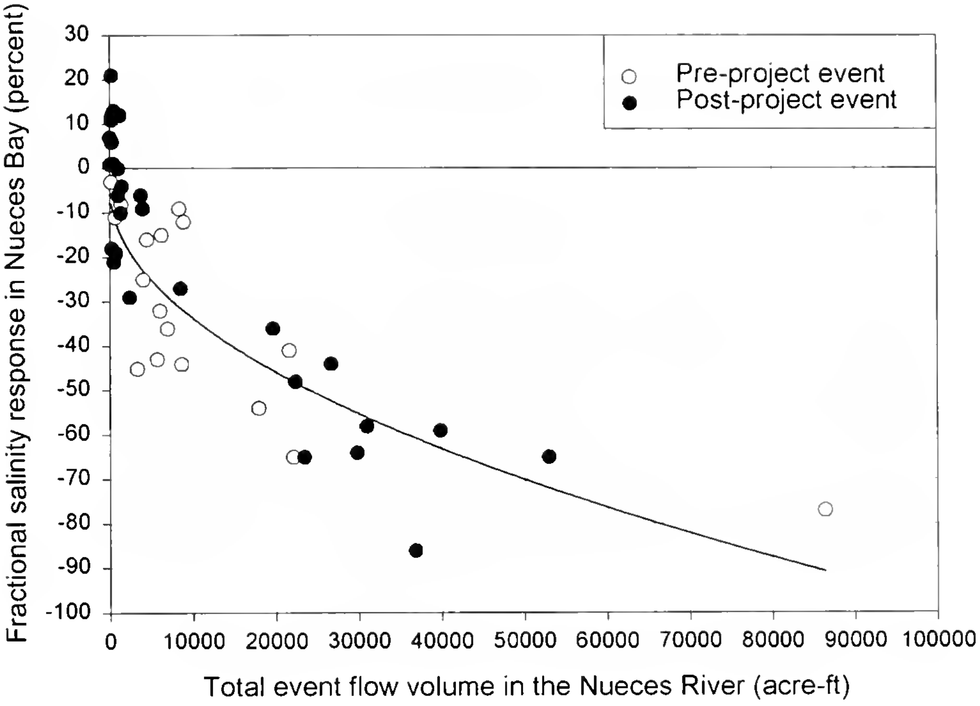

Figure 5: Fractional salinity response versus flow volume in Nueces River (measured at Calallen).
Note: 1 acre-ft = 1.2336 x 10^3 m^3

Nueces River was observed within the scatter of the data. That water diverted through the overflow channel would not measurably affect the response of bay salinity was not surprising, given the very small proportion of flow volume diverted through the overflow channel compared with that in the river.

Second, the rate of decrease of the fractional response (that is, the increase of negative values) with increasing flow in the Nueces River appeared to asymptotically trend to -100%. Considering that the mean water level volume of Nueces Bay is about 49,344 10^3 m^3 (40,000 acre-ft) (Ward 1997), one might have expected the fractional responses to equal -100 percent for flow volumes exceeding this 12,336 10^3 m^3. But this was not the case, probably because the definition of an "event" may encompass some of the period of salinity recovery. Moreover, there were also hydrographic processes that enabled water from lower in the bay (and containing higher salinity) to infiltrate back into Nueces Bay during the event period, including tides and wind forcing. Finally, the adjective effect of the Nueces River depended not only upon its volume, but also the period over which this volume is delivered.

Finally, for total event flow volumes in the Nueces River of less than 12,336 10^3 m^3 (10,000 acre-ft), the fractional salinity response became extremely noisy, and even became positive for a significant number of the events. Restating this observation in another way, below a threshold volume in the river, other non-hydrological factors become equally or more important in affecting the salinity of Nueces Bay, and the apparent value of this threshold is around 12,336 10^3 m^3. Similar threshold-type controls on salinity were theoretically expected and have been found to operate when salinity and flow data are adequate to characterize the response, such as in Trinity Bay in the Galveston system. Although quantification of this threshold was not relevant to evaluating the effects of the subject demonstration project, it may be important in devising operating strategies for future such diversions.

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APPENDIX C

Analysis of the Historic Flow Regime of the Nueces River into the Upper Nueces Delta and of the Potential Restoration Value of the Rincon Bayou Demonstration Project

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INTRODUCTION

Deltaic ecosystems are typically supported by at least one principal river system, and therefore have adapted to and are dependant upon the dynamic fluctuations of that river's flow pattern. This natural flow regime includes the full range of a river's flow quantity, timing and variability, which may fluctuate by hours, days, seasons, years and even decades. Until recently, the importance of the natural stream flow variability in maintaining healthy aquatic ecosystems has been underappreciated in a water development and management framework (Karr 1991, Poff *et al.* 1997). However, it has been shown that the integrity of flowing water systems depends largely upon the components of their natural dynamic character, which is critical in regulating a variety of ecological processes within these ecosystems (Poff and Ward 1989, Richter *et al.* 1996, Walker *et al.* 1995).

In south Texas, the ecological integrity of the Nueces Delta has been primarily determined by the natural flow regime of the Nueces River, which includes the *magnitude, frequency, duration* and *timing* of flow events in the river. Occasionally, high flows in the Nueces River cause the water elevation to exceed the diversion threshold (or, rise above the lowest point along the river bank) and spill into the upper delta. These periodic freshwater inundation events drive several key biological processes important for estuary productivity (Longley 1994). The magnitude of a given flow event is simply the amount of water moving past a fixed location per unit time. Event duration is the period of time associated with a specific flow condition. The frequency of an event refers to how often a flow at a given magnitude recurs over some specified period of time. And the timing of events, or their seasonal predictability, refers to the regularity with which flow events of a specified magnitude occur within a specified time scale.

In 1993, as part of a broader initiative to restore freshwater flows to the greater Nueces Estuary, the United States Bureau of Reclamation (Reclamation) began a multi-year demonstration project designed to increase the opportunity for natural freshwater flow events to enter the upper Nueces Delta. A key component of the Rincon Bayou Demonstration Project was a 900-m long overflow channel which was excavated to connect the Nueces River with the extreme upper reach of Rincon Bayou, the dominant hydraulic feature of the upper delta. A second overflow channel, which connected Rincon Bayou with a broad area of barren tidal flats in the upper delta, was also excavated. These features effectively lowered the flooding threshold of the upper delta and improved the distribution of diverted freshwater.

If the historic flow regime characteristics of the upper Nueces Delta could be defined for the recent past, the impacts of human activities, particularly that of reservoir development and management within the Nueces River watershed, could be analyzed explicitly. These same components could also be used to evaluate the potential alterations to the natural flow regime of the delta system resulting from a variety of restoration or enhancement activities.

OBJECTIVES

The objectives of this analysis were to characterize, through analysis of the magnitude, frequency, duration and timing of flow events:

1) changes in the *historic* freshwater flow regime of the upper Nueces Delta, and
2) the potential for *restoration* of freshwater flow resulting from the Rincon Bayou Demonstration Project.

BACKGROUND

DESCRIPTION OF THE STUDY AREA

As the Nueces River flows toward Corpus Christi Bay along the south Texas coast, it passes along the southern edge of a large delta located in southern San Patricio County (Figure 1). This delta is an integral part of the Nueces Estuary, and is roughly 70 square kilometers (km) in size. The water surface for most of the channels and ponds in the delta is very near sea level, and the low-lying flats are intermittently inundated from the bay by tides and storm surges. The delta is crossed from north to south by numerous buried pipelines and two Missouri-Pacific railroads. One of the most dominant hydraulic features of the upper delta is a broad, tidally-influenced channel known as Rincon Bayou. Between the railroads, the upper delta is separated by a modest ridge of high ground along the southern bank of Rincon Bayou. There is some evidence that this crest is what remains of early diking efforts in the delta, probably for agricultural purposes (US Engineer Office 1939). Downstream of the eastern-most railroad, the elevations are more uniform and tidal interactions make a separation of the northern and southern delta less distinct.

The Nueces River Basin has a total watershed area of approximately 44,224 km^2. Occasionally, larger flood flows in the river spill over the northern bank and inundate the delta with freshwater. These events usually occur shortly after periods of heavy rainfall in the basin, usually coinciding with tropical storm activity in early fall or with the passage of frontal systems in late spring. These sporadic flooding events supply freshwater to plant communities, transport detrital materials from the vegetation and sediments to the bay, provide a medium for nutrient exchange and buffer bay salinity. The Nueces Delta marsh is therefore one of the most important sources of nutrient material for the Nueces Estuary system (Texas Department of Water Resources 1981).

HISTORICAL CHANGES IN THE STUDY AREA

Physical Changes in the Nueces Delta

From a broad perspective, large-scale physical form of the delta has changed little during the period under review (*i.e.*, 1940-1999). Through comparisons of current and historic maps, each of the two railroads which cross the delta from north to south were in places by 1940, and most of the larger pools and channels in the delta resembled their present locations, shapes and sizes (US Engineer Office 1939). The two railroad crossings were elevated by fill material for most of their span, with the exception of a few bridged crossings over the more significant channels. This construction method undoubtedly changed the fundamental hydraulics of the delta system by isolating, restricting, and channelizing some it's water courses, but these changes had already occurred well before the beginning of the period under consideration (*i.e.*, 1940).

The road bridge over the Nueces River near Calallen has been in place since before 1930, but has been rebuilt on several occasions (Texas State Highway Department 1931). In 1931, a two-lane trestle bridge was constructed by the State of Texas as part of improvements to what was then called State Highway 9. This structure was removed and replaced with a standard bridge in 1956, and then improved to a four-lane bridge in 1959 as part of the upgrade to Interstate Highway 37 (Texas State Highway Department 1959). Finally, in 1983, the Interstate Highway 37 (IH 37) bridge was upgraded to its current form.

Presently, the flooding threshold for the majority of the north bank of the Nueces River in the upper reaches of the delta is about 2.36 m (7.75 ft) msl, although some lower channels are present. Given the natural effects of scouring and deposition during large flow events, the Nueces River has likely cut and filled a countless number of depressions in its geologic past, continually altering the flooding threshold with each event. In addition to natural causes, human activity has also contributed to this process of change. As one example, numerous large pieces of concrete rubble and re-bar have been unearthed along the north bank of the river just downstream of

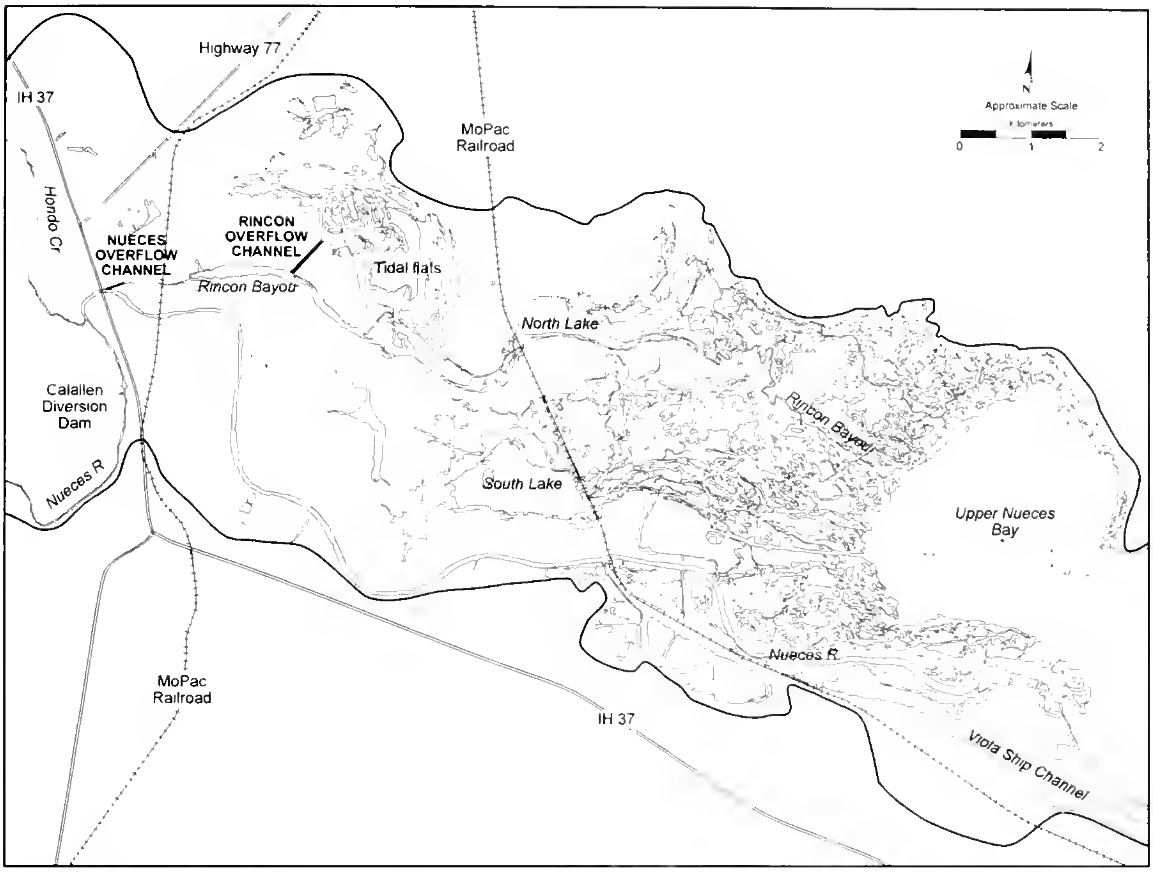


Figure 1: The Nueces Delta. Generally depicted are open water (shaded) and tidally influenced areas. Also shown are the overflow channels that were part of the Rincon Bayou Demonstration Project. Sources of base map: Salas 1993.

IH 37 (Bureau of Reclamation 2000). It is speculated that this material was intentionally placed in low portions of the bank to reduce flooding of adjacent pastures, and was probably acquired from the road bridge renovation during the late 1950's.

Reservoir Construction in the Nueces Watershed

Reservoir development in the Nueces Basin has primarily been initiated by the population centers along the coast in efforts to secure a reliable freshwater supply. The fundamental objective of building such impoundments was to capture large flood events in reservoirs instead of allowing the water to pass into the bays. Stored water could then be released slowly for municipal and industrial consumption, thereby providing a dependable freshwater supply for the community, especially during the periods of frequent drought.

The largest of these communities is the City of Corpus Christi, which was incorporated in 1852. At that time, its citizens obtained their domestic water from shallow wells, cisterns, and natural depressions existing in an arroyo that ran through town. However, during drought conditions, the City often suffered from water shortages when the cisterns and tanks became low or dry from lack of rainfall. Bay water was used to meet any fire fighting needs. In 1887, a committee appointed by the City investigated the possibility of obtaining an adequate water supply from local ground water, but exploration drilling found the source to be brackish and unsuitable for domestic purposes.

Abandoning the idea of using local groundwater, the City looked to the Nueces River. In 1893, the City finished construction of a steam-powered pumping station and distribution system that would provide raw water to the City. The pumping station was located on the south bank of the Nueces River at Calallen, some 16 miles to the northwest of the City. To prevent saltwater from being pumped and distributed during low-flow periods, the City constructed a temporary wooden dam (Calallen Dam) on the Nueces River just downstream of the intake. Then in 1898, a permanent rock-filled dam with a crest elevation of 0.46 m (1.5 ft) msl was completed at the same location. In 1916, the first treatment plant was added at the Calallen pump station. In 1935, the current concrete structure known as Calallen Diversion Dam was completed with a crest elevation of approximately 1.36 m (4.52 ft) msl.

During 1917, another drought threatened the municipal water supply of the growing City of Corpus Christi and the surrounding area. A series of engineering surveys identified a suitable site for a large reservoir on the Nueces River some 35 miles upstream of Calallen Dam. The purpose of the new dam would be to store water for release during the dry periods. Mathis Dam was originally constructed by the City of Corpus Christi early in 1930, but failed in November of that same year. In 1934, a second dam across the Nueces River (La Fruta Dam) was constructed. This new reservoir had a storage capacity of approximately 67,849 10^3 m^3 (55,000 acre-ft).

From 1930 to 1950, the population of the Corpus Christi area increased by over 400% (Corpus Christi 1990). As a result of this increase in demand for municipal and industrial water, and from the loss of reservoir storage in La Fruta Reservoir due to siltation, a new water source was sought, again from the Nueces River. After several years of study, the State of Texas financed the design and construction of Wesley Seale Dam (Lake Corpus Christi), which was completed in 1958. This dam was located about 300 m downstream from La Fruta dam site and was some 6 m higher, inundating the former structure. During the first six years of operation, Lake Corpus Christi was maintained at 26.8 m (88.0 ft) msl, or a capacity of 229,355 10^3 m^3 (185,922 acre-ft), to allow for depletion of oil fields located in the reservoir basin. The crest gates were finally closed on July 1, 1964, bringing the operational lake elevation to 28.6 m (94.0 ft) msl, thereby increasing the storage capacity to 372,550 10^3 m^3 (302,000 acre-ft).

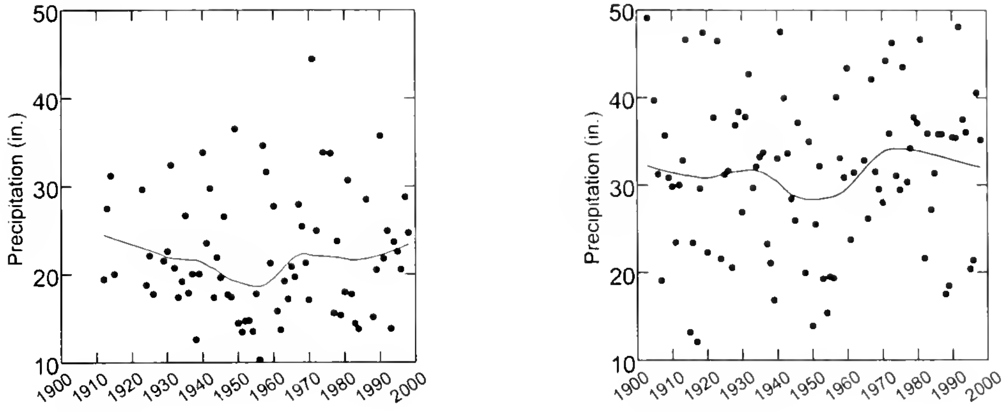
Forecasts of future water requirements for the Coastal Bend area indicated that demand would exceed the firm annual yield of Lake Corpus Christi during the 1980's. In response to the Area Development Water Subcommittee's recommendation, the City of Corpus Christi engaged the Bureau of Reclamation to survey the lower Nueces River Basin to determine a feasible location for a new reservoir to supplement Lake Corpus Christi. Reclamation began construction on Choke Canyon Dam in the summer of 1979, and the project was declared "substantially complete" on May 18, 1982. Due to a drought affecting the Frio River's 14,323 km^2 watershed, flow into the new reservoir was minimal during the first three years, and by May 31, 1987, the reservoir was only at 48% of capacity. However, record rainfall on the Frio River watershed filled the reservoir to 100% on June 18, 1987, and water was released as flood control for the first time. At this level, Choke Canyon Dam impounds approximately 852,584 10^3 m^3 (691,130 acre-ft).

Developed for the purposes of providing a reliable and municipal water supply and flood protection, these dams have contributed to reduced streamflow in the lower Nueces River by their diminutive influence on larger river hydrographs, and through direct water loss to consumptive uses and evaporation. The present permitted firm yield of the reservoir system is 139,000 acre-ft, and a portion of the delivered water returns to the estuary through treated return flows. Because of the relative shallow depth of the two reservoirs and the hot summer climate, evaporation from these two water bodies can remove a significant amount of water from the river system. For example, during 1999 alone, over 217,730 10^3 m^3 (176,500 acre-ft) were lost to evaporation from the combined reservoir system (Hilzinger 2000).

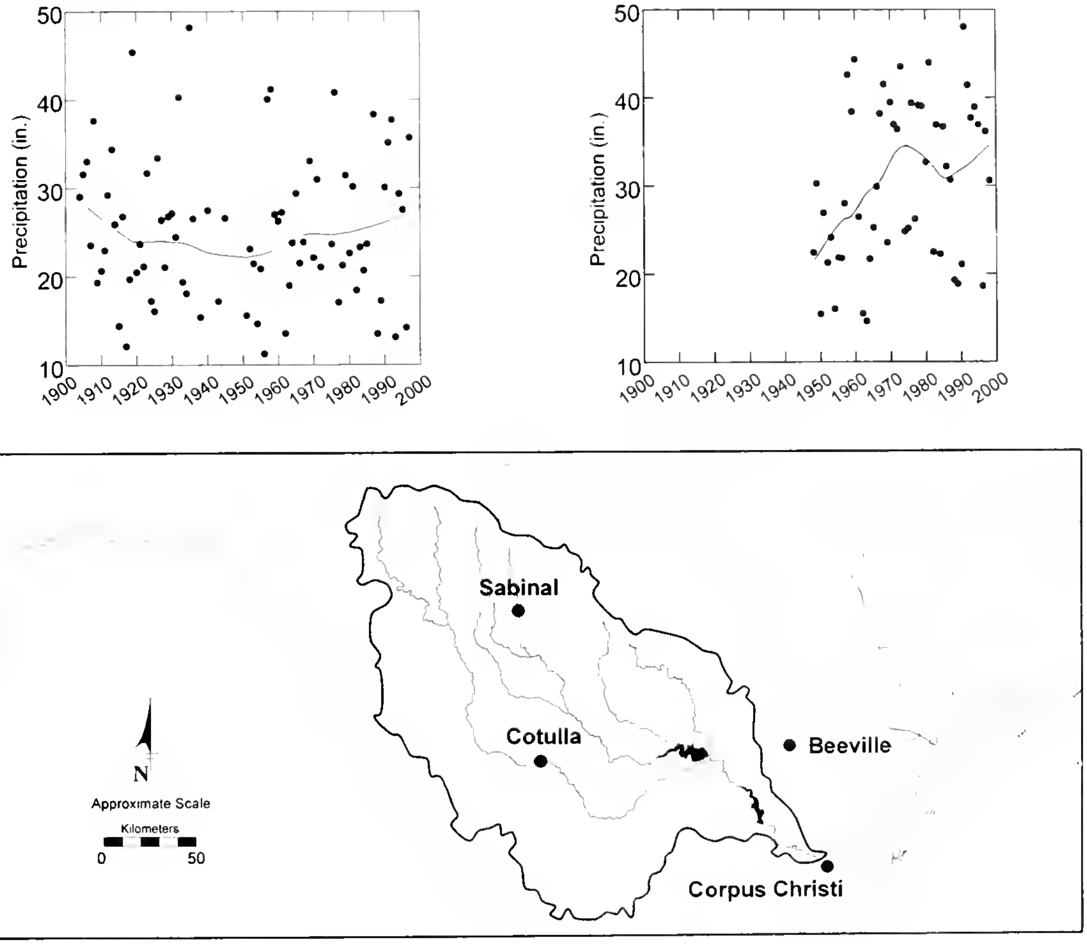
Other Changes in the Nueces Watershed

Another possible factor contributing to decreased stream flow in the lower Nueces River are increased non-reservoir surface water withdrawals in the greater watershed. For example, long-term (1940 to 1990) analysis of reported surface water withdrawls in the basin upstream of the reservoirs indicates an increase of about 60% from 1965 to 1990 (Greene and Slade 1995), which includes much of the operational time period of the current reservoir system.

Also, a decreasing precipitation trend in the Nueces River watershed would be expected to reduce streamflow. However, after analyzing rainfall data from four south Texas gauges (Cotulla, Beeville, Sabinal and Corpus Christi) reflecting conditions for the Nueces watershed, Medina (2000) found that annual precipitation (using a base period that consisted of data since 1900) produced no particular trend (Figures 2a through 2c). Using a baseline that began during the late 1940's (*e.g.*, Figure 2d), annual precipitation portrayed an increasing trend (Medina 2000). The most prominent and common feature of the precipitation data at all stations was the drought of the late 1940's and early 1950's. Similarly, Asquith *et al.* (1997) also found little evidence for statistical trends in precipitation along the Coastal Bend from 1968 through 1993.


(a) Cotulla

(b) Beeville


(c) Sabinal

(d) Corpus Christi

Figure 2: Annual precipitation trends at four gauges about the greater Nueces River watershed since about 1900.

Source: Medina 2000.

Note: 1 inch = 2.54 cm

METHODS

As previously discussed, the Nueces Delta has been a dynamic system in the past, experiencing changes from both natural and man-made causes. During the past 60 years, the major attributes of the delta like general topography, railroad crossings and channel locations have not changed significantly, while smaller modifications, such as flooding thresholds, have occurred. However, lacking the information necessary to define more subtle changes in the study area or to analyze their effects, the assumption was made for the purposes of this analysis that the delta's physical characteristics during the entire period under study have essentially resembled those observed in the field during 1993.

DATA SOURCES

Available data included daily discharge and stage records for several gauges on the Nueces River operated and maintained by the United States Geological Survey (USGS) (Figure 3).

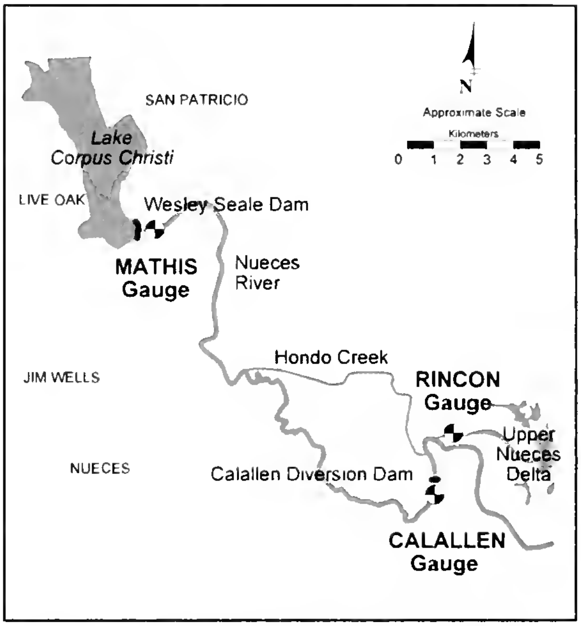


Figure 3: Diagram of the lower Nueces River showing the location of selected stream flow gauging stations..

Mathis Gauge

Station 08211000, the Nueces River Near Mathis, Texas (Mathis gauge), is located on the Nueces River 0.96 km downstream of Wesley Seale Dam (Lake Corpus Christi). The gauge receives flow from approximately 43,512 km^2, or 98.4%, of the watershed. Daily discharge and stage data were available from August 1939, to present. The maximum daily stage value recorded at the Mathis gauge was approximately 3,546 cubic meters per second (m^3/s) (125,000 cfs) on September 25, 1967.

Calallen Gauge

Station 08211500, the Nueces River at Calallen, Texas (Calallen gauge), is located on the Nueces River 0.64 km upstream from Calallen Diversion Dam, approximately 2.3 km upstream from the bridge on Interstate Highway 37 and some 54.6 km downstream from the Mathis gauge. This gauge receives flow from approximately 44,071 km^2, or 99.7% of the watershed. Unpublished daily stage data were available for the period of April 1920 through July 1950 from the USGS District office in Austin, Texas. Reliable daily discharge and stage data are published from October 1989, to present. The Calallen gauge is operated as a low-flow gauge, with daily discharges published only for days when instantaneous maximum discharge does not exceed 72.8 m^3/s (2,570 cfs) (Gandara *et al.* 1996), which corresponds to a daily stage value of about 2.48 m (8.14 ft). However, higher daily stage values up to 4.13 m (13.55 ft) were available from the unpublished record. Datum of the gauge is 0.84 ft above mean sea level.

Rincon Gauge

Station 08211503, Rincon Bayou Channel near Calallen, Texas, (Rincon gauge) was installed and operated by the USGS at the request of the U.S. Bureau of Reclamation as part of their Rincon Bayou Demonstration Project. The objective of this project was to increase the opportunity for freshwater flow events into the upper Nueces Delta. The main feature of the demonstration project was a 305-meter (m) overflow channel excavated from the Nueces River at the point of natural diversion to a small headwater of Rincon Bayou. The Rincon gauge is located in this headwater channel approximately 310 m downstream from the north bank of the Nueces River. Daily stage, discharge and precipitation data are available from May 1996 through December 1999. The maximum daily stage value recorded at the Rincon gauge was 2.21 m (7.25 ft) on October 21, 1998. Datum of the gauge is at mean sea level.

Developing a Daily Stage Record for the Nueces River at the Point of Diversion

The analysis of the Nueces River's flow regime and associated delta flooding characteristics over the past 60 years required a daily stage record for the Nueces River at the point of natural diversion, which was not available. The "point of natural diversion", for the purposes of this investigation, was generally defined as the 2,000-m reach of the north bank of the Nueces River from Interstate Highway 37 downstream to where it sharply bends to the south (Figure 4). In lieu of actual gauge data for this reach of the river, an artificial stage record was developed from correlations of data collected at other gauges in the lower Nueces watershed. This simulated daily record was then used to generally represent flow conditions at the point of diversion.

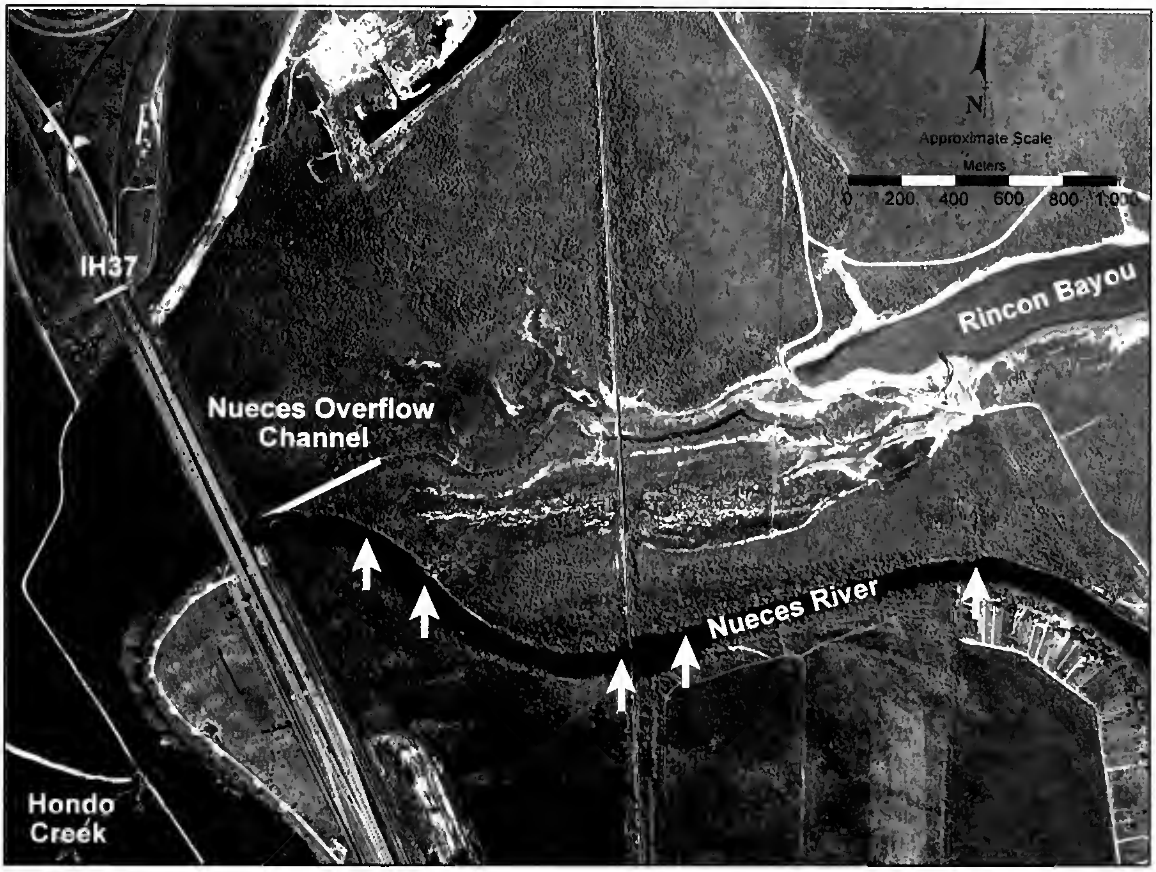


Figure 4: The "point of diversion" along the north bank of the Nueces River. The location of the five natural depressions in the river bank which contribute to delta inflow during a flood event are indicated by arrows (Bureau of Reclamation 2000).

Although measures were taken to minimize the error in the manufactured data record, the accuracy of specific quantitative values estimated by this method is debatable. However, this method does provide a reasonable estimate of general hydraulic conditions in the Nueces River and upper delta during the period under review, and therefore was considered to be acceptable for use in analyzing qualitative (*i.e.*, relative) differences in flow event characteristics. Furthermore, this analysis was exclusively focused on the upper Nueces Delta, or that northern portion of the delta primarily influenced by Rincon Bayou. No attempt was made to characterize the flow regime of the lower (or southern) portions of the delta.

The procedure used to create a daily record of discharge into the upper Nueces Delta from daily Mathis discharge data included two basic steps. First, gauge data was used to correct and correlate Mathis discharge with stage values at Calallen (the Mathis gauge provided the longest reliable daily flow and stage data for the longest continuous period of record on the lower Nueces watershed, or from August 1939 to present). Second, gauge data was used to correlate daily Calallen stage with stage values at the point of diversion.

Correlating Mathis Discharge to Estimated Stage at Calallen

Data from the concurrent periods shared by the Mathis and Calallen gauges (daily records from January 1940 through July 1950, and October 1989 through December 1999) were used to correlate *Mathis discharge* to *Calallen stage.* Prior to this correlation, several modifications to the original Mathis data set were made.

First, the travel time of flow events was examined for the period of concurrent data between the Mathis and Calallen gauges. Based upon this analysis, the average travel time for flow events in the Nueces River to travel from Mathis to Calallen was determined to be about two days. The entire Mathis data set was therefore corrected by delaying each daily flow value by 48 hours. When analyzed individually, however, the actual travel time for the flow peak of any one flow event, which depends greatly upon the characteristics of the individual flood event, has been estimated to take as many as 5 days (Ward 1985). The average correction was used because individual correction of each flow event was not possible for the entire data set due to the absence of daily stage data at Calallen for the period of 1950 through 1989.

Second, the resulting data set was corrected to account for channel losses in the reach between the Mathis and Calallen gauges. HDR Engineering, Inc., *et al.* (1991) calculated an average loss rate of 0.1243% per river kilometers, or a total of 7.0% for the entire 56.3 km reach between Lake Corpus Christi and Calallen Dam. This rate was based on field measurements reported by the United States Geological Survey (1968), and is representative of the loss rate during periods of normal water deliveries with minimal intervening flows. The distance between the Mathis and Calallen gauges is only 54.6 km, slightly shorter than between the two dams, which resulted in only a 6.8% loss rate. A conservative arbitrary value of 8.5 m^3/s (300 cfs) was used to represent the upper limit of "minimal intervening flow". Daily Mathis values below this limit were corrected by a loss of 6.8%. Stream flow losses for daily values in excess of 8.5 m^3/s were assumed to be constant at 0.58 m^3/s (20.4 cfs), or 6.8% times 8.5 m^3/s.

Third, the resulting data set was corrected to account for the estimated total daily municipal and industrial withdrawals made from the Nueces River at or before Calallen Diversion Dam. Estimated total annual withdrawals for every tenth year of the period of record were derived from a number of sources (Homer & Shifrin Consulting Engineers 1951, Bureau of Reclamation 1971, Corpus Christi 1990), and then estimated for each intervening year assuming a linear relationship between the decade totals. Each total annual withdrawal amount was then divided by an average monthly percentage of water use for the Coastal Bend area (Bureau of Reclamation 1971), and the resulting values converted from total volume to average daily flow. These daily values, which represent the estimated daily municipal and industrial withdrawal for that month and year, were then subtracted from the modified Mathis data set. The daily correction values range from 0.20 to 0.25 m^3/s (7 to 9 cfs) in 1940, and from 4.36 to 6.20 m^3/s (154 to 219 cfs) in 1999.

Once the Mathis data set had been thus corrected, the relation between this discharge data and published Calallen stage data was determined through linear regression (Figure 5). Daily values greater than 2.44 m (8.0 ft) from the unpublished Calallen data were also used. In addition, one point was added to the data set as an estimate of the extreme condition. The largest daily flow value recorded at Mathis was 3,539 m^3/s (125,000 cfs) on September 25, 1967, and was a result of the massive flooding caused by Hurricane Beulah. This event occurred during the period for which there is no available stage data at Calallen, but other sources have reported that the Nueces River at Calallen crested at 5.02 m (16.48 ft) the same day (Corpus Christi Times 1967).

This relationship therefore allows the use of Mathis daily discharge data as the independent variable to solve for the corresponding estimated daily stage at Calallen. The entire corrected Mathis discharge data set was then converted to estimated stage at Calallen using this relation.

There are three primary limitations to this method of correlating Mathis and Calallen gauge data. First, as previously discussed, travel times for each flow event vary, which compromises the temporal accuracy of the estimations. The inability to correct each flow event in the record for travel time requires the acceptance of this error. Second, although there is very little additional watershed below Mathis and above Calallen (only 559 km^2), some locally intense storms produce flow events at Calallen that are not recorded at Mathis. This relational difference between the Mathis and Calallen gauge data sets is especially high for tropical storm events that move onshore from the Gulf. Finally, stage data for the Nueces River at Calallen is not available for values in excess of 4.13 m (13.55 ft) (which roughly correspond to a discharge of about 50,000 cfs at Mathis), requiring extrapolation for higher discharge values.

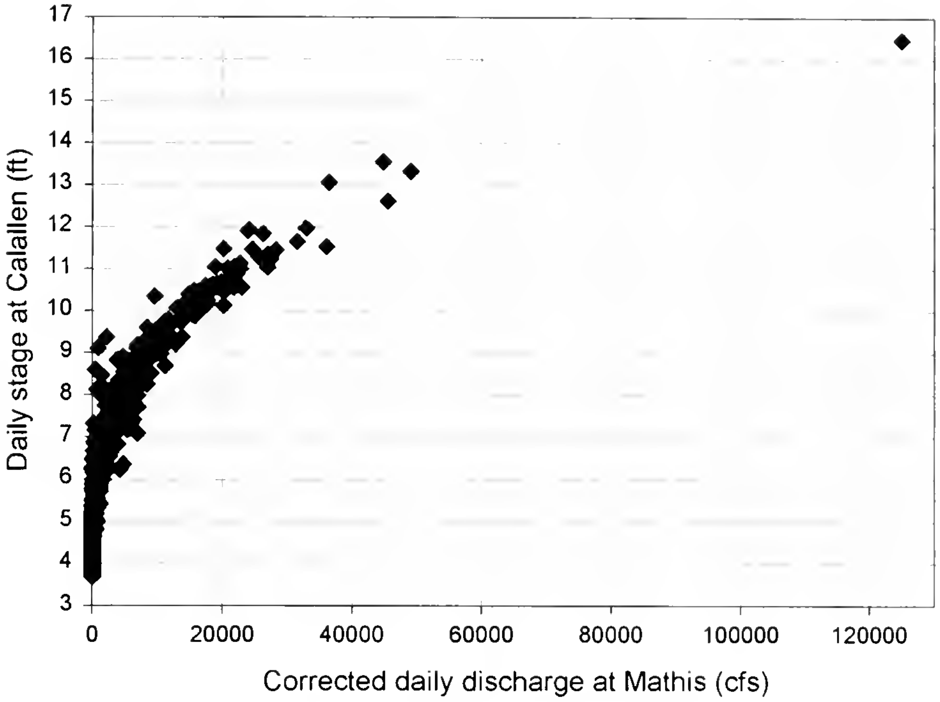


Figure 5: Regression analysis of corrected daily Mathis discharge and daily stage at Calallen.

Note: 1 cfs = 0.0283 m^3/s; 1 ft = 0.3046 m

Correlating Calallen Stage to Estimated Stage at the Point of Diversion

Stage or flow data for the Nueces River downstream of Calallen Dam is extremely limited, but were available from the Rincon gauge for a period of approximately 3½ years. This gauge was located in the headwater channel of Rincon Bayou, approximately 310 m downstream from the point of natural diversion of Nueces River. Therefore, the concurrent period shared by the Calallen and Rincon gauges (daily flow and stage records from May 1996 through December 1999) was used to correlate *Calallen stage* to estimated *stage at the point of diversion.* This included one modification to the original Rincon data set prior to the correlation.

At higher stage values, the Rincon gauge experienced a minor head loss during discharge events, which was estimated to be as much as 0.08 m (0.25 ft) by the Bureau of Reclamation using a hydraulic model (2000). The Rincon stage data was therefore corrected using this model to represent stage at the point of natural diversion before being correlated with Calallen gauge data.

Once the Rincon data set had been corrected, the relationship between daily Calallen stage values and corrected daily stage data at the point of diversion was determined through linear regression (Figure 6). Not used were data from several anomalous stage events recorded at the Rincon gauge (October 1996, November 1996, April 1997, June 1998, and May 1999) which were not associated with discharge at Calallen. In addition, data from two previous maximum stage events were used as estimates of the extreme conditions. First, during the flood of 1919, the maximum stage of the Nueces River recorded at Calallen by the USGS was 4.16 m (13.65 ft), and at the Interstate Highway bridge (representing point of diversion) was 3.75 m (12.3 ft) (Texas State Highway Department 1956). Second, during the 1967 flood, the maximum stage recorded at Calallen was 5.02 m (16.48 ft) (Corpus Christi Times 1967), and at the bridge was 4.63 m (15.2 ft) (Texas State Department of Highways and Public Transportation 1983).

This relationship therefore allows the use of Calallen daily stage data as the independent variable to solve for the corresponding estimated daily stage at the point of natural diversion. The entire estimated Calallen stage data set was then converted to estimated stage at the point of diversion using this relation.

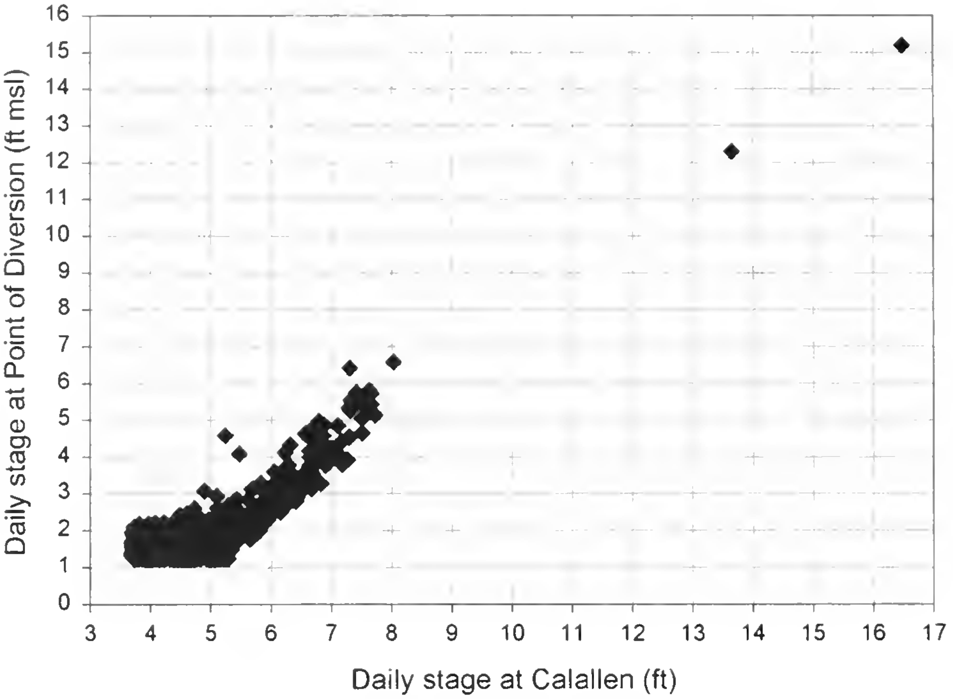


Figure 6: Regression analysis of Calallen daily stage values and daily stage at the Point of Diversion.

Note: 1 ft = 0.3046 m

There are three primary limitations to correlating Calallen stage to stage at the point of diversion. First, under certain conditions, Calallen gauge data does not represent the total river discharge under the IH 37 and past the point of diversion. At higher flows, a portion of the Nueces River spills out of the stream channel upstream of the gauge, and re-enters the river via Hondo Creek below Calallen Dam but above the point of natural diversion. This portion of the river's flow, although relatively small, evades detection at the Calallen gauge (Figures 3 and 7). Second, a variety of tides, storm surges and other hydrographic events in Nueces and Corpus Christi bays also affect the Rincon stage data. Because the Calallen gauge is insulated from all but the most extreme of these events by Calallen Diversion Dam, correlation between the two data sets, especially under low-flow conditions, was "noisy". Finally, the lack of a long-term record at Rincon limits the ability to analyze a full range of hydraulic conditions in the Nueces River.

In summary, the first two steps of this methodology produce a daily stage record which represents the approximate water level of the Nueces River at the point of natural diversion for the period of January 1, 1940, to December 31, 1999.

Figure 7: View of Hondo Creek under flood conditions, June 26, 1997. This road crossing is located approximately 2 miles upstream of the creek's confluence with the Nueces River, which is downstream of the Calallen gauge. The flow is a result of spills from the Nueces River at a point further upstream. Photo courtesy of the Bureau of Reclamation.

ESTIMATING FRESHWATER INFLOW INTO THE UPPER NUECES DELTA

Once a representative daily stage record had been developed for the Nueces River at the point of diversion, two different sets of stage-discharge rating curves were used to estimate daily discharge into the upper delta. Prior to this analysis, the Bureau of Reclamation, as part of their Rincon Bayou Demonstration Project, conducted (1996) and revised (2000) a hydraulic study of the relation between flow in the Nueces River and that in Rincon Bayou. These modeling efforts, which did not address the southern portion of the delta, produced a series of rating curves based on field conditions during March of 1993. Among the scenarios developed were the pre-project (or historical) condition, and the post-project (restored) condition.

Historical Freshwater Inflow into the Upper Nueces Delta

Under the without-project (historical) scenario analyzed by the Bureau of Reclamation (2000), a total of five natural depressions in the north bank of the Nueces River were identified that would naturally contribute to discharge into the delta at various stages in the river (Figure 4). The lowest of these drainage channels was along the west side of the Missouri-Pacific railroad bridge, which had an effective bottom elevation of about 1.64 m (5.4 ft) msl. The hydraulic characteristics of each of these depressions were combined into one commutative set of rating curves, including both a rising and falling limbs, for daily discharge into the upper Nueces Delta (Figures 8 and 9). The obvious "bend" in the rating curves reveal the natural flooding threshold for the greatest part of the river bank, which is about 2.36 m (7.75 ft) msl. Reclamation's without-project rating curves were used without modification, and estimated daily stage values for the Nueces River at the point of diversion were converted to estimate daily discharge into the upper Nueces Delta.

Potential for Restored Freshwater Inflow into the Upper Nueces Delta

Base on data obtained from the Rincon gauge, the Bureau of Reclamation (2000) also constructed a set of rating curves, including both rising and falling limbs, which estimated daily discharge into the upper Nueces Delta with the demonstration project features in place (restored condition) (Figures 8 and 9). Because of the compromising effect of tide on water elevations at the point of diversion, and therefore on discharge estimates, these curves did not estimate discharge into the upper delta when the stage in the Nueces River was 0.76 m (2.50 ft) or below.

However, when discharge estimates for individual events using the falling limb curve (which represented an average of several observed events) were compared with actual discharge data from the Rincon gauge, the results were unsatisfactorily inconsistent. Upon examination, it was discovered that, although the falling limb curve of each event expressed the same slope when plotted, the beginning point of each curve depended upon the maximum water surface elevation attained by the Nueces River during that particular event. Therefore, a series of falling limb curves were subsequently constructed by extrapolation of the average curve in 0.1-ft intervals. Discharge estimates for individual events using the modified, event-specific set of rating curves were then tested for accuracy, this time with acceptable results. For each of the eight (8) major freshwater flow events recorded at the Rincon gauge, the estimated discharge was within about 10% of the actual for five (5) events, and within about 25% of the actual for two (2) others (Table 1). The combined accuracy for all discharge estimates made using the revised rating curves for the restored condition, including all eight events, was about 14% over the actual gauged discharge value.

Once an acceptable set of rating curves for the "restored" condition was thus developed, the estimated daily stage values for the Nueces River at the point of diversion were converted to estimated daily discharge into the upper Nueces Delta.

DEFINITION OF FLOW REGIME PARAMETERS

From the two sets of daily inflow data (*i.e.*, historic and restored conditions), four separate flow regime characteristics were analyzed; including, event *magnitude*, *duration*, *frequency* and *timing*. First of all, event *magnitude* was used to indicate the amount of discharge from the Nueces River into the upper Nueces Delta during the period under consideration, and was determined by separating the estimated daily discharge values by period, and then averaging these by month. Next, event *duration* was used to express the cumulative length of flow events, and was determined by averaging the total number of days in which the stage of the Nueces River exceeded the flooding threshold (event days), regardless of discharge amounts. Also, event *frequency* was used to estimate the return period of peak daily flow events into the delta, and was determined by summing the number of events in each period that attained a given peak daily discharge amount, and then dividing this total by the

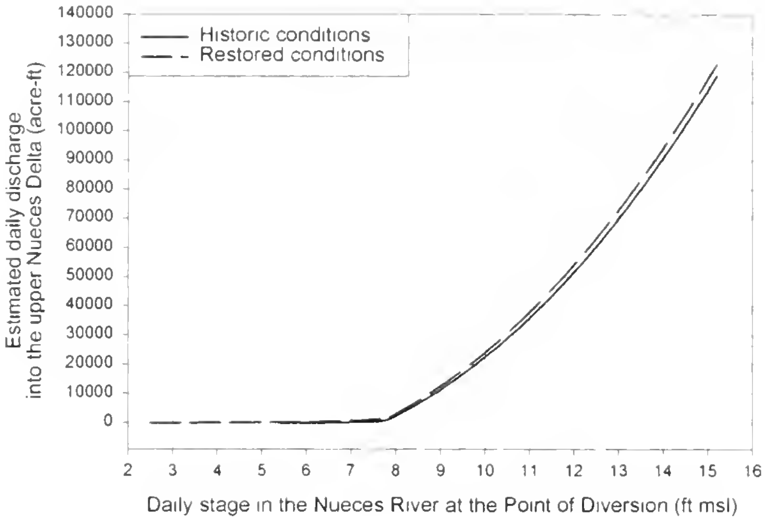


Figure 8: Stage-discharge rating curves for the Nueces River into the upper Nueces Delta, including both historic and restored conditions. Full range of stage values shown.

Note: 1 acre-ft = 1.2335 10^3 m^3, 1 ft = 0.3046 m.

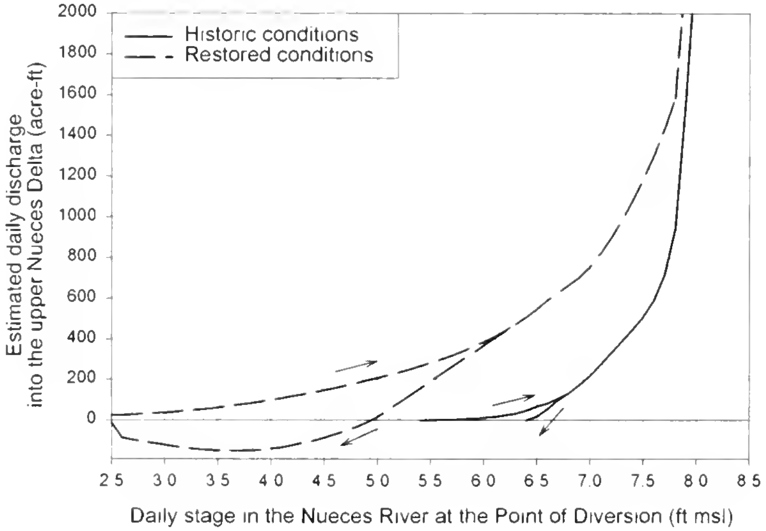


Figure 9: Stage-discharge rating curves for the Nueces River into the upper Nueces Delta, including both historic and restored conditions. Only lower stage values shown to emphasize the rising and (average) falling limbs of each curve.

Note: 1 acre-ft = 1.2335 10^3 m^3, 1 ft = 0.3046 m.

Table 1: Comparison of estimated versus actual discharge into the upper Nueces Delta using curves from Bureau of Reclamation (2000), with modified falling limb curves. Only daily stage values greater than 0.76 m (2.5 ft) msl during each event were used.

EVENT DATE		Total Duration (days)	Actual Discharge (acre-ft)	Estimated Discharge (acre-ft)	Deviation from Actual	Maximum Stage Attained (ft msl)
1997	**Jun 23 - Jul 10**	27	1,657	1,559	-5.9%	5.72
	Oct 9-17	9	486	1,232	153.5%	5.74
1998	**Mar 30**	1	24	26	8.3%	2.6
	Sep 5-21	17	614	547	-10.9%	4.43
	Sep 25 - Nov 11	48	3,609	3,888	7.7%	7.31
1999	**Mar 27 - Apr 7**	12	191	201	5.2%	3.36
	Jun 30 - Jul 7	8	171	130	-24.0%	3.22
	Aug 23 - Sep 13	22	988	1,254	26.9%	5.81
TOTAL			7,740	8,837	14.2%	

Note: 1 acre-ft = 1.2336 10^3 m^3, 1 ft = 0.3046 m

number of years in the period (annual frequency). Daily peak values greater than 123 10^3 m^3 (100 acre-ft) were rounded to the nearest hundred, and those less than this were rounded to the nearest ten. From annual frequency, cumulative frequency was then determined by incremental summation. The return period of peak flow events for a given magnitude in each period was then calculated as the inverse of cumulative frequency. Finally, event *timing* was used to identify seasonal and annual patterns in flow events, and was determined by summing daily discharge values by week for the entire period under review.

RESULTS

For purposes of comparison, the 60-year record under investigation was divided into three separate periods, each corresponding to the construction of a major reservoir in the basin (Table 2).

Period I extends from January 1, 1940 to April 9, 1958 (approximately 18.3 years). During this period the only major regulating structure in the basin was La Fruta Dam on the Nueces River. The dam's influence on larger flood events in the watershed was limited because the storage capacity of the reservoirs capacity was relatively small to begin with, and this decreased significantly overtime due to sedimentation (City of Corpus Christi 1990). Given the absence of data prior to this structure, Period I therefore represents approximate "baseline" conditions in the watershed with, minimal influences on stream flow from reservoir construction.

Period II extends from April 10, 1958, when Wesley E. Seale Dam was closed, to May 17, 1982 (approximately 24.1 years). Wesley Seale Dam was also constructed on the Nueces River just downstream of the La Fruta dam site, submerging and replacing it as the City of Corpus Christi's primary water supply. Once completed, the larger size of Wesley Seale Dam enabled it to more significantly affect flood events. Period II therefore represents an intermediate period of reservoir development in the watershed.

Period III extends from May 18, 1982, when Choke Canyon Dam on the Frio River was declared substantially complete, to December 31, 1999 (approximately 17.6 years). The addition of Choke Canyon Dam's storage capacity to that of Lake Corpus Christi increased the total storage capacity in the basin to over 1,221,165 10^3 m^3 (990,000 acre-ft). For the latter part of this period (since June 24, 1997), Lake Corpus Christi was operated at an elevation of only 27.74 m (91.0 ft) msl (effective storage capacity of approximately 229,431 10^3 m^3 (186,000 acre-ft)) because of safety concerns. Period III therefore represents the climax period (or present conditions) of reservoir development and operation in the watershed.

For each of these three periods, data from the largest flood event in that period was not considered in the analysis of flood event magnitude, frequency and duration for two primary reasons. First, these events were considered extra-ordinary, and therefore were not typical of the more frequent flow events of primary interest in this analysis. Second, the duration of each of the three periods was not deemed adequate to statistically appreciate the full dimensions of these events. For example, data for the flood event of 1967 (Period II), which is the largest on record in the past century, would have only been considered within a 24.1-year span, and would therefore have unacceptably skewed the results of that period, especially during the months in which the event occurred. Accordingly, the omitted flow events for Periods I, II and III were July 1942, September-October 1967, and June-July 1987, respectively. All flow events, however, were included in the analysis of event timing, which is a more subjective measure where the full dimensions of each event are relevant for purposes of historical comparison.

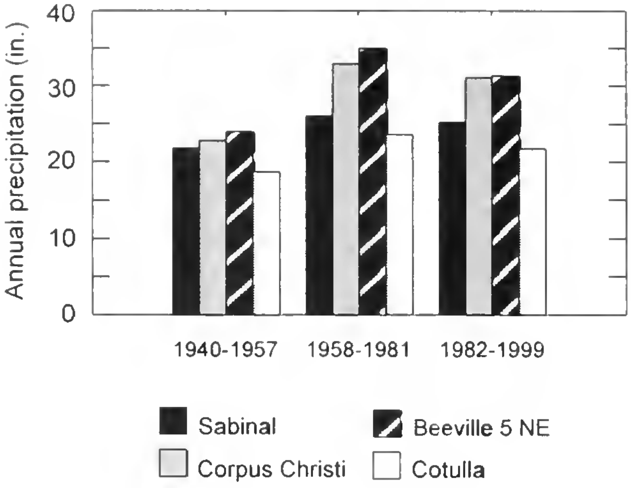


Figure 10: Mean annual precipitation of available data at four gauges about the greater Nueces River watershed.
Source: Medina 2000. Note: 1 inch = 2.54 cm

It is interesting to note that Medina (2000) found the mean annual precipitation in the greater watershed during the first period (1940 through 1957) was consistently the smallest when compared with the other two periods (1958 through 1981, and 1982 through 1999) (Figure 10). The distribution of large precipitation events were also found to be less frequent during the drought years of the late 1940's and early 1950's than in the latter two periods, which were not significantly different from each other (Medina 2000). This information is relevant because this first period, which was used as the baseline for calculating percent changes in delta inflow, likely under-represents, to some degree, the actual baseline conditions.

HISTORICAL FRESHWATER INFLOW INTO THE UPPER NUECES DELTA

Magnitude

Historical event magnitude during Period I exhibited two primary peaks, one in the spring (May) and one in the fall (September), each at over 43,173 10^3 m^3 (35,000 acre-ft) per month (Figure 11). During Period II, event magnitude also peaked twice during the year, but at lower discharge amounts. The spring peak (June), which was less defined than in Period I, attained only about 8,635 10^3 m^3 (7,000 acre-ft), while the fall peak (October) attained almost 30,838 10^3 m^3 (25,000 acre-ft). During Period III, the trend of decreasing event magnitude was observed in extreme. No annual peaks were obvious, and the highest monthly average discharge amount was less than 370 10^3 m^3 (300 acre-ft) (May).

Annual event magnitude represents the sum of all daily discharge values during the period divided by the period's duration in years. During Period II, or after the construction of Wesley Seale Dam, annual event magnitude decreased by 39% compared to Period I (Table 3). Since the construction of Choke Canyon Dam (Period III), the annual event magnitude of discharge events into the upper Nueces Delta decreased by over 99% from Period I.

Table 3: Summary of historic annual event magnitude in the upper Nueces Delta. Mean discharge values rounded to the nearest 10 acre-ft.

Period	Historic Mean Total Discharge per Year (acre-ft)	Percent Change from Period I
I: 1940-1958	128,000	-
II: 1958-1982	78,000	-39%
III: 1982-1999	540	-99.6%

Note: 1 acre-ft = 1.2335 10^3 m^3

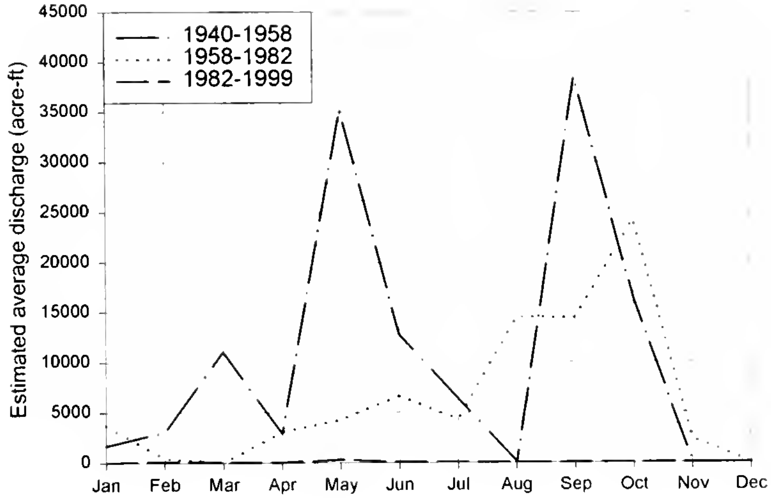


Figure 11: Historic magnitude of flow events into the upper Nueces Delta. Not included were data from the largest event in each time period.

Note: 1 acre-ft = 1.2335 10^3 m^3.

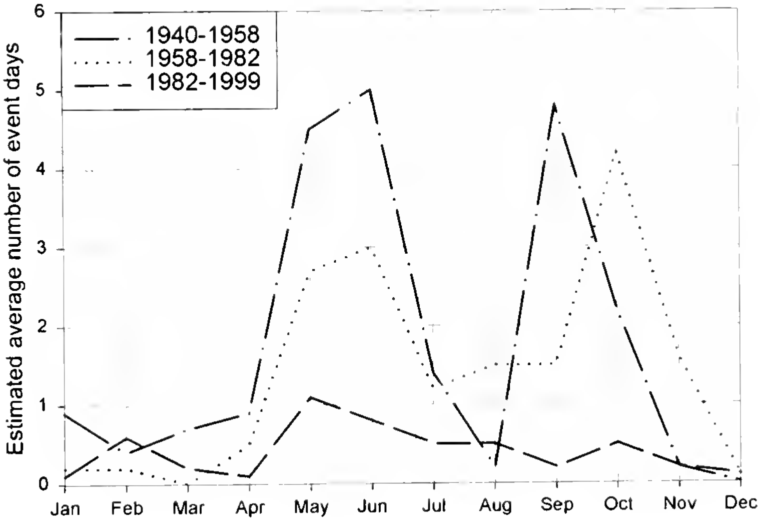


Figure 12: Historic duration of flow events into the upper Nueces Delta. Not included were data from the largest event in each time period.

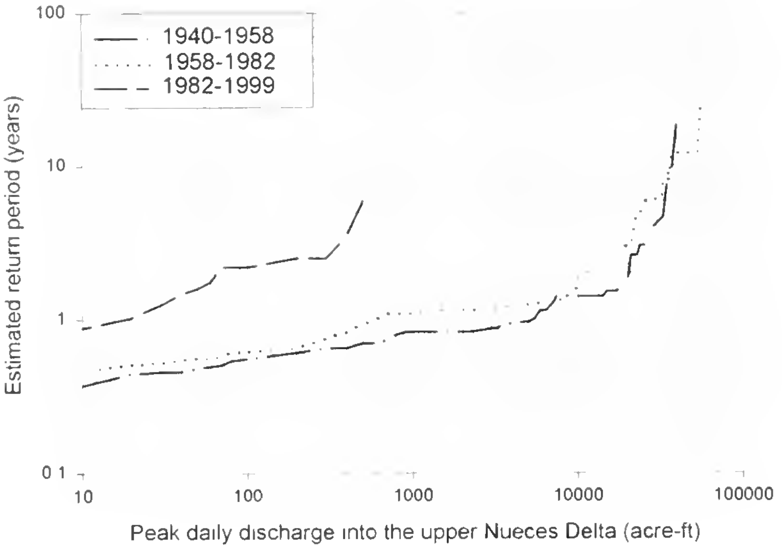


Figure 13: Historic return frequency (ogive) of flow events into the upper Nueces Delta. Not included were data from the largest event in each time period.
Note: 1 acre-ft = 1.2335 10^3 m^3.

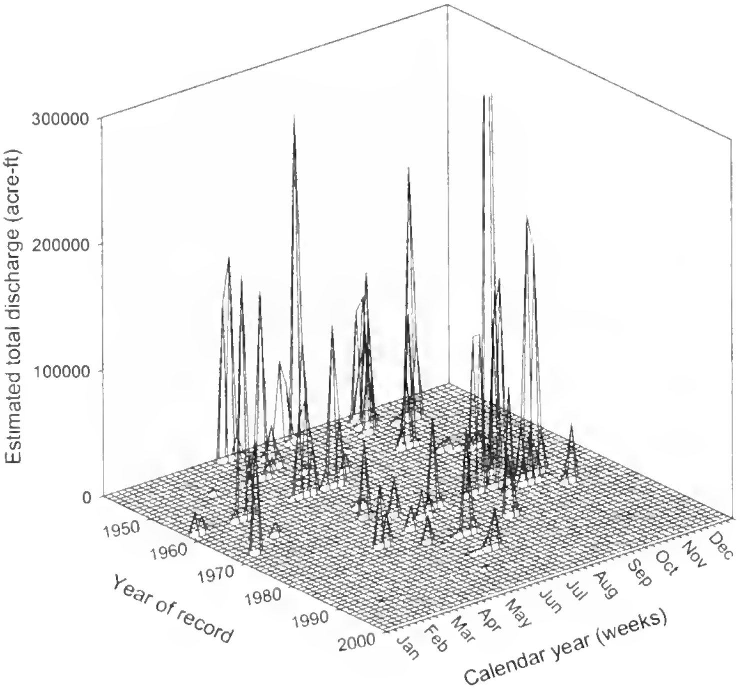


Figure 14: Historic timing of flow events into the upper Nueces Delta. Data from all events in each time period included. Scale of the y-axis is curtailed from 700,000 acre-ft (September 1967) to improve resolution of lower values.
Note: 1 acre-ft = 1.2335 10^3 m^3.

Duration

As with event magnitude, event duration under historical conditions also exhibited two seasonal peaks (Figure 12). During Period I, the spring peak (June) and fall peak (September) attained about 5 average event days per month (5.0 and 4.8, respectively). During Period II, the spring peak (June) was similar to that of Period I, but attained only 3.0 average event days per month, and the fall peak (October) about 4.2 average event days. In Period III, event duration also showed dramatic decreases, but unlike event magnitude, seasonal peaks were still discernable. The spring peak (May) peaked at about 1.1 average event days per month, and the fall peak (October) only about 0.5 average event days. During Period III, an anomalous third peak (February) attained about 0.6 average event days, which reflects a disproportional influence of an (uncommon) winter event in 1992.

Annual event duration represents the sum of all event days during the period divided by the period's duration in years. For Period I, event duration averaged about 21.1 average event days per year (Table 4). This mean fell to about 16.8 event days during the period after the closure of Wesley Seale Dam, and to about 4.5 event days during the period after the closure of Choke Canyon Dam.

Table 4: Summary of historic annual event duration in the upper Nueces Delta.

Period	Historic Mean Number of Event Days per Year	Percent Change from Period I
I: 1940-1958	21.1	-
II: 1958-1982	16.8	-20%
III: 1982-1999	4.5	-79%

Frequency

In general, the historical return period for event peak flows during Period I were slightly shorter than those in Period II (except for the largest values), but not appreciably (Figure 13). Period III, however, did exhibit a dramatic increase in the return period of event peak flows.

The difference in the return period of a flow event with a daily peak flow of 123.4 10^3 m^3 (100 acre-ft) between Periods I and II was an increase of less than a month (0.06 years) (Table 5). However, for the same event in Period III, the return period rose by over 19 months (1.64 years). There was no return period for events with daily peak flows of greater than 617 10^3 m^3 (500 acre-ft) during Period III.

Table 5: Summary of the historic return period for a flow event into the upper Nueces Delta with a daily peak flow of 100 acre-ft.

Period	Historic Return Period (years)	Percent Change from Period I
I: 1940-1958	0.56	-
II: 1958-1982	0.62	11%
III: 1982-1999	2.20	293%

Note: 1 acre-ft = 1.2335 10^3 m^3

Timing

In the three-dimensional presentation of event timing (Figure 14), the x-axis represents the calendar year in weeks, the y-axis represents the year of record and the z-axis represents total event discharge into the upper Nueces Delta. The seasonal peaks (spring and fall) observed in the magnitude and duration analyses were also manifest in event timing under historical conditions. As observed from the x-axis, spring flow events (May-June) were more frequent and smaller than fall flow events (September-October), which were more sporadic but generally larger during Periods I and II (Figure 13). This seasonal pattern, however, was noticeably absent during Period III. Winter (December-January) and summer (August) flow events for all periods were very rare.

From the perspective of the y-axis, "wet" or "dry" periods in the delta were evident over the past 60 years. The more significant "wet" years for each period include 1941, 1942, 1946 and 1957, during Period I; 1958, 1967, 1971, 1973 and 1981 during Period II; and 1987 and 1992 during Period III. Significant "dry" years in the delta include 1943, 1947, 1950, 1952, and 1955-56 in Period I; 1962-63, 1966, 1969, 1972 and 1978 in Period II; and all of Period III with the exception of 1987 and 1992. Except for an apparent decrease in the size of spring events during Period II, there was no obvious difference in flow event appearance between Periods I and II. There was, however, a marked difference in the comparison of flow events in Period III with either of the two preceding periods. The only discernable events in Period III were the summer event of 1987 (which would have been a much more significant event had not a large part of the flooding event served to fill and spill a nearly empty Choke Canyon Reservoir), and the late winter and spring events of 1992. Even so, these two events, while the largest in Period III, would be considered extremely small events in either of Periods I or II. Therefore, both the relative number and size of flow events in the delta contrasted starkly with the two preceding periods.

POTENTIAL FOR RESTORED FRESHWATER INFLOW INTO THE UPPER NUECES DELTA

One way of assessing the potential for how the Rincon Bayou Demonstration Project might restore freshwater flows to the upper Nueces Delta is to assume that it had been in place in the past, and compare the results with what actually occurred. Event magnitude, duration, frequency and timing were therefore analyzed assuming that the demonstration project features had been in place since the completion of Choke Canyon Reservoir (Period III), which was generally assumed to represent realistic future conditions. The results from this "restored" condition, when compared to those of the historical condition, would then give an indication of the restorative potential of the project.

Magnitude

The restored event magnitude for Period III, when compared with average monthly volumes that historically flowed into the upper Nueces Delta during Periods I and II, was almost imperceptible (Figure 15). The largest average monthly discharge amount (May) was only 1,208 10^3 m^3 (980 acre-ft), which represented only a fraction of the average for the same month during Periods I or II (2.5% and 16.8%, respectively).

However, in the limited context of present conditions (*i.e.*, Period III only), the restored event magnitude compared much more favorably, increasing the estimated average monthly discharge by several times over what had occurred without the demonstration project. When analyzed annually, the restored event magnitude increased by over 633% from the historical Period III amount (Table 6).

Table 6: Summary of restored annual event magnitude in the upper Nueces Delta. Mean discharge value rounded to the nearest 10 acre-ft.

Period	Restored Mean Total Discharge per Year (acre-ft)	Percent Change from Historic Period III Conditions
III: 1982-1999	3,420	633%

Note 1 acre-ft = 1 2335 10^3 m^3

Duration

Restored event duration, unlike restored magnitude, compared very favorably with the historical duration of events flowing into the upper Nueces Delta (Figure 16). Both seasonal peaks were strongly evident, and the spring peak (May) was approximately the same duration as that of the Period I. The restored event duration even slightly exceeded the historical duration of both Periods I and II for seven (7) of the twelve (12) months of the average year, and in only two months was it lower than the historical Period II values. The only notable limitation of the restored event duration was that of the fall peak, which only attained an average of 2.5 days (October), compared to the historical fall peak of 4.8 days (September) in Period I and 4.2 days (October) in Period II.

From the perspective of present conditions (Period III) only, the restored event duration also greatly surpassed historic levels (Table 7). The restored annual event duration increased by over 578% from that historical (without-project) level to 26.0 days.

Table 7: Summary of restored annual event duration in the upper Nueces Delta.

Period	Restored Mean Number of Event Days per Year	Percent Change from Historic Period III Conditions
III: 1982-1999	26.0	578%

Note 1 acre-ft = 1 2335 10^3 m^3

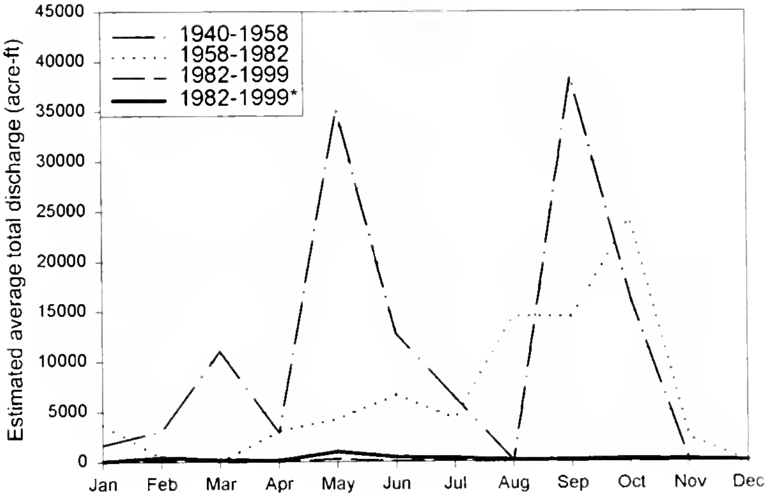


Figure 15: Potential for restored flow event magnitude* into the upper Nueces Delta during Period III, which assumes the features of the Rincon Bayou Demonstration Project had been in place since 1982. Not included were data from the largest event in each time period.

Note: 1 acre-ft = 1.2335 10^3 m^3.

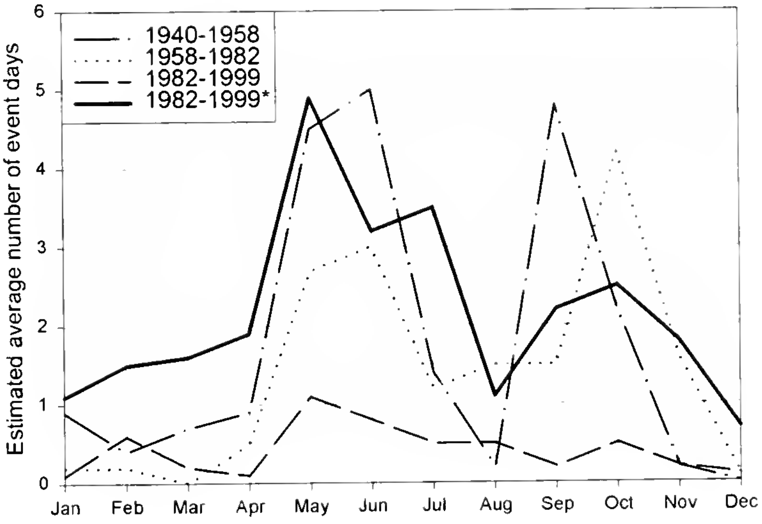


Figure 16: Potential for restored flow event duration* into the upper Nueces Delta during Period III, which assumes the features of the Rincon Bayou Demonstration Project had been in place since 1982. Not included were data from the largest event in each time period.

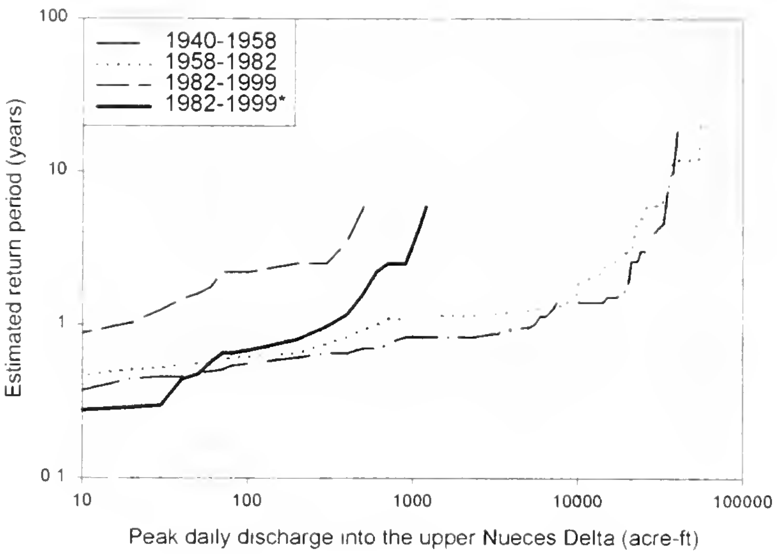


Figure 17: Potential for restored flow event return frequency (ogive)* into the upper Nueces Delta during Period III, which assumes the features of the Rincon Bayou Demonstration Project had been in place since 1982. Not included were data from the largest event in each time period.

Note: 1 acre-ft = 1.2335 10^3 m^3.

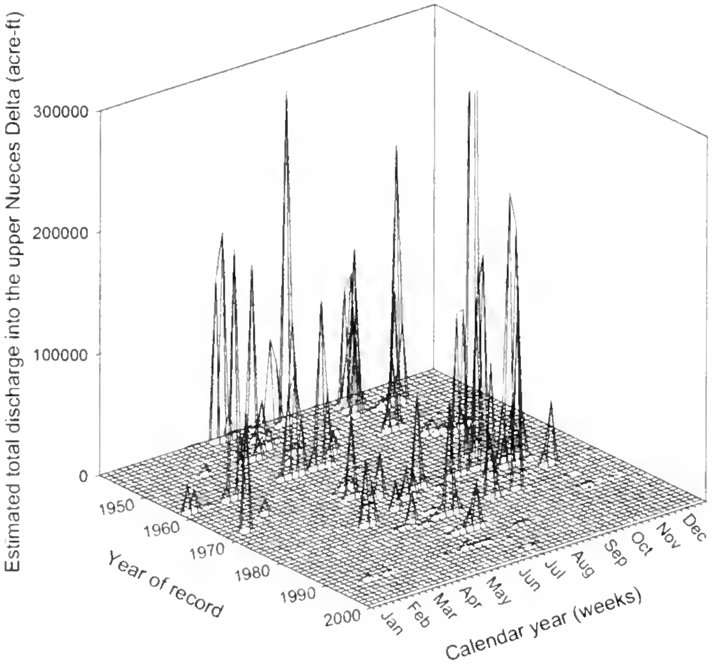


Figure 18: Potential for restored flow event timing* into the upper Nueces Delta during Period III, which assumes the features of the Rincon Bayou Demonstration Project had been in place since 1982. Data from all events in each time period included. Scale of the y-axis is curtailed from 700,000 acre-ft (September 1967) to improve resolution of lower values.

Note: 1 acre-ft = 1.2335 10^3 m^3.

Frequency

Table 8: Summary of the restored return period for a flow event into the upper Nueces Delta with a daily peak flow of 100 acre-ft.

Period	Restored Return Period (years)	Percent Change from Historic Period III Conditions
III: 1982-1999	0.68	-324%

Note: 1 acre-ft = 1.2335 10^3 m^3

The results of restored event return frequency varied depending upon the peak flow considered (Figure 17). For example, for events with peak daily flows below 49 10^3 m^3 (40 acre-ft), the estimated return period decreased to below historical levels of either Period I or II. Above about 123 10^3 m^3 (100 acre-ft), the return period was greater than Periods I and II, but substantially less than that of Period III. If a peak flow event of 123 10^3 m^3 were used to illustrate the change in restored event return frequency from historical Period III conditions, the return period for this event would have decreased by about 18 months, or by 324% (Table 8).

Timing

From inspection of Figure 18, and comparison with Figure 14, it is evident that the restored timing of freshwater flow events into the upper Nueces Delta, both in seasonal and annual distribution, would improve from Period III conditions. However, events under the restored condition would in no way attain the relative numbers or size of flow events that occurred during historical times. Each of the visible events under restored conditions, although noticeably larger and longer, would still be considered only extremely small events in either historical Periods I or II.

DISCUSSION

HISTORICAL FRESHWATER INFLOW

Without exception, a decreasing trend over time was observed in each of the four historical flow regime characteristics analyzed. Event magnitude, duration, frequency and timing all declined with varying degrees from Period I through Period III. When compared to Period I, which represents a conservative reservoir scenario, flow regime characteristics during the period after the construction of Wesley Seale Dam (Period II) generally exhibited a lesser degree of change than did the period immediately after the completion of Choke Canyon Dam (Period III), which showed a more dramatic change. This would be expected, as Choke Canyon Dam provided over twice the amount of storage capacity of Lake Corpus Christi and was operated in conjunction with the latter, adding its effect upon the other.

The magnitude of flow events during Period II decreased substantially from Period I levels, especially in regards to the spring event. During Period III, event magnitude was virtually eliminated when compared to previous periods. Changes in event duration closely reflected those in event magnitude, except that Period III levels did not decreased as significantly. The differences between the return period of flow events into the upper delta during Periods I and II were not as pronounced as with event magnitude and duration, but Period III again showed a significant departure from previous periods. Finally, event timing dramatically changed with the virtual elimination of meaningful seasonal flow events. This change was so distinct, that the entire post-Choke Canyon Reservoir period (with the exception of 1987) could be likened to a perpetual "dry" year, which occurred only infrequently during the previous two periods.

POTENTIAL FOR RESTORED FRESHWATER INFLOW

When compared with present conditions (represented by the historic Period III), each of the flow regime characteristics analyzed under the restored Period III conditions were substantially increased. Annual event magnitude was increased by over 633%, and annual event duration by over 578%. Event return frequency was also improved, and even exceeded that which occurred in Periods I and II for lower peak flow events. Finally, event timing also showed some improvement in the relative size and length of freshwater flow events.

However, when compared with the historical flow regime of Periods I and II, the restored regime characteristics, with the exception of event duration, compared less favorably. The restored event magnitude was still only a fraction of even Period II levels, and event frequency was not affected for peak flow events greater than about

1,234 10^3 m^3 (1,000 acre-ft). Also, improvements in event timing were not sufficient to eliminate the significant number of seasonal and annual "dry" periods in the Period III historical record.

COMPARISON OF FRESHWATER FLOW INTO THE UPPER NUECES DELTA VERSUS INFLOW INTO NUECES BAY

This analysis was focused exclusively on flow event characteristics into the upper (northern) Nueces Delta, and not on the total freshwater inflow into Nueces Bay. However, one minor digression worth consideration is the difference between changes in the historical freshwater inflow pattern of the upper delta compared with that of Nueces Bay. Clearly, flow into the upper Nueces Delta represents only a fraction of the river's total inflow to the receiving bays and estuary. Consequently, the results of a historical analysis of total estuarine inflow, without consideration of the delta component, would be expected to differ considerably from the results of this investigation.

And this is indeed the case. Asquith *et al.* (1997) evaluated the mean and median annual stream flow of the Nueces River near Mathis for the period 1940-1996, and performed statistical tests for historical trends with time. Their results indicated that the change in stream flow from 1958 through 1982 (or Period II) was negligible (an 0.8% decrease in mean annual flow, and an 18.5% decrease in median annual flow), while the change in stream flow after impoundment of Choke Canyon Reservoir was large (a 55.0% decrease in mean annual flow, and a 63.4% decrease in median annual flow). This conclusion is in contrast to the results of the present analysis, which indicate the decrease in annual mean volume of water entering the upper Nueces Delta during Period II was considerable (about a 39% reduction), and during Period III was extreme (over a 99% reduction).

This pragmatic explanation of this difference between the historic flow characteristics of the upper Nueces Delta and those of the greater Nueces Bay lies in the concept of "flooding threshold" at the point of natural diversion. Because of the higher threshold imposed by the elevated river bank, freshwater diversions into the delta system are extremely sensitive to the peak segments of flood events in the Nueces River. Therefore, if the flooding threshold is not met, the flow event in the river will bypass the delta, providing Nueces Bay with an freshwater inflow event without the same courtesy for the delta. Hence, changes in river flow patterns which lower the peak flows of flood events disproportionately affect the upper delta as compared to the bay.

The value of the distinction between delta inflow and total estuarine inflow is fully appreciated when recognizing the fact that the Nueces Delta is a distinct and critical component of the greater estuary system. Without consideration of this point, one may erroneously conclude that, for example, the reductions in freshwater inflow during Period II did not meaningfully alter the freshwater flow regime of the Nueces Estuary ecosystem because total mean inflow into Nueces Bay was reduced by only one percent.

CONCLUSIONS

The historic flow regime of the Nueces River into the upper Nueces Delta has changed dramatically over the past 60 years. In each of the flow event characteristics analyzed, a strong declining trend was observed from Period I through Period III. The Rincon Bayou Demonstration Project would restore a considerable amount of freshwater to the upper Nueces Delta and significantly improve the flow regime characteristics compared to the present (historical Period III) conditions. However, the demonstration project would not restore the delta's inflow patterns to historic (Periods I and II) levels.

Reservoirs in the basin and deltaic inundation events have a unique relation to peak flow events in the lower Nueces River. On one hand, because of the high flooding threshold of the north bank of the river, the upper Nueces Delta relies almost exclusively on the peaks of flow events for freshwater inflow. On the other hand, main-stem reservoirs, by design, significantly attenuate the peaks of flow events in the watershed for purposes of water storage and flood control. This relation is exemplified by the fact that, during the period after the construction of Lake Corpus Christi (Period II), although annual mean flow of the river into Nueces Bay was reduced by about 1% (Asquith *et al.* 1997), the annual mean flow into the upper Nueces Delta was reduced by about 39%. Similarly, during the period after the construction of Choke Canyon Dam, while the annual mean flow of the Nueces River into the bay was reduced by about 55% (Asquith *et al.* 1997), the annual mean flow into the upper delta was all but eliminated (reduced by 99%).

Therefore, if the upper delta's historical contribution to the estuary ecosystem is to meaningfully exist in the future, the multi-component flow regime of the Nueces River into the upper Nueces Delta must be considered in the context of reservoir operation and management.

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APPENDIX D

Recent Trends in Precipitation Occurring on the Nueces River Watershed of South Texas

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ABSTRACT: Precipitation from the Nueces River watershed was analyzed for recent trends as part of the Rincon Bayou Demonstration Project (Rincon Project) conducted by the United States Bureau of Reclamation. Of interest were comparisons of precipitation across the three periods, 1940-57, 1958-81, and 1982-99, of interest to the Rincon Project, a demonstration and study of impacts on the ecology of the upper Nueces delta Bay from enhanced inundations of the marsh. The role is discussed of the El Niño-Southern Oscillation (ENSO) and other climate variables to tropical cyclone occurrence in the Atlantic basin and in particular, the Gulf of Mexico. The potential modulation by ENSO of watershed precipitation was investigated. A multivariate comparison was conducted of daily precipitation sampling distributions across project study periods. The occurrence of large precipitation events was of particular interest because they could lead to natural inundations of the marsh. Analyses indicated no particular watershed precipitation trend unless the basis of comparison was the extreme drought period of the 1950s. The La Niña (El Niño) phase does appear to lead to more (less) tropical cyclone impacts in the western Gulf of Mexico than baseline years. Of 21 years (since 1948) with large precipitation events (=> 4 inches per day) impacting Corpus Christi, 6 were El Niño years, 8 were La Niña years and 7 were baseline years. Tropical cyclones occurred in 7 of the 21 large-event years; 5 were La Niña years and 2 were baseline years. Of 7 years with annual precipitation exceeding 40 inches, 5 years were baseline years, 1 year was La Niña, and the largest-amount year was El Niño. Two of the seven highest years did not have a high daily event. The multivariate comparison revealed the sampling daily precipitation of the drought years differed from the other two study periods, otherwise no differences.

INTRODUCTION

The United States Bureau of Reclamation (Reclamation) is sponsoring and partnering in the Rincon Bayou Demonstration Project (Rincon Project) aimed at determining marsh response to increased freshwater inundation caused by construction of an overflow channel on the Nueces that flows into Nueces Bay just north of Corpus Christi, Texas (see Figure 1). The occurrence of natural over-banking events from the Nueces River into the Nueces Delta was reduced by the construction in 1958 of Lake Corpus Christi on the Nueces River and in 1982 by Choke Canyon Reservoir on the Frio River (Irlbeck and Ward 2000). In addition to regulated flows into the Nueces River, precipitation in the Frio and Nueces watersheds, and locally in the delta, also impact the delta ecosystem. The question arises as to how much, if any, of the observed decreases in the magnitude, frequency, duration and timing of delta inundation events since 1958 (Irlbeck and Ward 2000) has been caused by variations in climate.

The weather systems impacting south Texas migrate from the temperate zone to the north or the tropics. Some disturbances originate in southwesterly or westerly flow over Mexico. Tropical disturbances approach the Nueces watershed generally from the southeast or east. Except in circumstances of deep continental flow, the troposphere over south Texas generally contains ample moisture for precipitation, but often lacks a trigger mechanism to build storm clouds. Perturbations moving toward the Rincon area generally provide the triggers. For example, a slow-moving front or tropical wave can trigger the development of clouds that can produce small amounts to several inches of precipitation, often in isolated patterns rather than general coverage. So, a weather system may produce little precipitation at a location, but a short distance away can produce three inches

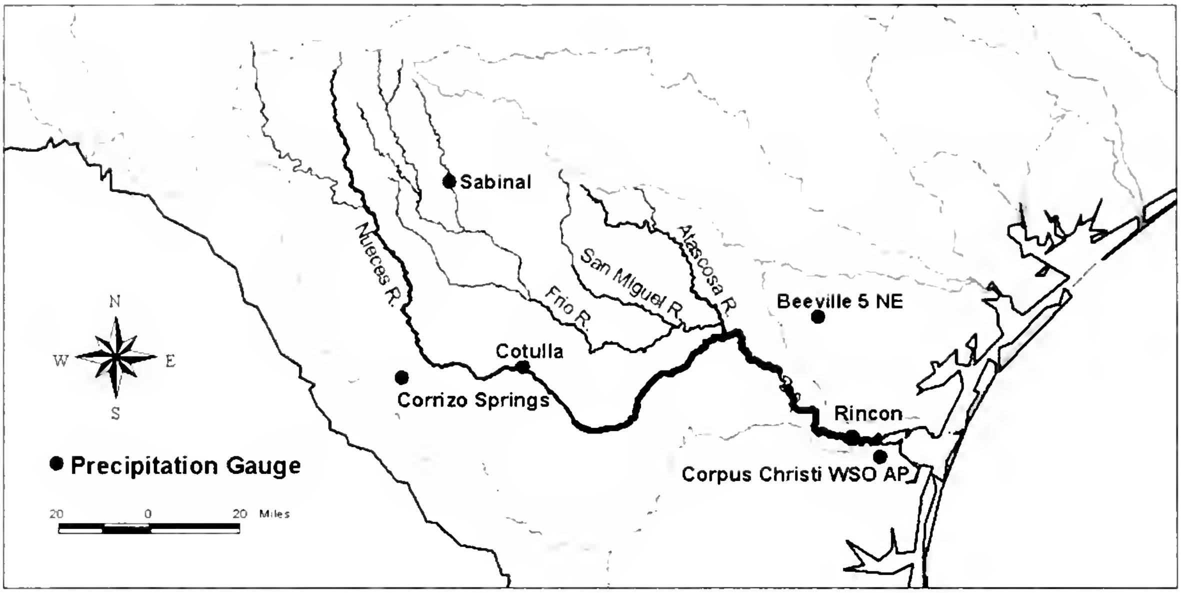

Figure 1: Nueces River Basin and precipitation gauges.

Trends in precipitation should be described within an a priori selected time period. For example, a short-term trend following a drought would be increasing precipitation. The duration of such trends is of great interest and the ability to forecast them is constantly sought. For purposes of the Rincon project, precipitation trends over 1940-99, a 60-year period, are the main concerns of study. Additionally, Rincon area precipitation is compared among the periods 1940-57, 1958-81, and 1982-99, that correspond to different construction influences on Nueces River flows.

On the National basis, the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration routinely develops temperature and precipitation trend estimates (available on the Internet, address ftp://ftp.ncep.noaa.gov/charts.html/). CPC uses 102 climate regions of near equal area for the lower 48 states. Each climate region is composed of one or more climate divisions. Monthly data are assembled into time series for three-month periods and an annual average. Baseline values were developed from data to 1966. The linear change per decade is computed from the base line value through the current year. Current trends are based on 1941-1998 data for temperatures and 1931-1998 data for precipitation. The CPC trends indicate National increases of 0.15 °F and 0.9 inches of precipitation per decade. For south Texas, no trend in mean annual temperatures is indicated, but a 0.2 to 0.6 inch increase in precipitation per decade is revealed.

The following covers a discussion of precipitation in the Nueces River watershed based on data from several gauges located there. A summary is given of some study results on the El Niño-Southern Oscillation (ENSO) and other climate variables, and their relationship to tropical cyclone occurrence in the Atlantic basin and in particular, the Gulf of Mexico. Nueces River watershed precipitation anomalies stratified by ENSO type are presented. Finally, daily precipitation distributions for one watershed gauge are developed and discussed in the context that for different periods there can occur different precipitation distributions causing differing runoff while maintaining similar annual precipitation.

NUECES RIVER WATERSHED PRECIPITATION SURVEY

The 30-year mean precipitation for gauges shown in Figure 1 portray differences across the Rincon area. Mean annual precipitation (1961-1990 record) for Corpus Christi WSO AP, Cotulla, Carrizo Springs, Beeville 5 NE, and Sabinal are the respective 30.14, 22.95, 21.22, 31.97, 25.45 inches. These values support lesser precipitation occurs in the southwestern Rincon area and higher amounts along the coastline. Figures 2 through 5 present annual precipitation totals for Cotulla, Corpus Christi, Beeville 5 NE, and Sabinal through 1999, with a Lowess (Cleveland, 1979; 1981) smoothing line (average of weighted values in a moving window that allows adjustable flex by changing the window size) that suggests trends. These precipitation gauges are distributed across the Rincon Project drainage supplying the delta and possess the better quality data for that area. Annual precipitation recording began shortly after 1900, except for the Corpus Christi record that began in 1948. The figures show the prominent drought of the 1950s (and several years of the late 1940s). The Lowess curves show short-term recent rising precipitation at three of the four gauges. The Corpus Christi Lowess curve portrays an unrealistic initial pattern because of analysis effects from initial data from the drought. The inclusion of the drought years to the CPC baseline largely caused the positive trend in precipitation.

Line plots (not given) of the Corpus Christi WSO AP, Sabinal, and Beeville 5 NE gauges produced respective positive, negative, and positive slopes using the available annual precipitation for each gauge. The Corpus Christi WSO AP data yields a negative slope if precipitation is restricted to 1965 or more recent information. The Beeville 5 NE precipitation produces a negative slope if restricted to 1960 or more recent.

Asquith et al (1997) conducted a study to determine the current mean freshwater inflows to bay systems that included the Corpus Christi Bay. As part of their study, they examined temporal trends in inflows. They studied trends in precipitation of several precipitation gauges. Asquith et al (1997) applied the Mann-Kendall test (Helsel and Hirsch, 1992; Hollander and Wolfe, 1973) to time series of seasonal and annual rainfall from the Corpus Christi WSO AP and Refugio 7 North (located approximately 30 miles east of the Beeville 5 NE gauge) gauges. The Mann-Kendall test is a rank-based nonparametric test similar to the familiar Wilcoxon-Mann-Whitney procedures to test for monotone increasing character in data. Results of the statistical analysis indicated P-values not significant at the 0.05 level in all seasonal and annual time series of 1968-93 data for Refugio 7 North, and similarly for Corpus Christi WSO AP data excepting winter (January, February, March) that produced an upward trend with a P-value of 0.05. The annual Corpus Christi data produced a 0.25 P-value.

Figure 6 presents the mean annual precipitation computed separately for the four gauges, Sabinal, Corpus Christi, Beeville 5 NE, and Cotulla for each time period of interest to the Rincon Project. This portrayal of gauge mean precipitation shows the change across time periods and gauges. Because the Corpus Christi record began in 1948, the first period duration was restricted to 10 years; other period lengths were 24 and 18 years. The figure shows all gauges displaying the same general pattern over the three periods, least precipitation during the drought period, greatest amount during the second period, and intermediate amounts during the third and most recent period.

Precipitation in the Nueces watershed is not monotonic increasing over the three study periods. However, there could be patterns of rainfall amounts that could cause more inundations of the Nueces Delta than other patterns with similar annual precipitation. Namely, the annual precipitation could occur in relatively few large amount events. This could occur from increased tropical disturbances numbers, more persistent frontal patterns that favor precipitation in the watershed, or perturbations in a persistent moist Pacific flow across northern Mexico and the southern United States (shown in Figure 9).

Figures 7 and 8 present cumulative adjusted annual precipitations over the gauge record periods for the Sabinal and Corpus Christi WSO AP gauges (through 1998), respectively. Annual precipitation values were adjusted by removing the long-term annual mean. Difference values were then summed in time and plotted. The cumulative precipitation differences are related to soil moisture. Though such cumulative difference figures are impacted by the choice of data starting point, the figures for the Rincon Project study area portray the substantial annual precipitation deficit created by the severe drought of the late 1940s and 1950s. The longer-term Sabinal record shows the contrasting conditions prior to and after the 1950s. The plot for Sabinal suggests that the upper Nueces River basin may have frequently been in below-normal soil moisture conditions.

ENSO AND TROPICAL CYCLONES IN THE ATLANTIC BASIN

The relative maximum in precipitation that occurs in the fall season in the Nueces River watershed is largely the result of, (1) mid-latitude perturbations that in fall strengthen, adequate to reach south Texas as the subtropical and polar jets reestablish in the stronger north/south temperature gradient, and (2) tropical perturbations that impact the western Gulf of Mexico. Tropical cyclones can substantially impact western Gulf precipitation. Landsea et al. (1999) studied Atlantic hurricanes, United States (lower 48 States) land-falling hurricanes and U.S. normalized damage (adjusted for changes in inflation, coastal county population, and wealth) time series for

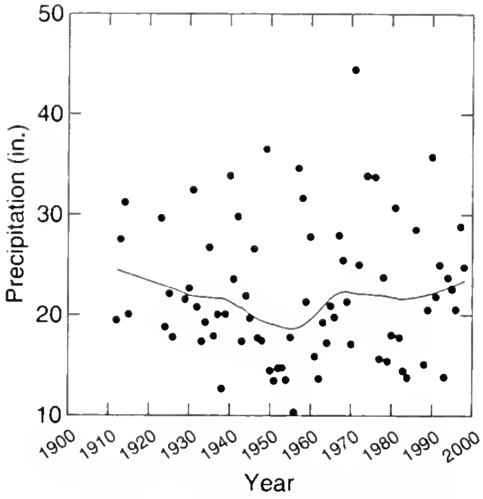

Figure 2: Cotulla annual precipitation.

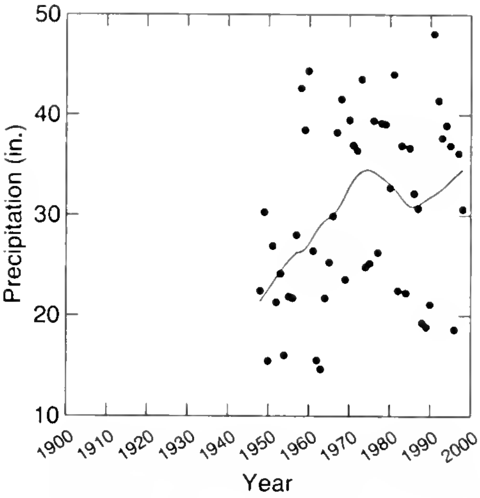

Figure 3: Corpus Christi WSO AP annual precipitation.

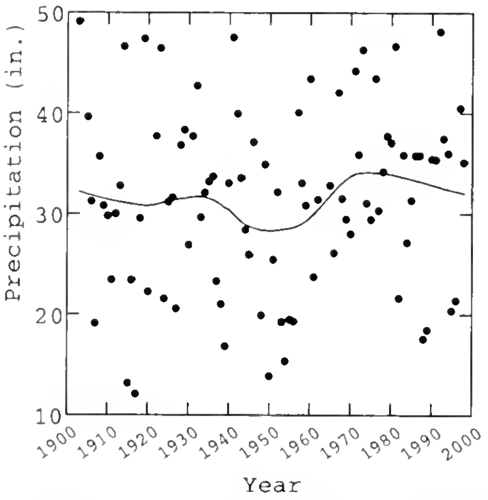

Figure 4: Beeville 5 NE annual precipitation.

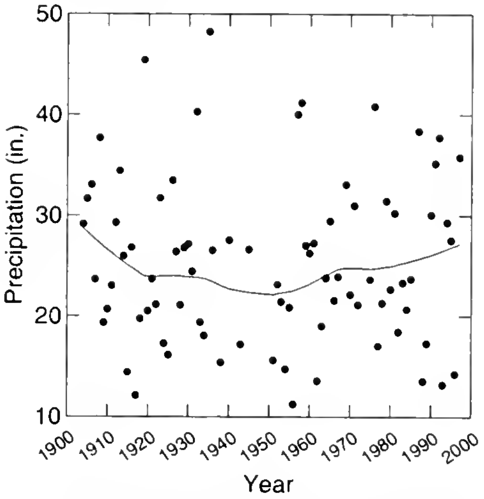

Figure 5: Sabinal annual precipitation.

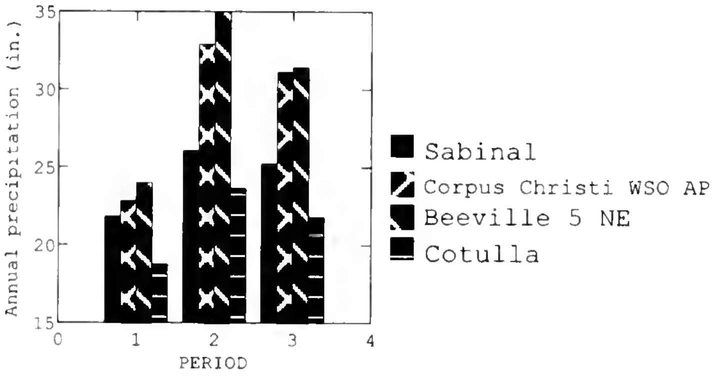

Figure 6: Mean annual precipitation per each time period of 1940-57, 1958-81, and 1982-99.

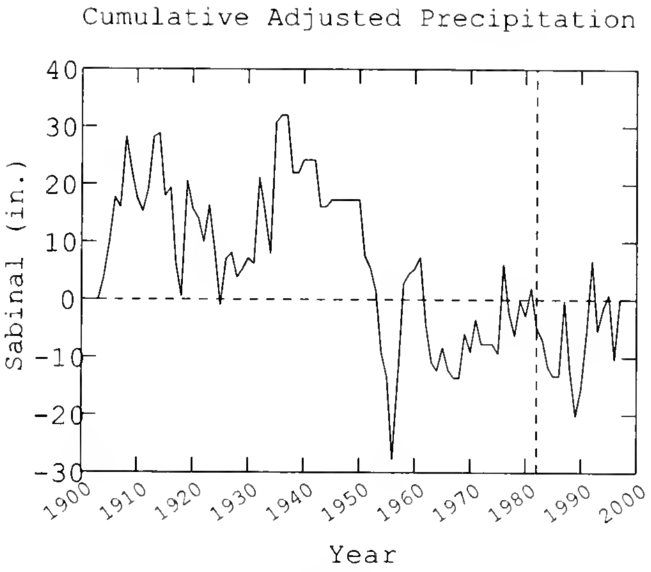

Figure 7: Sabinal cumulative annual precipitation that was adjusted by subtracting the long-term mean. A dotted vertical line is placed at 1982 indicating the beginning of the Rincon third study period.

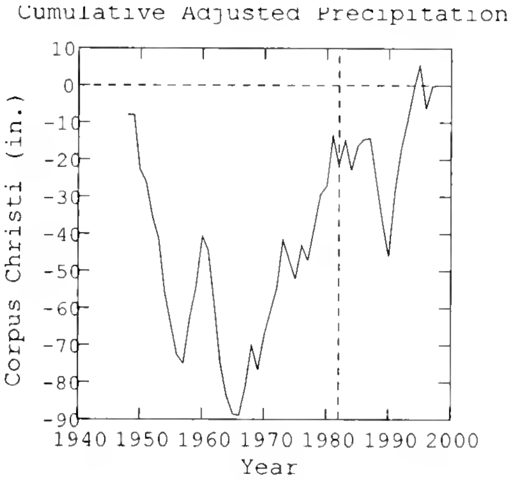

Figure 8: Same as figure 7 except for Corpus Christi Gauge information.

inter-annual trends and multi-decadal variability. They used records on tropical disturbances back to the 1940s for basin-wide Atlantic cases, and the turn of the 20th century for U.S. land-falling systems. Various environmental factors were considered including Caribbean sea level pressures, 200-millibar zonal winds, stratospheric Quasi-Biennial Oscillation (described below), El Niño-Southern Oscillation (ENSO, described below), African West Sahel rainfall and Atlantic sea surface temperatures. All variables indicated significant, concurrent relationships to the frequency, intensity and duration of Atlantic hurricanes. The ENSO was found to be significantly linked to changes in damages by tropical cyclones that impact the United States.

Gray et al (1993) found that various relationships can be determined if data are stratified into spatial location and by disturbance intensity. The linear trend in hurricane activity of the Atlantic basin is very weak (Landsea et al., 1999). Multi-decadal variability is more characteristic of the region. This is suggested in that intense Atlantic hurricanes (50 m/s or more) were common in the 1940s through the 1960s, but much reduced from the 1970s through the early 1990s (Landsea, 1993). In 1995 and 1996, there occurred a return to high levels of tropical cyclone activity similar to earlier active decades. There were similarities in hurricane duration variations with longer-lived systems (about 25-40 tropical cyclone days per year) in the 1940s through the 1960s and fewer hurricane days (around 10-25 days per year) in the decades of the 1970s through early 1990s.

While the Atlantic basin exhibits multi-decadal variation, the United States Gulf Coast from Texas to the Florida panhandle expresses much weaker intense hurricane strike variability (Landsea et al, 1999). The variation pattern is quite different as above average activity occurred only in the 1910s and reduced activity only in the late 1940s and early 1950s. Thus, some components of the Atlantic basin may exhibit markedly different intense hurricane variation.

ENSO events induce moderate-sized changes in the frequency and intensity of Atlantic basin tropical cyclones (Landsea et al, 1999). The ENSO state can be characterized by the sea surface temperature (SST) anomalies in the eastern and central equatorial Pacific (Philander, 1989). Warm SSTs in this region are referred to as El Niño events, and cool SSTs are known as La Niña events. The state of ENSO can also be characterized by the Southern Oscillation Index (SOI), the standardized difference in sea level pressure between Tahiti and Darwin, Australia. High (low) pressure at Darwin and low (high) pressure at Tahiti corresponds to El Niño (La Niña) events.

Figures 9 and 10 present schematics of the winter tropospheric jet streams and major cyclone/anticyclone features of the El Niño and La Niña events, respectively. The schematics show the El Niño Pacific jet stream transporting moisture into the southern States thus favoring wetter conditions there, while under the La Niña structure the storm track is further north. ENSO events alter the global atmospheric circulation patterns and are able to affect tropical cyclone frequencies. The mechanisms for the latter are the alteration of the lower tropospheric source of vorticity (measure of rotation in a fluid) and the vertical wind shear profiles (Gray, 1968, 1979). ENSO fluctuates on the scale of a few years (Philander 1989).

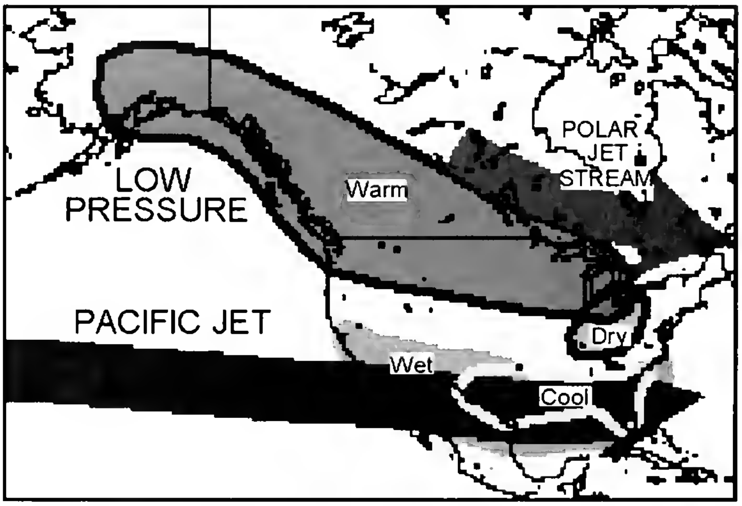

Figure 9: El Niño winter atmospheric features.

El Niño events are associated with fewer numbers of Atlantic basin tropical cyclones (recall that El Niño leads to more nontropical storms particularly during the cool season). La Niña events cause 36 percent more named/subtropical storms than El Niño events. Their mean intensities are also 6 percent stronger (Landsea et al, 1999). Though ENSO events modulate hurricane landings in the Caribbean region and the United States, the impacts are only weakly significant for the Gulf Coast intense hurricanes (and not significant for weaker storms).

For intense hurricane strikes along the Gulf Coast, the single largest factor of influence is the phase of the Quasi-Biennial Oscillation (QBO; Gray 1984, Shapiro 1989). The QBO is an east-west oscillation of stratospheric-level winds that encircle the globe near the equator. In the west phase, Atlantic hurricane activity is enhanced, but is diminished in the east-phase QBO years. The QBO is followed in importance by the 200-millibar zonal winds and sea-level pressure anomalies, such that westerly winds and high pressures in the Caribbean favor more tropical cyclone landings (Knaff, 1997). With regard to interannual variation, normalized United States' damages are well related to ENSO, such that significantly less damage occurs during El Niño events and than during La Niña events.

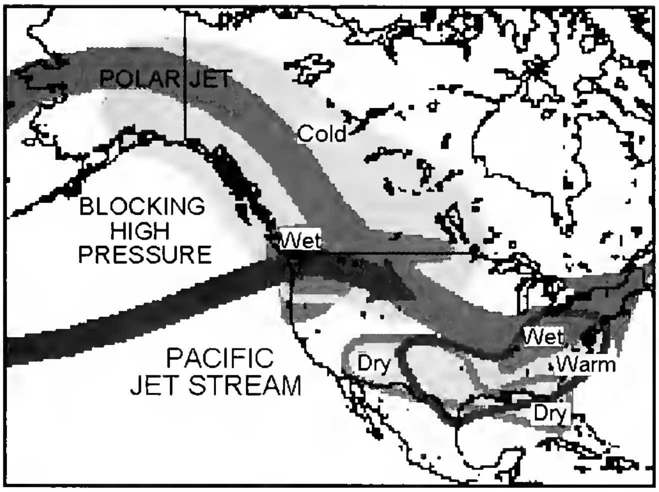

Figure 10: Winter features for La Niña.

Lack of hurricane variation consistency in the Gulf of Mexico compared to East Coast occurrences is likely caused by the dominance of local conditions over basin-wide factors that can lead to intense hurricane development (Landsea et al, 1999). An example is tropical storm development along a stationary frontal boundary of strongly contrasting conditions. This occurred in the case of hurricane Alicia in 1983. The prominent role of local conditions is likely why there is no distinct multi-decadal variation of intense hurricanes in the Gulf of Mexico (Landsea et al, 1992).

Tropical cyclone activity in the western Gulf of Mexico during the three periods of interest to the Rincon Project somewhat followed the causal/correlated patterns discussed previously. Table 1 gives tropical cyclone occurrences by ENSO type and baseline (non-ENSO) years. Classification of years was according to Pielke and Landsea (1999). More tropical cyclones impacted the western Gulf of Mexico in La Niña years than El Niño years, generally following the script. However, table 1 shows that six tropical cyclones impacting the western Gulf occurred during the relatively low Atlantic basin activity period of the 1970-80s. In the first Rincon study period (1940-57), only hurricanes' Alice and Audrey affected the western Gulf of Mexico. During the second study period (1958-81), 11 tropical cyclones impacted the Gulf coast. In the third study period (1982-99), four hurricanes (Arlene, Charley, Frances and Bret) occurred, three during El Niño years and the fourth (Bret) during the La Niña year of 1999.

WATERSHED PRECIPITATION ANOMALIES AND ENSO PHASE

Table 1 shows twice as many tropical cyclones occurring in the western Gulf of Mexico during La Niña years as El Niño years. The question arises as to whether Nueces River watershed precipitation is sensitive to ENSO phases. For example, do La Niña months record more precipitation baseline-year months. To investigate this issue, monthly precipitation for 1950-99 for Corpus Christi WSO AP, Beeville 5 NE, and Sabinal were stratified into baseline (16 years and 4 tropical cyclones), El Niño (18 years and 4 tropical cyclones), and La Niña years (16 years and 8 tropical cyclones). All months for a particular category (ENSO, baseline) were used in analyses to capture the effects on precipitation of nontropical storms as well as tropical cyclones. For each precipitation gauge, the 75 percentile precipitation was determined in the base years to serve as the benchmark of comparison. The analysis technique applied, similar to Gershunov and Barnett (1998), determined the proportion of months of record with a precipitation amount that equaled or exceeded the benchmark. The proportion determined is compared to 0.25 and the quotient is reduced by 1.0 and converted to percent anomaly.

Table 1: Tropical cyclones during ENSO and baseline years.

El Niño Years	La Niña Years	Baseline Years
1940	1942	1943
1941	1944	1946
1951	1945	1947
1953	1948	1952
1957 (Audrey)	1949	1958
1963	1950	1959
1965	1954 (Alice)	1960 (TS1)
1969	1955	1962
1972	1956	1966
1976	1961 (Carla)	1968 (Candy)
1977	1964	1979
1982	1967 (Beulah)	1980 (Allen, Danielle)
1986	1970 (Celia)	1981
1987	1971 (Fern)	1983
1990	1973 (Delia)	1984
1991	1974	1985
1993 (Arlene)	1975	1989
1994	1978 (Amelia)	1992
1997	1988	1996
1998 (Charley, Frances)	1995	
	1999 (Bret)	

Table 2 lists the anomalies calculated. It is noted that the baseline months included the effects on precipitation from four tropical cyclones. Additionally, because proportions developed use counts of months rather than precipitation amounts, extreme events cannot excessively and unrealistically skew results. The results reveal a mixture with El Niño monthly precipitation ranging from a (positive) 1.3 percent anomaly in the Beeville 5 NE data to a -30.7 percent anomaly in the Corpus Christi data. La Niña anomalies ranged from -12.7 to 25.9 percent, also a mixed result. Four of six ENSO anomalies were negative. Both ENSO phases led to negative anomalies at the Corpus Christi gauge, but a smaller anomaly (-12.7 percent) for La Niña months that included the effects from 8 tropical cyclones. The inland gauge, Sabinal, yielded the same pattern of a more positive anomaly from La Niña months, but this pattern was not maintained in the Beeville 5 NE data. While the Beeville 5 NE and Corpus Christi WSO AP gauges yielded the same anomaly for La Niña months, there was a large difference in the El Niño related anomaly despite being separated by only about 40 miles (however, Beeville 5 NE is inland about 35 miles). There is a "weak" suggestion that ENSO events may lead to a somewhat higher proportion of negative anomalies than expected by randomness (discounting the zero anomaly, there is a 23 percent probability of obtaining 4 negative anomalies in 6 possibilities). More data from additional gauges would be needed to further explore this possibility. Generally, these analyses in search of a precipitation dependence on ENSO do not reveal any well-defined pattern, but rather expressed the high variability in the precipitation data.

Table 2: Percentage anomaly of monthly ENSO rainfall when compared to base year 75 percentile benchmark precipitation.

Beeville 5 NE	Sabinal	Corpus Christi
La Niña: -12.7%	La Niña: +25.9%	La Niña: -12.7%
El Niño: +1.3%	El Niño: -6.8%	El Niño: -30.7%

DAILY PRECIPITATION DISTRIBUTION COMPARISONS

While there appears little indication of a trend in the annual and monthly precipitation of the Nueces River watershed during the 1940 to 1999 period, there remained the possibility that there could have been a difference in the distribution of daily precipitation across the three periods of interest in the Rincon Project study. For example, the mean monthly precipitation during the second period could have been similar to that during the third period but a differing daily amount distribution could cause highly differing delta inundations in one period versus the other period. One approach to study this possibility is the cross-tabulation of daily precipitation. The Corpus Christi WSO AP daily precipitation was selected for analysis because of better quality, despite the shorter record period that initiated in 1948.

Given in table 3 are the frequencies from cross-tabulation of the Corpus Christi daily precipitation in approximately one-inch size categories. Inspection of the frequency patterns over time suggests some differences in shorter time periods of about 10 years (particularly the first 10 years). The number of years per each of the 3 Rincon Project periods in succession was 18, 24 and 18 years. Available Corpus Christi WSO AP data limited the initial study period to 10 years (1948-99). Cross-tabulations present outcomes such that pattern comparisons for selected periods can often be made using mulitvariate analysis. A distribution-free permutation test was selected and applied in exploratory analysis to explore whether the three distribution patterns differed. The statistical test applied is one of a family of tests known as multi-response permutation procedures (MRPP) (Mielke et al., 1976, 1982). These tests avoid making the unjustified assumption that the joint distribution of the response measurements is multivariate normal or some other specific distribution.

Application of the MRPP yielded a P-value of 0.08 in comparing frequency patterns of all three periods. In the exploratory sense, the first 10 years of frequencies were separately compared with those of each of the 24 and 18 year periods using MRPP, and in both applications found to differ at better than the 5 percent level. Application of MRPP in a comparison of frequencies of the 24 versus 18 year periods was not significant at the 5 percent level. In this exploratory analysis, no attempt was made to correct for experimentwise error rate under a partial null hypothesis in which some comparisons are equal but others differ (Miller, 1981). The results of these comparisons are not surprising given the extreme level of drought in the 1950s. Additionally, shorter comparison periods, such as the 10-year period in this data, likely increase the probability of finding significant differences, given the dependence in time in precipitation data. Multivariate analyses of crosstabulated daily precipitation from the Corpus Christi WSO AP gauge express differences in the precipitation distribution of the 1950s drought years versus distributions from the other study periods of the 60-year record under consideration. The second study period precipitation distribution did not differ from that of the third and most recent period.

Inspection of event frequencies of large precipitation amounts (=> 4 inches per day) revealed 25 events in the Corpus Christi WSO AP data. There were 14 years of the record with tropical cyclone occurrences (8-La Niña, 3-El Niño, 3-baseline). Ten large events (40 percent) occurred in La Niña years of which seven events (70 percent) were during five tropical cyclone years. Seven large events (28 percent) occurred in El Niño years but none in tropical cyclone years. Eight events (32 percent) occurred in baseline years of which three events (38 percent) were in tropical cyclone years. Seven of 21 years with large events involved tropical cyclones. The three largest category events were La Niña events in years without tropical cyclones. Two of the three largest events occurred during the drought years of the 1950s. These results suggest somewhat over one-third of large precipitation events occur during the La Niña phase and often in years (La Niña) with tropical cyclones. A modest number of large events seem to occur during the El Niño phase but seldom involving years with tropical cyclones. Large events occur in baseline years, some of which may be tropical cyclone years. These results are generally consistent with those of the computed precipitation anomalies. An additional multivariate comparison of interest that was not conducted is the comparison of distributions between ENSO types and baseline years.

The crosstabulated data revealed 21 (40 percent) of 52 years included large precipitation events. Of the 21 years, 6 were El Niño, 8 were La Niña, and 7 were baseline years. Tropical cyclones occurred in seven high-event years: five were La Niña years and two were baseline years. Annual precipitation exceeded 40 inches in 7 years of the record. Five years were baseline years, one year was La Niña, and one year was El Niño and the greatest amount (48.07 inches) of the record. Two years of the high seven years did not have a high daily-amount event. These results express a role by ENSO but also other mechanisms in causing Nueces River watershed precipitation.

Table 3: Frequencies are given from cross-tabulation of Corpus Christi WSO AP daily precipitation. Column names are coded to indicate the precipitation category. The LT1 code represents precipitation less than one inch but greater than zero, and 1TO2 represents precipitation greater than one inch and less than or equal to 2 inches, etc.

YEAR	ZERO	LT1	1TO2	2TO3	3TO4	4TO5	5TO6	6TO7	7TO8
1948	305	53	4	3	0	0	0	0	0
1949	281	75	6	3	0	0	0	0	0
1950	311	47	5	1	0	0	0	0	0
1951	291	66	3	4	0	1	0	0	0
1952	297	62	5	2	0	0	0	0	0
1953	294	64	6	0	0	0	1	0	0
1954	311	50	3	1	0	0	0	0	0
1955	308	53	2	1	0	0	0	0	1
1956	314	48	2	1	0	0	0	0	1
1957	295	60	8	2	0	0	0	0	0
1958	274	78	6	5	1	1	0	0	0
1959	278	76	7	2	1	1	0	0	0
1960	266	90	6	2	1	0	1	0	0
1961	297	61	4	1	2	0	0	0	0
1962	301	62	2	0	0	0	0	0	0
1963	305	56	3	1	0	0	0	0	0
1964	291	70	4	0	1	0	0	0	0
1965	284	75	5	1	0	0	0	0	0
1966	281	77	2	4	1	0	0	0	0
1967	297	58	6	0	3	0	0	1	0
1968	271	85	3	6	1	0	0	0	0
1969	290	69	5	1	0	0	0	0	0
1970	288	67	6	2	0	1	0	1	0
1971	301	55	4	3	2	0	0	0	0
1972	274	83	4	3	2	0	0	0	0
1973	268	83	10	3	0	1	0	0	0
1974	285	73	7	0	0	0	0	0	0
1975	284	73	7	1	0	0	0	0	0
1976	281	72	10	2	1	0	0	0	0
1977	286	73	4	1	0	1	0	0	0
1978	287	68	5	2	1	2	0	0	0
1979	278	78	6	2	0	0	0	1	0
1980	298	59	6	1	0	0	0	2	0
1981	276	75	9	3	1	1	0	0	0
1982	307	54	1	2	0	1	0	0	0
1983	287	65	7	6	0	0	0	0	0
1984	299	61	3	3	0	0	0	0	0
1985	290	62	12	0	0	0	1	0	0
1986	279	76	8	2	0	0	0	0	0
1987	283	70	10	2	0	0	0	0	0
1988	300	62	2	2	0	0	0	0	0
1989	305	55	5	0	0	0	0	0	0
1990	286	74	4	1	0	0	0	0	0
1991	259	94	7	3	0	1	0	1	0
1992	269	84	8	4	1	0	0	0	0
1993	292	63	3	3	4	0	0	0	0
1994	288	66	5	5	0	0	1	0	0
1995	288	68	5	3	0	0	0	0	1
1996	311	50	4	1	0	0	0	0	0
1997	268	86	6	3	2	0	0	0	0
1998	287	69	7	1	1	0	0	0	0
1999	300	56	5	3	0	1	0	0	0

SUMMARY

Precipitation from the Nueces River watershed was analyzed for recent trends. Of particular interest were comparisons of precipitation across the three periods, 1940-57, 1958-81, and 1982-99, selected for study in the potential long-term effects of the Rincon Project (Irlbeck and Ward 2000). Tropical cyclone occurrences in the Atlantic basin and possible relationships with ENSO and climate variables were investigated. An analysis was conducted of Nueces River watershed precipitation anomalies stratified by ENSO type, to assess whether ENSO may affect watershed precipitation. A multivariate comparison was conducted of daily precipitation sampling distributions for the Rincon three study periods using data from the Corpus Christi WSO AP gauge. Differences could point to more potential inundations of the Nueces delta marsh, despite possible similar annual precipitation amounts.

Precipitation analyses indicated highest amounts occurred along the Nueces Bay coastline of the Rincon Project study area. Least amounts occurred in the west-central area of the watershed. Precipitation from three gauges located across the watershed displayed the same general pattern across the three study periods: least annual amounts during the 1950s' drought, highest amounts during 1958-81 (second study period), and intermediate amounts during 1982-99. Using a base period that included the 1950s, annual precipitation portrayed an increasing trend. However, a broader time view using a base period that consisted of pre-1950s data produced no particular trend in Nueces River watershed precipitation.

The survey of studies of ENSO and some climate variables, and their possible relationships to tropical cyclone activity in the Atlantic basin yielded results of analyses of interannual trends and multi-decadal variability. The studies found that only weak linear trends can be ascribed to the hurricane activity and that multi-decadal variation is the stronger characteristic present (in particular; Gray, 1979, 1984; Gray et al, 1993; Landsea, 1993; Landsea et al, 1992, 1999). Various environmental factors including are analyzed for interannual links to the Atlantic hurricane activity. Environmental variables showing significant, concurrent relationships to the frequency, intensity and duration of Atlantic hurricanes include the stratospheric Quasi-Biennial Oscillation, Atlantic sea surface temperatures, 200mb zonal winds, Caribbean sea level pressures, African West Sahel rainfall, and ENSO. ENSO was linked to changes in tropical cyclone-caused damages. More damage occurred during La Niña years followed by baseline years and El Niño years.

ENSO related precipitation anomalies in the Nueces River watershed were investigated using monthly data stratified by ENSO phase to develop proportion of months of record with precipitation that equaled or exceeded a benchmark determined from the baseline years. Analyses were separately conducted for three gauges of the Nueces River watershed. Results were variable and did not definitively point to either phase expressing a consistent anomaly sense (positive or negative). Suggestions in the results include that two of three gauges yielded more positive anomalies in La Niña months (eight tropical cyclones) than was obtained for El Niño months (four tropical cyclones). Four of six anomalies were negative. Overall, the results suggest that high variability in the watershed precipitation can mask whatever ENSO effects occur. Perhaps data for more watershed gauges would be more revealing.

The sampling distribution of Corpus Christi WSO AP daily precipitation was investigated per each Rincon Project study period. While annual precipitation changed little after the 1950s drought, possibly the distribution of daily amounts differed from one Rincon study period to another. Differing distribution could favor more marsh inundations in some study period. Multivariate analysis was used to compare the sampling distributions of the three study periods. Exploratory analyses revealed that the precipitation distribution of the first study period that included the 1950s drought differed from each of the other two study periods. The second period data did not differ from the third period data, suggesting that neither period would on average be dominant in potential natural inundations of the Nueces delta marsh.

The crosstabulated Corpus Christi WSO AP data revealed 21 (40 percent) of 52 years (since 1948) with large precipitation events (=> 4 inches per day): 6 were El Niño years, 8 were La Niña years and 7 were baseline years. Tropical cyclones occurred in seven high-event years: five were La Niña years and two were baseline years. Annual precipitation exceeded 40 inches in 7 years of which 5 years were baseline years, 1 year was La Niña, and 1 year was El Niño and the greatest amount (48.07 inches) of the record. Of the seven high-annual years, two years did not have a high daily-amount event.

This study revealed that the most prominent feature of Nueces River watershed precipitation since 1940 was the 1950s drought. No particular precipitation trend was apparent unless the basis of comparison is largely the period of drought years. While on average, the La Niña ENSO phase leads to more tropical cyclones in the western Gulf of Mexico, no consistent anomaly across the Nueces River watershed was revealed. This result is important because the Atlantic basin may be returning to a more active tropical cyclone period possibly leading to more related storms impacting the Nueces delta.

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APPENDIX E

Utilization of Estuarine Organic Matter During Growth and Migration by Juvenile Brown Shrimp *Penaeus aztecus* in a South Texas Estuary

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ABSTRACT: The trophic dynamic links of migratory juvenile brown shrimp *Penaeus aztecus* were investigated along the South Texas coast from the Aransas Pass to Corpus Christi and Nueces Bay and to the nursery ground in the Nueces Delta. Shrimps and their potential food sources were measured for $\delta^{13}C$ and $\delta^{13}N$ ratios between December 1995 and July 1996. During this period, shrimp length increased from 10-11 mm when the animals entered Corpus Christi Bay as larvae to 80-90 mm when they returned to Mexico Gulf as subadults. Brown shrimp exhibited spatial and temporal $\delta^{13}C$ variation (from -25.2 to 12.5‰) indicating a high diversity of food sources throughout their migration. From $\delta^{13}C$ values, the main sources used as food sources by juvenile brown shrimp in the Rincon Bayou marsh, were *Spartina alterniflora* and *Spartina spartinae* detritus and benthic diatoms. $\delta^{13}C$ and $\delta^{15}N$ values showed that organic matter inputs carried by the river inflow can also contribute significantly to the feeding of migratory brown shrimp. In these marsh habitats, shrimp isotopic ratios changed rapidly suggesting high tissue turnover rates. The study showed that coastal marshes after restoration through the introduction of freshwater inflow may provide feeding habitats favorable for growth and development of juvenile brown shrimp.

KEY WORDS: *Penaeus aztecus*, food sources, migration, nursery area, $\delta^{13}C$ and $\delta^{15}N$

INTRODUCTION

Many marine species utilize salt marshes, coastal lagoons and estuaries during part of their life cycle (Day et al. 1989). The brown shrimp, *Penaeus aztecus* Ives, is widely distributed along the Texas coastline where it is an important commercial fishery. Like most penaeids, the life history of brown shrimp is complex (Dall et al. 1990). In the Gulf of Mexico, after offshore spawning, post-larval brown shrimps are carried by on-shore water movement and enter bays and shallow estuarine waters where they generally find productive areas and are protected from storms and predators (Day et al. 1989, Fry 1981). Following growth of juvenile shrimp in nursery areas there is a subsequent offshore migration of subadults to complete their life cycle. More precisely, throughout the Texas bay systems, most of the larval brown shrimp enter marine bays from late winter through early spring, spend about 3-4 months in estuarine nursery grounds, and return to the offshore Gulf of Mexico in early summer (Moffett 1970). However, the shrimp fishery is an exploited resource in the Gulf of Mexico (Parker et al. 1988). Restoration of coastal marshes, which act as nurseries, could contribute to increased brown shrimp populations because the marshes provide habitats for juveniles. Enhancing freshwater inflow may have at least two beneficial effects for restoring shrimp habitats: terrestrial inputs may be used as food sources

(Hackney & Haines 1980 Riera & Richard 1996), and freshwater inflow may increase the total primary production through nutrient inputs (Nixon et al., 1986).

The food sources utilized by juvenile brown shrimp during migration are more difficult to determine than that of adults, which live in deeper offshore environments that are generally phytoplankton-based systems (Fry & Parker 1979). As juvenile penaeids migrate, they occupy different habitats, which correspond to different feeding grounds (Dall et al. 1990). Food availability can differ greatly within and between these habitats (Fry 1981), and different food sources may be used preferentially by shrimp. For example, stomach content analyses of small juvenile *Penaeus semisculatus* were composed of a large variety of prey including diatoms, meiofauna, insect larvae and seagrass (Heales et al 1996). Moreover, Wassenberg & Hill (1987) observed large intraspecific differences in the food ingested by *Penaeus esculentus* collected from widely separated areas. Using immunological methods, it was found that the *Penaeus aztecus* and *Penaeus setiferus* have a diverse diet (Hunter & Feller 1987).

Stable isotope analysis has been used successfully to determine original food sources of marine and estuarine invertebrates (Harrigan et al. 1989). Stable isotopes assess food sources assimilated over time (Fry & Sherr 1984), so they are valuable for feeding studies when material in gut contents are difficult to identify due to digestion and trituration. Variation in d^{13}C values of the migratory brown shrimp along the South Texas coast has been investigated previously (Fry & Parker 1979, Fry 1981). These studies have pointed out that seagrass meadows of shallow-water habitats were important feeding grounds for migratory juvenile brown shrimp. However, little is known about spatial and temporal variation of food sources encountered by brown shrimp throughout a complete migration between oceanic waters and upper estuarine reaches. As suggested by Fry (1981), habitats other than seagrass meadows may contribute significantly to the feeding of migrating shrimps. Therefore, it is important to know which feeding habitats contribute the most to the growth and development of the brown shrimp along the Texas coastline.

The aim of the present study was to identify the trophic dynamic links of migratory *Penaeus aztecus* with food sources in various habitats along the South Texas coast. Shrimp migrations were followed from the Aransas Pass to Corpus Christi and Nueces Bay and to the ultimate nursery ground in the Nueces Delta. A primary objective was to determine if the primary production in a coastal marsh, which is being currently restored by the re-introduction of freshwater inflow, can support the feeding and growth of juvenile brown shrimps. Shrimp and potential food sources were determined by stable isotope analyses (δ^{13}C and δ^{15}N).

Material and Method

SAMPLING AREA

The study was carried out in the Nueces Estuary (Fig.1). The estuary consists of the Nueces River, the Rincon Bayou marsh and the Rincon Bayou mouth. The Nueces River empties into Nueces Bay, which is connected to Corpus Christi Bay, which is connected to the Gulf of Mexico by the Aransas Pass. Historically, the Nueces River fed into Rincon Bayou, which is in the center of the Nueces Delta. A dam was created early in the 20th century to contain Nueces River water. Recently, the dam was lowered to allow flood events from Nueces River to flow into the Rincon Bayou to restore the Rincon Bayou marsh. Sampling locations into Rincon Bayou marsh (Fig.1) were distributed from the freshwater entrance into Rincon Bayou marsh (River site) to the Rincon Bayou mouth (Rincon mouth). Sampling stations also included "Up Marsh" and "Down Marsh" within Rincon Bayou marsh, and "Aransas Pass" which connected Corpus Christi Bay to the Gulf of Mexico. These sites have been considered because, as reported by Moffett (1970), they may lie on the migratory route of brown shrimps that enter Corpus Christi Bay through Aransas Pass.

COLLECTION AND PREPARATION OF SAMPLES

Sampling for organic matter sources and brown shrimp was carried out during from December 1995 to July 1996. Shrimp were collected by otter trawls or hand-thrown cast nets. They were sorted by hand and kept in seawater from the sampling site so that guts would be purged prior to analysis. At the laboratory, shrimp were identified to the species levels using a magnifying glass and keys, measured (length) and were frozen (-80°C). For stable isotope analyses shrimp were prepared according to Fry & Parker (1979). White muscle tissue was dissected from the shrimp abdomen, acidified (10% HCl) to remove any residual carbonates from cuticules, rinsed with distilled water, and dried in a oven at 60°C. Then, the white muscle of each individual was ground to a fine powder with a mortar and pestle to homogenize the sample. Individuals were used as samples except where shrimp were too small to obtain sufficient tissue for accurate δ^{13}C and δ^{15}N analyses. For larval shrimp, 6 or 8 individuals (10-11 mm size length) from the same sampling occasion were combined. Some of the brown shrimp collected and analysed for δ^{13}C were also measured for δ^{15}N. Zooplankton was collected with a (176 µm) mesh net in Nueces Bay near Rincon mouth (Fig.1). Samples of zooplankton were acidified (10% HCl) to remove any residual carbonates from cuticules, rinsed with distilled water, dried in a oven at 60°C and ground to a fine powder with a mortar and pestle to homogenize the sample.

Corixidae *Corix* sp and mysids *Mysidopsis almyra* were sampled at Up Marsh at different occasions, between April 1995 and February 1996, by using the same procedure as for brown shrimp. Composite samples of corixidae (8 individuals) and mysids were prepared in the same way as for zooplankton and brown shrimp, respectively.

For sampling particulate organic matter (POM), 15 l of water were collected, then filtered on precombusted Whatman GF/F glass fiber filters under moderate vacuum within five hours after collection. Samples were acidified (10% HCl) to remove carbonates, dried at 60°C and kept frozen (-80°C) until analysis. For sedimented organic matter (SOM) analysis, sediment samples were taken in the Nueces River at "River site" and in the Rincon Bayou marsh at "Up Marsh" and "Down Marsh" by scraping the upper 1 cm of mud. At the laboratory, samples were homogeneized, dried at 60°C, ground using a mortar and a pestle, and then acidified (10% HCl) to remove any inorganic carbon. These samples were not rinsed to prevent any loss of dissolved organics. They were dried overnight at 50°C under a slight vacuum to evaporate the acid. Once dried, the sediment was mixed with Milli-Q water, freeze-dried, ground again to a fine powder and kept frozen (-80°C) until analysis.

At "Rincon mouth", leaves and twigs of the two dominant marine phanerogames, *Spartina alterniflora* and *Salicornia* sp, were collected. For samples of terrestrial organic matter, leaves of the dominant vascular plants, namely *Salix* sp, *Fraxinus* sp and the switchgrass *Panicum virgatum*, were collected along the Nueces River up "River site". Most samples within Rincon Bayou marsh were the Gulf Cord Grass *Spartina spartinae* which dominates along the Rincon Bayou channel. These plant samples were cleaned of epibionts, and prepared similarly to shrimp muscle tissue. Blue green algal mats were collected in the Rincon Bayou channel and acidified (10% HCl), rinsed with distilled water, freeze-dried, and frozen until analysis. Benthic diatoms were also sampled from muddy sediments near the Rincon Bayou channel, and separated using a procedure from Couch (1989) as modified by Riera & Richard (1996). Briefly, the surficial sediments with dense microalgal mats was scraped and brought into the laboratory where it was spread on flat trays to a depth of about 1 cm. A nylon screen (63 µm mesh) was laid upon the sediment surface and covered with a 4 to 5 mm layer of combusted silica powder (60-210 µm). After 12 hours, the top 2 mm of the silica powder was gently scraped and then filtered on previously combusted glass fiber filters, acidified (10% HCl), rinsed with distilled water, freeze-dried, and frozen (-80°C).

STABLE ISOTOPE ANALYSIS

Samples for isotope analyses were combusted at 900°C using CuO as an oxydant in evacuated quartz tubes (Stump & Frazer 1973). Samples for isotope analyses were prepared as in Boutton (1991). Before the purification of CO_2, N_2 was trapped on silica gel granules in a stopcock sample ampule and analyzed immediatly after CO_2 collection (Mariotti 1982). The carbon and nitrogen isotope ratios were measured using a Sigma 200 (CJS Sciences) double inlet, triple collector isotope ratio mass spectrometer. Data are expressed in the standard d unit notation where $\delta X = [(R_{sample}/R_{reference})-1] \times 10^3$, with $R = {}^{13}C/{}^{12}C$ for carbon and ${}^{15}N/{}^{14}N$ for nitrogen, and reported relative to the Pee Dee Belemnite standard (PDB) for carbon and to air N_2 for nitrogen. The typical precision of the overall procedure (i.e., preparation plus analysis) was ± 0.1 ‰ for carbon and ± 0.2 ‰ for nitrogen.

Results

δ^{13}C AND δ^{15}15N OF POM, SOM, SOURCES AND INVERTEBRATES

δ^{13}C and δ^{15}N of POM, SOM, plant sources and invertebrates are presented in Table 1. There was a gradient in carbon isotope values from the sea to the river. At Aransas Pass, POM δ^{13}C values were δ^{13}between -24.8‰

and -22.0‰ while at the Nueces River site, POM $\delta^{13}C$ ranged from -28.8 to -26.3 ‰. POM $\delta^{13}C$ at Rincon Bayou mouth ranged from -27.2‰ to -20.8‰. Within Rincon Bayou marsh, POM exhibited a large range for $\delta^{13}C$, from -26.3‰ to -17.4‰ at Down Marsh, and from -24.1‰ to -17.1‰ at Up Marsh. Corresponding $\delta^{15}N$ values for POM ranged from 3 to 11 ‰ at Aransas Pass, from 8.8 to 10.8 ‰ at Nueces River and from 9.2 to 9.4 ‰ at Rincon Bayou mouth. Within Rincon Bayou marsh, POM $\delta^{15}N$ ranged from 2.6 to 9.3 ‰. $\delta^{13}C$ for SOM (i.e., including benthic algae) ranged from -24.0 to -22.2‰ at Nueces River and from -21.8 to -20.2 ‰ in Rincon Bayou marsh. SOM $\delta^{15}N$ values were between 7.1 to 8.2 ‰ in Rincon Bayou marsh. At Rincon Bayou mouth, $\delta^{13}C$ values ranged from -27.8 to -26.3 ‰ for *Salicornia* sp and from -16.2 to -13.7 ‰ for *Spartina alterniflora*, typical of $\delta^{13}C$ for C3 and C4 plants, respectively (Fry & Sherr 1984, Currin et al. 1995) and close to values previously observed for *Spartina* sp and *Salicornia* sp by Creach (1997). Within Rincon Bayou marsh, $\delta^{13}C$ for *Spartina spartinae* ranged from -16.8 to -14.5 ‰. Benthic diatoms inhabiting muddy sediments near the Rincon Bayou channel had $\delta^{13}C$ values from -18.5 to -16.3 ‰. Blue green algae had $\delta^{13}C$ from -15.7 to -15.9 ‰ typical of ^{13}C-enriched surficial blue-green algal mats from Texas (Calder & Parker 1973). Blue green algae were the most ^{15}N-depleted primary producers with $\delta^{15}N$ from -0.7 to 1.7 ‰. $\delta^{13}C$ values for leaves of the most common terrestrial vegetation along Nueces River, from -30.3 to -27.6 ‰, for *Fraxinus* sp and *Salix* sp, were typical of terrestrial C3 plants (Degens 1969). $\delta^{13}C$ of *Panicum virgatum* ranged from -15.9 to -14.6 ‰ indicating a C4 photosynthetic pathway (Fry & Sherr 1984). At Rincon Bayou mouth zooplankton was ^{13}C-depleted (from -26.3 to -25.6 ‰) and ^{15}N-enriched (11.7 ‰). Within Rincon Bayou marsh *Corix* sp and *Mysidopsis almyra* showed $\delta^{13}C$ from -20.8 to -16.2 ‰ and from -21.6 to -20.5 ‰, respectively. Corresponding $\delta^{15}N$ values were -0.2‰ for *Corix* sp and from 10.5 to 10.8 ‰ for Mysidopsis almyra.

SIZE LENGTH, $\delta^{13}C$ AND $\delta^{15}N$ OF *PENAEUS AZTECUS*

Early in the study, only small larval shrimp were found in the Aransas Pass during their migration into the bay (Fig. 2). Shrimp length increased from 10-11 mm (larvae) in January 1996 to 80-90 mm (subadults) in July 1996 when they migrated seaward, out of the Pass. Shrimp size increased from about 40 mm to 60 mm in the nursery habitat (Fig. 2). Isotope values of $\delta^{13}C$ and $\delta^{15}N$ for *Penaeus aztecus* also differed between Aransas Pass and Nueces River and within sites over the period January to July 1996 (Table 2). Although the sampling procedure was similar at each sampling occasion, the number of shrimp collected was unequal at the different sites and dates, owing to abundance fluctuations throughout the migration. In particular, on the different sampling dates, brown shrimps were not found at every site (Table 2) confirming the migratory pattern of the juvenile brown shrimp previously observed along the South Texas coast (Moffet 1970, Fry 1981). However, the sampling procedure did not allow an accurate quantitative evaluation of shrimp abundance at the different sites over the sampling period.

Shrimp feeding habitats and assimilated carbon and nitrogen were different in the animals at various stages of the migratory life cycle. At Aransas Pass, $\delta^{13}C$ values for brown shrimps varied between -21.7 and -20.7 ‰ for larval stages (10-11 mm) in winter and from -16.4 to -12.5 ‰ for sub-adults (80-90 mm) in summer. $\delta^{13}C$ values for juvenile shrimps ranged from -20.6 to -14.8 ‰ at Rincon Bayou mouth, from -21.3 to -14.5 ‰ at Down Marsh and from -18.4 to -15.3 ‰ at Up Marsh. At the Nueces River site, brown shrimp were collected between mid-May and mid-June and their $\delta^{13}C$ ranged from -25.2 to -20.4 ‰. $\delta^{13}C$ for *Penaeus aztecus* were significantly different among the sampling sites (Kruskal-Wallis test=35.3, df=4, $p<0,001$). At Aransas Pass, $\delta^{15}N$ values were between 5.5 and 7.7 ‰ for larval shrimp and between 3.3 and 9.7 ‰ for sub-adults. $\delta^{15}N$ ranged from 4.5 to 13.1 ‰ at Rincon Bayou mouth, from 1.0 to 9.9 ‰ at Down Marsh and from 1.2 to 5.1 ‰ at Up Marsh. At the Nueces River site, $\delta^{15}N$ values ranged between 6.6 and 13.9 ‰. $\delta^{15}N$ values were significantly different among the sampling sites either (Kruskal-Wallis test=36.8, df=4, $p<0,001$).

DISCUSSION

$\delta^{13}C$ VARIATIONS OF *PENAEUS AZTECUS* THROUGHOUT THE MIGRATION

Spatial and temporal $\delta^{13}C$ of migrating brown shrimp exhibited variation throughout migration (Fig.3) confirming the migratory pattern of juvenile brown shrimp in Texas bays previously observed (Moffet 1970, Fry 1981). The range of $\delta^{13}C$ values for *Peneaus aztecus* (from -25.2 to -12.5 ‰) is similar to the range of $\delta^{13}C$ observed for the main sources of organic matter (from -30.3 to -13.7 ‰). This observation is consistent with the hypothesis that a high diversity of food sources is used by brown shrimp throughout the migration. However, during each sampling date from January 25 to July 29 (Table 2, Fig.3), there was little variation in shrimp $\delta^{13}C$ values (sd < 2 ‰), indicating that the shrimps had a similar diet at specific sites and times (de Niro & Epstein 1978). Wide ranges of $\delta^{13}C$ for invertebrates have been previously observed along salinity gradients (Incze et al. 1982, Hughes & Sherr 1983). The oyster *Crassostrea gigas* exhibited significantly different $\delta^{13}C$ variations between sites along an estuarine gradient, reflecting the preferential utilization of different food sources, namely, terrestrial detritus, benthic diatoms and marine phytoplankton (Riera & Richard 1996). The present study suggests that individual $\delta^{13}C$ variation of a migrating species (*Penaeus aztecus*) along an estuarine gradient can be as large as inter-individual $\delta^{13}C$ variation of a sedentary species (*Crassostrea gigas*).

CONTRIBUTION OF SALT MARSH SOURCES TO BROWN SHRIMP DIET

Salt marsh habitats appear to be important food sources for young brown shrimp. When entering Corpus Christi Bay through Aransas Pass, brown shrimp larvae had typically $\delta^{13}C$ values (-21.7 to -20.7 ‰) characteristic of animals feeding primarly on an oceanic planktonic food source (Fry & Parker 1979, Incze et al. 1982). However, as they entered the mouth of Rincon Bayou through the *Spartina alterniflora* and *Salicornia* sp marsh, brown shrimp became more ^{13}C-enriched (-19.4 to -16.8 ‰) indicating a significant contribution of a ^{13}C-enriched source to shrimp diet. At Rincon mouth, suspended POM, *Salicornia* sp and zooplankton were too ^{13}C-depleted (-27.3 to -24.2 ‰) to explain the enrichment in ^{13}C of migratory brown shrimp (Table 1, Fig.3). Moreover, assuming phytoplankton is the main food source for zooplankton, and that the trophic $\delta^{13}C$ enrichment is about 1 ‰ per trophic level (de Niro & Epstein 1978), phytoplankton $\delta^{13}C$ should be about -27 ‰, which is too negative to be a major contribution to brown shrimp diet. The ^{13}C-enrichment of brown shrimp at the mouth of Rincon Bayou can be explained by a significant contribution of carbon derived from *Spartina alterniflora* detritus (-16 to -14.5 ‰). Consistent with these results, plant detritus derived from *Zostera* sp, *Phragmites* sp or *Spartina* sp were found in gut contents of post-larval penaeids indicating that marsh detritus may be a food source for these shrimps when they occupy that habitat (see Dall et al., 1990 for a review). Likewise, mangrove detritus has been shown to contribute to the diet of juvenile *Penaeus merguiensis* inhabiting tidal creeks in Peninsular Malaysia (Newell et al. 1995). In contrast, from feeding experiments Gleason & Wellington (1988) reported that *Spartina alterniflora* detritus and its epiphytes contributed only a small part of *Penaeus aztecus* assimilated carbon. Finally, Dall et al (1990) concluded that plant detritus itself is not a major food source for prawns.

The results of the present study indicated that detritus derived from *Spartina alterniflora* can be an important carbon source to juvenile brown shrimp. However, *Penaeus aztecus* may assimilate carbon that is ultimately derived from *Spartina* via several routes other than direct feeding on plants detritus. It is possible that *Penaeus aztecus* may obtain part of its carbon derived from *Spartina alterniflora* detritus through microbial mediation. For example, in ^{14}C labelling experiments, the grass shrimp *Palaemonetes pugio* could assimilate carbon from detrital *Spartina alterniflora* with 38,4 % efficiency via bacterial mediation between non-living organic detritus and shrimp (Crosby 1985). In fact, bacteria associated with debris of refractory plant material can facilitate the carbon transfer from plant sources to bivalves (Langdon & Newell 1990, Crosby et al. 1990).

As brown shrimp occupied the down and up marsh, they remained ^{13}C-enriched (-19 to -17 ‰), indicating a persistence in their utilisation of a relatively heavy ^{13}C source (Fig.3). Although there is no *Spartina alterniflora* within the Rincon Bayou marsh, these $\delta^{13}C$ values may be explained by utilization of benthic diatoms, blue green algae and/or detritus derived from *Spartina spartinae* as carbon source (Fig.3). However, the respective contributions of these ^{13}C-enriched sources to brown shrimp feeding cannot be established from $\delta^{13}C$ values alone. It is known that benthic microalgae from mudflats represent one of the dominant food source for juvenile penaeids within tidal creeks in Peninsular Malaysia (Newell et al. 1995). Also, a positive growth rate of postlarval brown shrimp can be supported over 16 days by feeding only on the planktonic diatom, *Skeletonema costatum* (Gleason & Zimmerman 1984). Although living microalgae can be more readily used than detritus of vascular plants, as shown for marine bivalves (Bayne *et al.* 1987, Crosby *et al.* 1989), a significant contribution of detritus derived from *Spartina spartinae* to shrimp diet may also account for the observed carbon isotope values. These results are in accordance with recent isotopic data of Deegan and Garritt (1997) showing a preferential utilisation of local sources organic matter in coastal marsh areas by invertebrates.

CONTRIBUTION OF RIVERINE INPUTS TO BROWN SHRIMP DIET

$\delta^{13}C$ values also changed as shrimp moved near and into areas that are subject to freshwater inundation. In May and June 1996, juvenile brown shrimp were collected at the Nueces River site up to Rincon Bayou marsh (Fig.1). Other shrimp, (e.g. *Penaeus merguiensis* (Staples 1980) and *Penaeus setiferus* (Dall et al. 1990)), have also been observed in lower salinities environments far upstream from the river mouth. As juvenile brown shrimp occupied Nueces River, their $\delta^{13}C$ became significantly more negative (-24 to -21 ‰) compared with $\delta^{13}C$ measured within Rincon Bayou marsh (Fig.3). This depletion in ^{13}C indicates that a significant part of brown shrimp carbon at Nueces River is derived from terrestrial detritus and/or riverine phytoplankton carried by freshwater inflow, because Rincon Bayou marsh lacks a ^{13}C-depleted source (Fig.3). Unfortunately, $\delta^{13}C$ for riverine phytoplankton could not be estimated in the present study. However, previous results showed phytoplankton $\delta^{13}C$ values of -44 to -47 ‰ in rivers (Rau 1978) and of -40 ‰ (Hedges et al. 1986) in a lake. Similarly, $\delta^{13}C$ of freshwater phytoplankton in the Charente River (France) ranged between -41.8 and -31.2 ‰ (Riera & Richard 1996). Considering this higher depletion in ^{13}C for freshwater phytoplankton compared with terrestrial C3 plants, a primary contribution of riverine phytoplankton to the diet of brown shrimp is unlikely, but cannot be excluded from these results.

In fact, because the metabolic ^{13}C-enrichment during assimilation is close to 1 ‰ (De Niro & Epstein 1978, Rau et al. 1983), shrimp $\delta^{13}C$ values at Nueces River are consistent with a significant utilisation of terrestrial C3 plants (-29 to -28 ‰) as food source. Moreover, the similarity of $\delta^{13}C$ values of terrestrial C3 plants (*Salix* sp, *Fraxinus* sp) and POM in the Nueces River indicates that detritus from C3 plants contribute predominantly to river POM. Therefore, the results of this study can explain the depletion in ^{13}C for brown shrimp observed in lower salinity bays that are flushed by freshwater inflow or are most influenced by river inputs along the South Texas coast (Fry 1981). This result is consistent with the hypothesis that terrestrial organic inputs could be incorporated into estuarine food weebs (Hackney & Haines 1980, Incze et al. 1982). In fact, previous results showed the significant contribution of terrestrial detritus derived from C3 plants to the diet of oysters (*Crassostrea gigas*) in the upper reaches of the Charente Estuary (Riera & Richard 1996), and in the middle estuarine reaches as a high river discharge period occurred (Riera & Richard 1997). In addition, from $\delta^{13}C$ analyses, Stephenson & Lyon (1982) reported that the bivalve *Chione stutchburyi* inhabiting the Avon-Heathcote Estuary (New Zealand) could utilise carbon of terrestrial origin depending upon its position in the estuary and local hydrology. Freshwater inputs can be an important source of nutrition for juvenile brown shrimp in habitats lacking salt marsh plants and benthic diatoms. Therefore, during periods of high river discharge, riverine inputs may support a substantial part of the food webs in South Texas bays and elsewhere as well.

OFFSHORE MIGRATION OF SUBADULT *PENAEUS AZTECUS*

Subadult *Penaeus aztecus* that are migrating offshore have different diets than the subadults found in marshes. An enrichment in ^{13}C for *Penaeus aztecus* (-13.8 ± 1.5 ‰) was observed at Aransas Pass at the end of July 1996 (Fig.3). Brown shrimp in Aransas Pass were likely returning towards the nearshore Gulf of Mexico because they were sub-adult size and offshore migration occurs in summer in Texas bays (Moffet 1970). Similar $\delta^{13}C$ values, between -12.6 and -14.6 ‰, were also observed by Fry & Parker (1979) for brown shrimp collected offshore in the Gulf of Mexico, but more negative $\delta^{13}C$ were observed for other shrimps (*Penaeus setiferus*) from the same area. This enrichment in ^{13}C in shrimp tissues is not likely to be a result of a metabolic effect as shrimp grow due to a variation of carbon fractionation. In fact, the inter-individual $\delta^{13}C$ variability among animals having a similar food source does not usually exeed 2 ‰ for fishes and invertebrates, these differences being attributed to size, age or sex (Fry & Parker 1979, Hughes & Sherr 1983). The 8 ‰ mean enrichment in ^{13}C in shrimp tissues (Fig.3) between the marsh and pass locations in spring and summer may have other interpretations.

At Aransas Pass, phytoplankton was likely to be the main organic matter source for brown shrimps because there are no seagrass meadows. However, considering the $\delta^{13}C$ of -22.7 ‰ for marine phytoplankton in the Northern Gulf of Mexico given by Thayer et al. (1983), the enrichment in ^{13}C due to metabolic fractionation between phytoplankton and brown shrimps would be much more than 1 ‰. Most likely, less negative $\delta^{13}C$ for brown shrimp, as they enter the offshore area, may be explained by a progressive enrichment in ^{13}C as shrimps returned from Nueces River environments towards offshore waters (Fig.3), as suggested by Fry & Parker (1979). In fact, the shrimps collected in late July, at the end of the migration, exhibited $\delta^{13}C$ typical of the feeding habitats recently encountered where they used ^{13}C-enriched food sources, e.g., marsh grass or seagrasses. Particularly, within Corpus Christi and Redfish Bays, seagrasses have the highest $\delta^{13}C$ values (-3 to -13 ‰) in the ecosystem as reported by Fry and Parker (1979). High $\delta^{13}C$ of -10 ‰ were also observed recently for seagrasses of Laguna Madre in south Texas (Street et al. 1997). Additionally, macroalgae is known to occur in bay bottoms and along the jetties at Aransas Pass, but we have not sampled this source. As they returned towards marine waters through Rincon Bayou mouth shrimp may also increase their feeding on *Spartina* detritus directly or through predation on detritivores. Therefore, as subadult brown shrimp feed offshore, their $\delta^{13}C$ should progressively converge on the $\delta^{13}C$ value characteristic of offshore environment, close to -18 ‰ (Fry 1981).

TEMPORAL $\delta^{13}C$ VARIATION: IMPORTANCE FOR TISSUE TURNOVER

Tissue turnover rates are important to know to interpret temporal $\delta^{13}C$ variation. There was about a 3.5 ‰ decrease in $\delta^{13}C$ values from the up marsh to the Nueces River site (Fig.3) indicating a high tissue turnover rate for brown shrimp as they migrate. This isotopic $\delta^{13}C$ variation occurred over a distance of less than 5 km and within a period of 9 weeks. From one feeding habitat to another the "old carbon" of shrimp tissue is progressively diluted due to 1) growth of new tissue using "new carbon" and 2) metabolic loss due to tissue turn over (Anderson et al. 1987). Therefore, after a variation in food, shrimp $\delta^{13}C$ will change isotopically as rapidly as tissue turnover rate will allow (Fry 1982). In the present study, the $\delta^{13}C$ decrease of migratory brown shrimp is consistent with a high tissue turnover rate, which support the hypothesis of a high growth rate in the nursery habitat. This suggestion is consistent with previous results based on experimental observations showing that postlarval shrimp can increase in weight by a factor of 4 within a week or less at 25°C (Zein-Eldin & Aldrich 1965). A 14‰ variation for $\delta^{13}C$ of postlarval brown shrimp has been observed after a 3.9 fold increase in weight after a change in food source, indicating a high tissue turnover rate (Fry & Arnold 1982). From feeding experiments Gleason (1986) showed that the half-life of the initial tissue carbon of *Penaeus aztecus* fed with plant and animal diets was reached before the first doubling of weight. Finally, juvenile shrimp (initially $\delta^{13}C$:-18.6 ‰) in an experimental feeding pond with feed at $\delta^{13}C$: -22.9 ‰ for 8 weeks attained an equilibrium $\delta^{13}C$ at -21.3 ‰ after 3 weeks and an increase in weight of 300 % (Parker et al. 1988). High tissue turnover rate for young shrimp can be related with behaviour and feeding activity. In fact, small juveniles of *Penaeus semisculatus* were active and fed both day and night and are thought to feed continuously and to digest most of their food within only one hour (Heales et al 1996). It is likely that the variation in carbon isotope values of brown shrimp in the Rincon Bayou Marsh are a result of changed food sources and rapid growth in this nursery habitat.

FOOD SOURCES DETERMINATION FROM $\delta^{15}N$ VALUES

Although only part of the shrimp collected were measured for $\delta^{15}N$, a dual isotope approach is useful for identifying food sources. In up and down Rincon Bayou marsh, $\delta^{15}N$ for brown shrimp showed a high variability both between sampling periods and between individuals (Table 2). This is consistent with a higher range in $\delta^{15}N$ values for sources in this habitat (i.e., from -0.7 to 7.6‰) and suggest a high diversity of nitrogen sources for shrimps (i.e., *Spartina spartinea*, benthic diatoms, blue green algae). Lower $\delta^{15}N$values that were observed for some shrimps in Rincon Bayou marsh could be explained by a depletion in ^{15}N during nitrogen assimilation (Mako et al 1982). In fact, these authors observed a mean $\delta^{15}N$ fractionation of -0.3‰ for the amphipod *Amphithoe valida* fed with fresh and detrital algae. However, this hypothesis is unlikely for *Penaeus* species because feeding experiments demonstrated a trophic enrichment in ^{15}N of 2.4‰ for *Penaeus vannamei* (Parker et al. 1988). These lower $\delta^{15}N$ values for brown shrimp may partly result from a preferential assimilation of specific chemical components of plant tissues (Mako et al 1982) and/or by the utilisation of ^{15}N-depleted blue green algae (Table 1). Therefore, in the present study, $\delta^{15}N$ was not as valuable as $\delta^{13}C$ to characterize food sources of brown shrimp. This result is consistent with the suggestion of Fry & Sherr (1984) that $\delta^{15}N$ is not as discriminating as $\delta^{13}C$ for food sources determination in coastal ecosystems. However, at the Nueces River mean $\delta^{15}N$ for shrimp (i.e., 8.2, 10.1 and 11.7 ‰) are consistent with a significant utilization of the terrestrial C3 plants *Fraxinus* sp (i.e., 6.6 ‰) and/or *Salix* sp (8.3 ± 1.1 ‰) when taking into account the mean trophic enrichment for $\delta^{15}N$ (i.e., 3.5 ‰ given by Minagawa & Wada 1984). In this riverine habitat, where terrestrially-derived organic matter dominated, $\delta^{15}N$ values confirmed $\delta^{13}C$ results.

IMPORTANCE OF TROPHIC MEDIATION THROUGH PREDATION

Predation on animals can also be important for brown shrimp. Like many *Penaeus* species, *Penaeus aztecus* can feed on different prey taxa including oligochaetes, polychaetes, crustaceans, mysids, mollusks and meiofauna (Hunter & Feller 1987, Dall et al. 1990). In fact, the utilization of detritus derived from terrestrial and marsh vascular plants could occur indirectly through infaunal prey or through bacterial mediation (Gleason & Zimmerman 1984). For example, juvenile *Penaeus merguiensis* may use mangrove leaf detritus as a food source indirectly through predation on small detritivorous invertebrates (Newell et al. 1995). Detritus from *Spartina alterniflora* salt marshes may be predominant in the diet of meiofauna when an accumulation of detrital *Spartina* is associated with the development of an important microbial biomass (Couch 1989). Then, meiofauna may also have a role in the trophic mediation between plant detritus and brown shrimp in these habitats. Likewise, benthic diatoms can be an indirect food source for juvenile shrimp through direct grazing or through intermediate infaunal prey (Stoner & Zimmerman 1988). In the present study, Corixidae (*Corix* sp) and mysids (*Leptomis* sp and *Mysidopsis almyra*), which were collected frequently at the Nueces River and the Rincon Bayou marsh, could be part of the diet of *Penaeus aztecus*. δ^{13}C values (mean: -17.9‰) and δ^{15}N (-0.2‰) of *Corix* sp may explain partly the enrichment in ^{13}C and the depletion in ^{15}N observed for individuals of *Peneaus aztecus* in Rincon Bayou marsh (Table 2). In contrast, isotopic values measured for both for zooplankton near Rincon Bayou mouth and *Mysidopsis almyra* in Rincon Bayou marsh were too ^{13}C-depleted and ^{15}N-depleted to contribute significantly to the feeding of brown shrimp in these two habitats.

VARIATION IN TROPHIC LEVEL OF BROWN SHRIMP

Brown shrimp may vary their food sources and feed at different trophic levels during their migratory life cycle. Variations in brown shrimp feeding can be directly related with habitats. However, the habitat variations may be associated with a variation in the trophic level of shrimp. Variations in the diet of *Penaeus* sp with size and age were partly attributed to the variation from a herbivorous to a carnivorous feeding mode as shrimp grow (Chong & Sasekumar 1981). Therefore, shrimp δ^{15}N should become more positive as size increases. This effect should be more obvious in animal tissue with δ^{15}N than δ^{13}C values, due to a higher δ^{15}N fractionation during assimilation. The relationship between δ^{15}N and shrimp length varies in each feeding habitat occupied by migratory brown shrimp, because nitrogen isotopic values at the base of the food chain can vary among the different habitats (Fig.4). At Aransas Pass, this effect should have been especially clear, because brown shrimp size range was largest there. However, there was no significant Pearson correlation between δ^{15}N and shrimp size at Aransas Pass ($r=-0.22$, $p>0.5$), at Rincon Bayou mouth ($r=0.12$, $p>0.5$), at Rincon Bayou marsh ($r=0.18$, $p>0.1$) and at Nueces River ($r=0.35$, $p>0.1$). These results indicate that differences in food sources of *Penaeus aztecus* thoughout its growth and migration are not associated with an increase in trophic level with size but mostly related to feeding habitats, as indicated by δ^{13}C.

In addition, large ranges of δ^{15}N observed for shrimps within the different habitats (Fig.4) suggest that shrimps may use the different sources both directly and indirectly through predation. This hypothesis could explain a higher variability for shrimp δ^{15}N values compared to corresponding δ^{13}C (Table 2) due to the higher trophic enrichment during nitrogen assimilation. Therefore, the results of the present study are consistent with an omnivore feeding mode for migratory juvenile brown shrimp. This is concordant with gut content analyses, which indicate that animal prey is part of the food ingested by *Penaeus aztecus*, but that there is no variation in dietary breadth and prey preference as shrimp grow (Hunter & Feller 1987).

In conclusion, δ^{13}C values suggest that the main food sources for juvenile brown shrimp (*Penaeus aztecus*) in the Rincon Bayou marsh are *Spartina* detritus, benthic diatoms and blue green algae. Tissue turnover rates in these marsh habitats are apparently high, because shrimp isotopic signatures change rapidly. Moreover, δ^{13}C and δ^{15}N results show that terrestrial inputs carried by the freshwater inflow can contribute significantly to the diet of juvenile brown shrimp in the Nueces River. Finally, these results show that the restoration of coastal marshes through the introduction of freshwater inflow can provide nursery areas favorable for feeding and growth of juvenile brown shrimp.

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Table 1: Average stable isotope values for food sources from different habitats

Sources		δ ^{13}C	δ ^{15}N
Nueces River	Riverine POM	-27.6 ± 0.9 (n=6)	9.5 ± 1.0 (n=3)
	Riverine SOM	-23.2 ± 0.9 (n=3)	4.7 (n=1)
	Fraxinus sp.	-28.5 ± 0.6 (n=5)	6.6 (n=1)
	Salix sp.	-29.8 ± 0.4 (n=6)	8.3 ± 1.1 (n=3)
	Phragmites sp.	-15.2 ± 0.6 (n=5)	-1.6 (n=1)
Rincon Bayou Marsh	POM upper marsh	-21.2 ± 2.8 (n=18)	5.5 ± 2.2 (n=10)
	POM lower marsh	-22.8 ± 0.8 (n=2)	6.5 ± 0.9 (n=2)
	Marsh SOM	-21.2 ± 0.5 (n=7)	7.6 ± 0.7 (n=2)
	Marsh Grass	-15.6 ± 1.1 (n=3)	7.6 (n=1)
	Benthic diatoms	-17.5 ± 0.9 (n=5)	4.6 ± 1.9 (n=2)
Rincon Bayou Mouth	POM marsh	-24.3 ± 2.9 (n=4)	9.3 ± 0.1 (n=2)
	Spartina sp. (fresh leaves)	-16.0 ± 0.3 (n=2)	
	Spartina sp. (old leaves, stems)	-14.5 ± 0.6 (n=6)	2.6 (n=1)
	Salicornia sp. (fresh leaves)	-27.3 ± 0.4 (n=4)	
	Salicornia sp. (old leaves, stems)	-27.1 ± 0.6 (n=5)	5.4 ± 1.9 (n=3)
	Zooplankton	-26.0 ± 0.3 (n=3)	11.7 (n=1)
Aransas Pass Inlet	Ocean POM	-23.5 ± 0.9 (n=8)	8.1 ± 3.0 (n=5)

Table 2: Spatial and temporal changes in stable isotope compositions of Brown Shrimp

	Locations									
Dates	Aransas Pass Inlet		Rincon Bayou Mouth		Rincon Bayou Lower Marsh		Rincon Bayou Upper Marsh		Nueces River	
(1996)	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$
Jan 25	-20.7	7.7								
Feb 9	-20.7	5.5								
Mar 4	-21.7	5.8								
Apr 10					-19.3 to -18.0	3.4				
Apr 25			-19.3 to -14.8	4.8 to 8.7	-17.9 to -14.5	4.5				
May 14					-21.3 to -17.0	1.0 to 6.6	-18.3 to -15.3	1.2 to 5.1	-25.2 to -23.9	6.6 to 9.9
May 30			-20.3 to -16.3	6.5 to 10.2	-20.4 to -15.5	5.2 to 9.9				
Jun 2							-18.0 to -18.4	1.3 to 2.3	-23.2 to -21.7	9.5 to 11.0
Jun 19									-21.8 to -20.4	10.1 to 13.9
Jun 21			-20.6 to -18.4	4.5 to 13.1	-20.1 to -16.5	5.6 to 6.4				
Jul 29	-16.4 to -12.5	3.3 to 9.7								

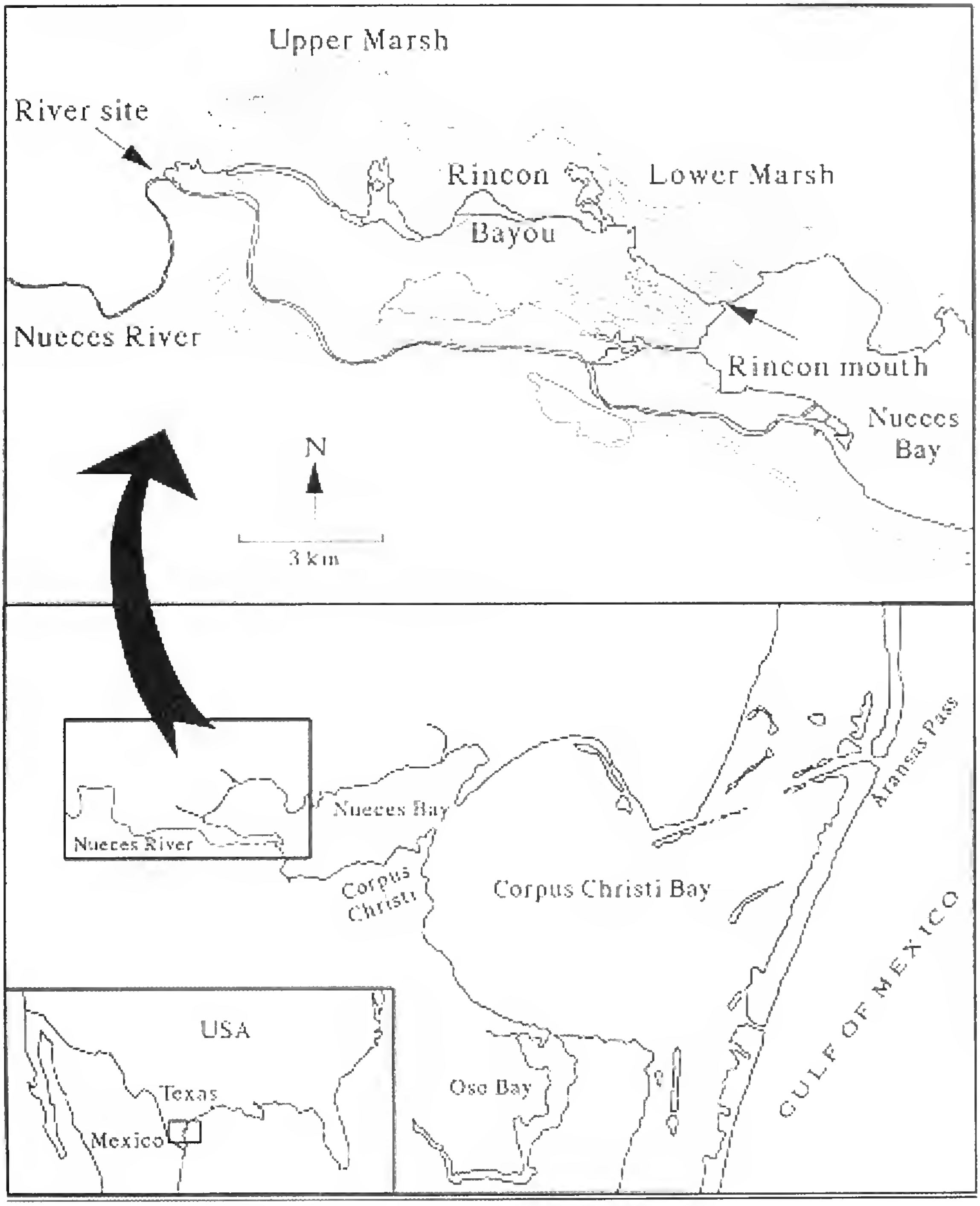

Figure 1: Locations of sampling sites in various shrimp habitats.

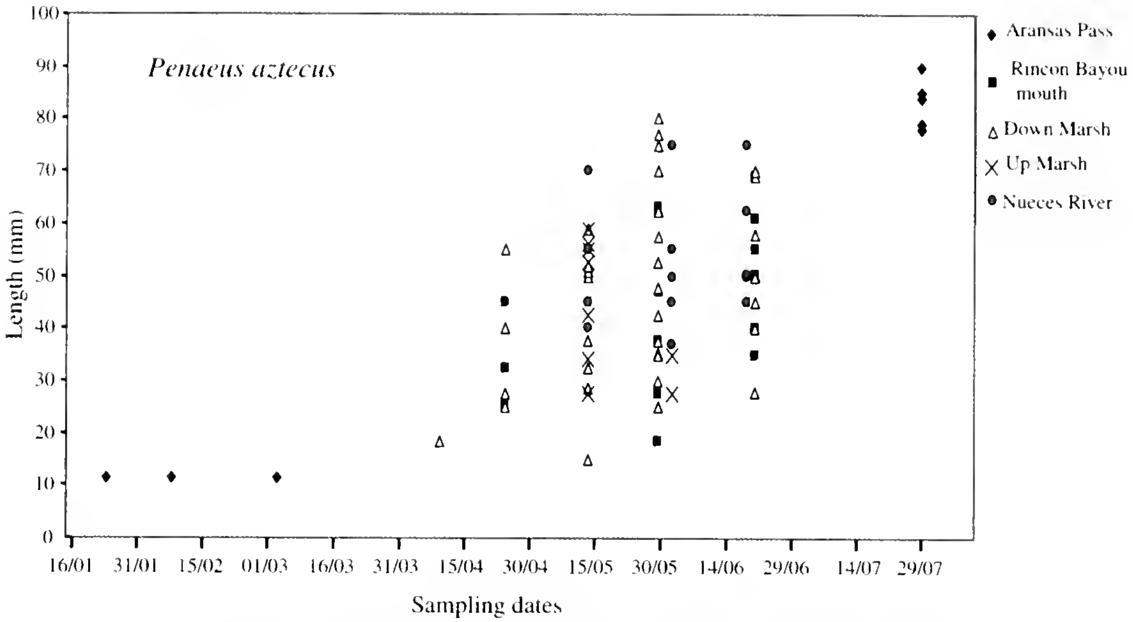

Figure 2: Size of brown shrimp *Penaeus aztecus* caught on sampling dates, in different locations.

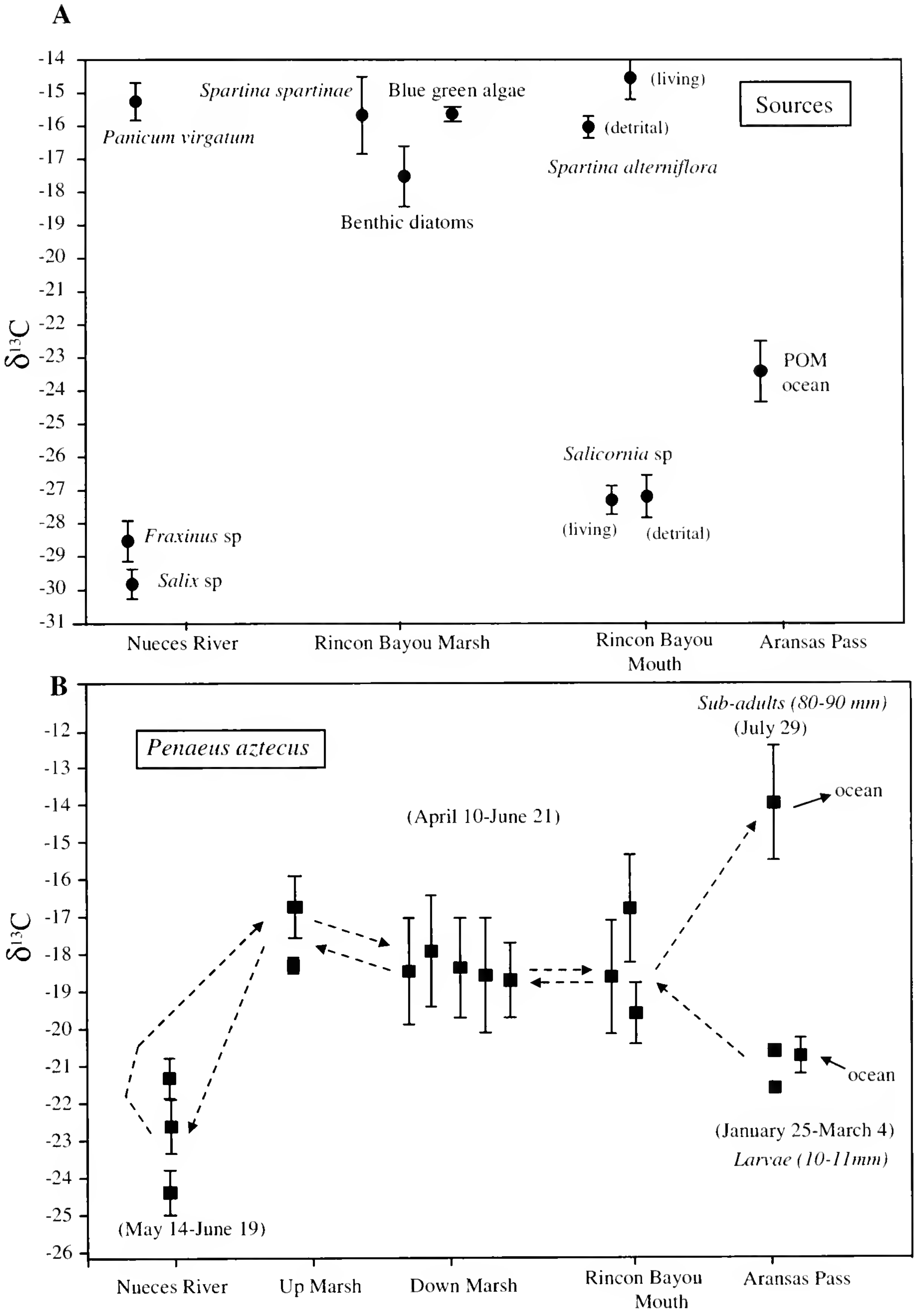

Figure 3: Variation of carbon isotopic ratios in different feeding habitats. A. Potential food sources. B. Juvenile brown shrimp *Penaeus aztecus* as they migrate through ecosystem as indicated by dotted lines with arrows.

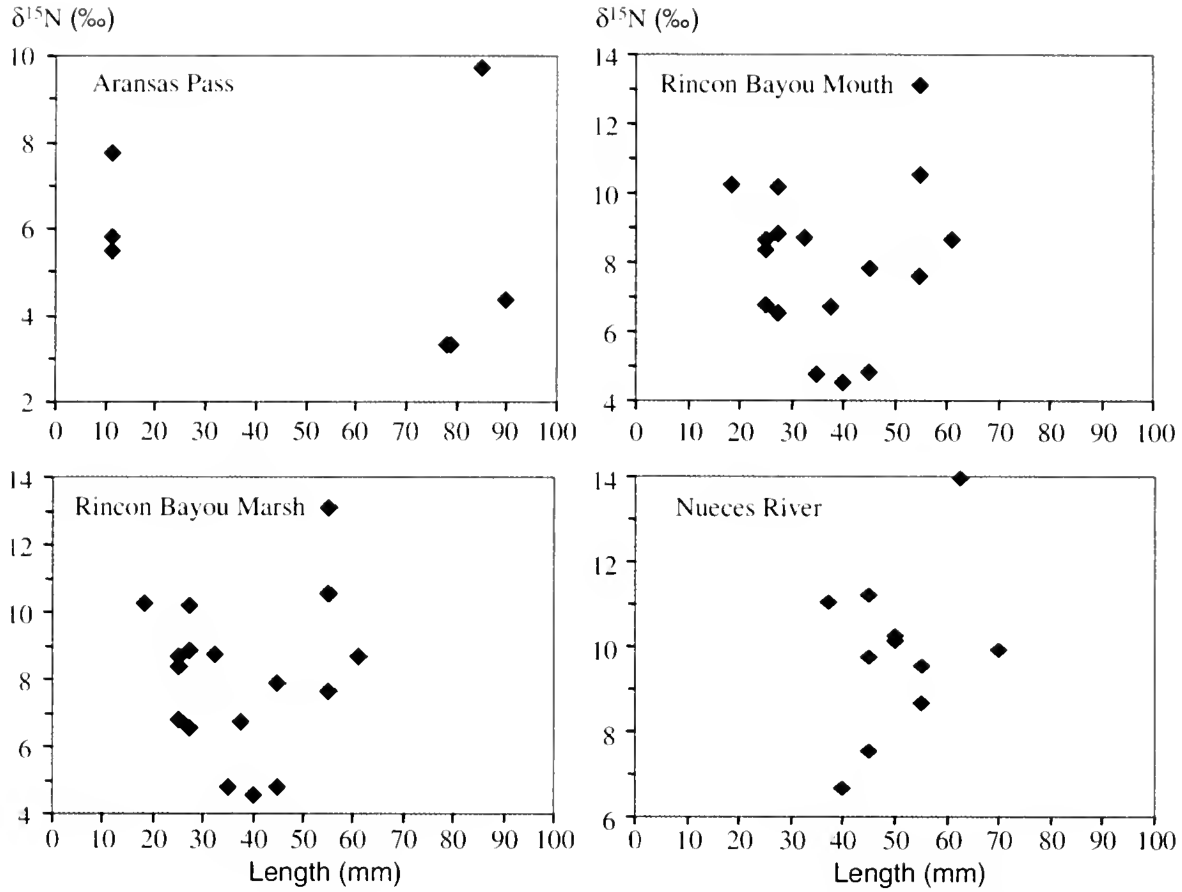

Figure 4: Relationship between δ^{15}N and length (mm) of brown shrimp *Penaeus aztecus* in different habitats.

APPENDIX F

Effects of Temporality, Disturbance Frequency and Water Flow on an Upper Estuarine Macroinfauna Community

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ABSTRACT: The effects of disturbance frequency and altered flow on estuarine macrobenthic community structure and colonization were studied in Rincon Bayou, a low-inflow, microtidal, shallow habitat in the upper Nueces Delta, Texas. Three flow treatments were used: increased flow (within a weir), natural flow (control), and decreased flow (between nets). Four disturbance frequency treatments were used: undisturbed, biweekly, monthly, and bimonthly disturbance. Disturbance was imitated by placement and replacement of 6.5-cm diameter trays filled with defaunated sediment. Significant flow velocity differences were found among flow treatments, but turbidity, abundance, biomass, and diversity were not different. Significant differences among disturbance frequencies were found. Abundance and biomass decreased with increasing disturbance frequency indicating post-disturbance community persistence is important in regulating community structure. In the flow experiment, structure and tray effects were evident because abundance and biomass were higher near structures and in trays than in controls. The higher abundance and biomass in defaunated sediments relative to background sediments indicates disturbance plays an important role in community production of early succession communities. Collection date was the most important determinant of community structure, thus natural variability overwhelmed effects of both experimental manipulations. The temporal changes were driven by a Streblospio benedicti recruitment event (resulting in densities as high as 1.3 10^6 m^{-2}) captured 20 June 1997, and a flood event that began 22 June 1997. After the flood, S. benedicti density declined rapidly and freshwater species invaded, leading to three distinct community states over the 14-week period of the study. The overwhelming significance of "temporality" (i.e., short-term temporal change in community structure) is the unexplained temporal component of community variation in experimental manipulations. Temporality is simply a smaller temporal scale than seasonality.

KEY WORDS: benthos, disturbance, estuary, flow, macrofauna, Streblospio benedicti

INTRODUCTION

Flow dynamics in estuaries result from complex interactions among tidal cycles, estuarine circulation, hydrology, climatological forcing, and rate of freshwater inflow. Flow dynamics may vary over the course of a day, month, season, or on climatological scales. Characteristic flow patterns of an estuary depend on its size, shape, and location. Numerous mechanisms exist by which an estuary's flow regime may affect macrobenthic populations. Changes in flow velocity can affect the sediment flux of ammonium (Asmus et al. 1998), depth of oxygen penetration (Berninger and Huettel 1997), and benthic aerobic respiration and chemical oxygen demand (Boynton et al. 1981). Flow velocity also plays an important role in larval dispersal and settlement (Butman 1986a, 1986b, 1987, 1989), food availability (Smaal and Haas 1997), and suspension feeder growth rates (Eckman and Duggins 1993, Hentschell 1999a, 1999b). The pattern of flow dynamics (or frequency of change) characteristic of an estuary may play an important role in determining macrobenthic community structure (Pearson and Rosenberg 1987). Atypical changes in flow dynamics, such as those occurring during storms, may also be important determinants of benthic community structure (Renaud et al. 1996).

Physical disturbances (e.g., dredging, trawling, or major storms) affect macrobenthic communities within the context of the flow regime and ambient environmental conditions. The frequency of disturbance may be a major determinant of community structure. Connell (1978) hypothesized that more frequent disturbances will maintain a community at an earlier stage of succession, which is characterized by lower diversity, abundance, and biomass than reference communities of lower disturbance frequencies. Because flow dynamics can vary on short temporal scales, it could be an important physical regulator of community change.

The purpose of this study was to determine temporal effects of disturbance frequency and altered water flow on macroinfauna early succession. Macrobenthic recruitment and community structure were expected to change for each flow treatment (Rhoads and Young 1970). Increased flow was expected to promote suspension feeder populations and growth rates (Hentschel 1999a; 1999b). Communities subjected to greater frequencies of disturbance were expected to have lower diversity, abundance and biomass than those subjected to less frequent disturbance as predicted by Connell (1978). Early succession was expected to be dynamic and vary among flow treatments because the dominant organism at the study site, Streblosio benedicti, is an opportunistic species (Grassle and Grassle 1974), can recruit in excess of 25,000 m^{-2} a month (Levin 1984), and can increase growth rates with flow speeds between 9 and 18 cm s^{-1} (Hentschel 1999b).

METHODS

SITE DESCRIPTION

Rincon Bayou is a tidal creek in the Nueces-Corpus Christi Bay estuarine ecosystem. Rincon Bayou lies west of Nueces Bay and north of the Nueces River. It may have once been the primary channel of the Nueces River but is now connected to the Nueces River via an overflow channel constructed in October 1995 (Irlbeck and Erger 1998).

Rincon Bayou is a low-inflow environment, subject to hypersalinity during droughts and freshets during floods. Monthly discharges from the Nueces River into Rincon Bayou ranged from -1200 to 300,000 m^3 between May and December, 1996, but about 60 % of daily discharges were < ± 1200 m^3 (USGS unpublished data 1997). Rincon Bayou receives little tidal influence (< 0.2 m) and water movement is predominantly wind driven (Salas 1994), or inflow driven during floods.

The location within Rincon Bayou, station C (27° 53.927' N, 97° 36.250' W), was chosen because it lies approximately along the axis of prevailing winds, which blow from the southeast and south (Port of Corpus Christi Authority 1993). In addition, station C is part of a quarterly sampling program begun in 1994 from which a historical context can be drawn. Surface sediment is approximately 86 % silt and clay, and contains 0.7 % total organic carbon. Salinity averages 40 ‰, but has ranged between 0.2 - 160 ‰ over a four-year monitoring period (Montagna unpublished data). Dissolved oxygen averaged 7.36 mg l^{-1}, but has ranged between 1.01 - 15.32 mg l^{-1} over the same period. Six macrobenthic taxa were commonly found at station C: the polychaetes Streblospio benedicti Webster and Laeoneris culveri (Webster), the crustaceans Ostrocoda and Hemicyclops sp., and insect larvae of Ceratopogonidae and Chironomidae.

EXPERIMENTAL DESIGN

The goal of the present study was to determine the effects of flow alteration and disturbance frequency on short-term changes of macrofauna (Fig. 1). Three flow treatment levels were used: increased flow, decreased flow, and control. Increased flow was effected through the use of weirs parallel to currents. Weirs are used to increase water pressure, and hence flow, over a specific area (Fig. 2a). Decreased flow was effected through the use of nets perpendicular to currents. Nets are commonly used to reduce wave energy by slowing water velocity. Control flow was areas perpendicular, but away from structures and represents the natural flow conditions of the Bayou (Fig. 2b).

Two plots of each flow treatment were constructed (Fig. 1). The plots, thus represent replication at the treatment level. Two control plots, 1 m x 1 m area, were delineated by PVC corner poles. Two weir plots (increased flow) were constructed of 1 m x 0.5 m, 3/4" (1.9 cm) plywood attached to 1.5 m PVC poles (Figs. 1 and 2). Net plots (decreased flow) were 2 m long and 1 m wide and made of 2.5 cm mesh attached to 1.5 m PVC poles (Fig. 2a). All PVC poles extended 1 m into the sediment. The open faces of the weirs and the long sides of the net faced southeast, the direction of predominant tidal and wind driven flow (Montagna et al. 1998). All experimental sampling areas were 1 m x 1 m squares within the central region of each structure (Fig. 2a).

Structures were built within a 0.25 km^2 region (Fig. 2b). Furthest downstream were a weir plot and a net plot. Furthest upstream were a control plot and a net plot. In between were a weir plot and a control plot. Plots were staggered to limit possible structure interactions and were all roughly the same water depth. Structure interactions are unlikely because Rincon Bayou is generally a low-inflow, microtidal environment.

Frequency of disturbance was varied. Four disturbance frequency treatment levels (i.e., undisturbed, biweekly, monthly, and bimonthly) were nested within each flow treatment plot (Fig. 1). Disturbance was imitated by emplacement of defaunated sediment in trays. Undisturbed sediment was the control for the disturbance frequency treatment. Bi-weekly disturbance was the most frequent disturbance investigated and trays remained in the field for 2 weeks. Monthly disturbance was the moderate frequency level and trays remained in the field for 4 weeks. Bimonthly disturbance was the least frequent disturbance investigated and trays remained in the field for 8 weeks. Short-term frequencies of disturbance were used to determine effects on development of early succession communities.

Disturbance trays were constructed from 6.5-cm diameter acrylic tubes, 3 cm high, and fused to 7 cm x 7 cm square bottoms. Trays were filled with sediment collected from station C and defaunated using a microwave. Approximately 500 ml of sediment were microwaved for 15 minutes to bring sediment temperatures to roughly 100 °C. Microscopic investigation of subsampled sediment yielded no live animals following defaunation. Trays were filled with well-mixed defaunated sediment in the field, and placed at predetermined random positions within the experimental area of each flow plot. Flagged rods were used for treatment identification and to avoid tray loss. Only one tray was turned over and lost during the study.

The disturbance frequency experiment was replicated two different ways: by initial placement date (23 April and 04 June), and by ending sampling date (20 June and 01 August) (Fig. 3). This required eight sampling dates over a 14-week period (Fig. 3). On each sampling date, three replicate tray samples and three undisturbed samples (the top 3 cm of a 6.5-cm diameter core) were taken in each disturbance frequency level (Fig. 1).

MEASUREMENTS

Hydrographic data (e.g., salinity, temperature, dissolved oxygen) were collected from each flow treatment plot on each field date using a Hydrolab 4000 Sonde. Three turbidity samples were collected from each flow treatment plot and analyzed using a HACH model 2100A turbidimeter. Rainfall, tidal stage, and flow volumes were collected from a gage placed at the mouth of Rincon Bayou where it connects to the Nueces River (unpublished data collected by the United States Geological Survey at Station 08211503, Rincon Bayou Channel near Calallen, Texas).

Flow velocity was measured twice for each flow treatment plot and level to determine the effect of the structures. Flow velocity was measured only twice because flooding prevented equipment deployment and retrieval on most dates. Flow was measured on 07 May and 17 July 1997 using a UNIDATA Starflow Ultrasonic Doppler flow meter. Velocity, depth, and temperature were recorded every two minutes for 6 to 24 minutes per flow plot per date while sediment samples were being taken from the adjacent flow plot.

Macrofauna were extracted from sediment using a 0.5-mm sieve, identified to the lowest taxonomic level practicable, and counted. Lecithotrophic larvae were assumed to be Streblospio benedicti, which are more common at Rincon Bayou than the alternative Polydora cornuta (Montagna and Ritter unpublished data). Biomass was determined for each taxonomic group by drying samples for 24 hours in a 55 °C oven and weighing to the nearest 0.01 mg. Abundance and biomass were converted to a per meter basis and (natural logarithm) transformed for statistical analysis as follows: $\ln(n\ m^{-2}+1)$ and $\ln(g\ m^{-2}+1)$ respectively. Hill's diversity (N1), and Peliou's evenness (E1) were calculated to summarize community structure characteristics.

Diversity was calculated as $N1 = (\exp)^{H'}$, where $H' = \Sigma\ (p_i \ln p_i)$, where $p_i = n_i\ /\ n$, where n_i = abundance of species i, and n = total abundance (Ludwig and Reynolds 1988). Evenness was calculated as $E1 = \ln(N1)\ /\ \ln(N0)$, where N0 = total number of species (Ludwig and Reynolds 1988). N1 is the number of abundant species, and E1 is the familiar J'.

STATISTICAL ANALYSIS

A two-way analysis of variance (ANOVA) was used to determine turbidity and velocity differences among flow treatments and sampling dates. More complex ANOVA was used to test for differences in macrobenthic response among flow, disturbance frequency, and sampling date treatments. All ANOVA models were calculated using SAS GLM procedures (SAS 1985).

A three-way, incomplete factorial, randomized block design was used to test for community differences in over all sampling dates (Fig. 1). Main effects (i.e., treatments) were flow, disturbance frequency, and sample collection date. The randomized block was flow plot. Blocks are replicates that do not have interactions with main effects. The design is incomplete factorial because disturbance frequency treatments were not started or ended on the same dates. Because some date cells are missing in the biweekly, monthly, and bimonthly frequency levels, the frequency*date interaction and flow*frequency* date interaction do not exist in the ANOVA model (Table 1). In this model, date is more like a block (controlling nuisance variation) than a main effect.

Full rank, three-way ANOVA models do exist for subsets of the data set (Fig. 3). The experiment was replicated two different times: as starting dates and as ending dates. So, macrobenthic data was analyzed with a three-way randomized block design twice: Once for trays deployed on two dates: 23 April and 4 June 1997, and once for trays collected on two dates: 20 June and 1 August 1997. These analyses are referred to as "initiating" and "ending" sampling dates respectively (Table 1).

Interpretation of results from complex ANOVA designs is often obscured by significant interactions, because the main effects tests are invalid. To simply interpretation of the present study, two-way, incomplete, randomized block models were calculated by a treatment level. Examination of the simple main effects allows testing and interpretation of the first main effect at all levels of the second main effect. The simple main effects models were calculated by disturbance frequency for flow and sampling date treatments with plot as a randomized block. Tukey multiple comparison tests were used to determine differences among levels of flow or disturbance frequency cell means. The implementation of Tukey uses the harmonic mean of cell sample sizes when sample sizes are unequal (SAS 1985). Variance components analysis was used to estimate the percent of variation attributable to each main and interaction effect in all ANOVA models.

Principal component analysis (PCA) was used (SAS 1985) to determine treatment effects on species composition. The covariance matrix of log transformed species abundance, standardized to a normal distribution was used for PCA. Using the covariance, instead of the correlation matrix, eliminates problems encountered where many rare species with zero counts exist. The multivariate PCA method is a species dependent analysis of community structure, unlike the species independent analysis of diversity indices.

RESULTS

HYDROGRAPHY

Hydrographic conditions at station C varied during the course of the experiment (Fig. 4). The small (about 5 ‰) drop in salinity from 23 April - 22 May 1997 is due to local rainfall. Average salinity peaked on 20 June 1997 at 25.6 ‰, but dropped to 0 ‰ on 2 July. The fresh conditions correspond with a flood event that began on 22 June. The flood resulted primarily from rain in the watershed northwest of the delta. Dissolved oxygen was highest 23 April and 7 May, but lowest 4 June. On 4 June, dissolved oxygen data collected prior to 9:30 a.m. were 2.4 mg l^{1} at weir 1, and 2.88 mg l^{-1} at net 1, indicating hypoxic conditions probably occurred during the previous night. Temperature generally increased with onset of summer.

A significant (p = 0.0020) flow*date interaction was present because there were greater differences among flow rates on 17 July than on 07 May (Fig. 5). On both dates, weir structures had increased flow velocities, and the net structures had decreased flow velocities relative to control plots. Average flow velocities were highest in between weir structures (132 mm s^{-1}), were lower in control plots (102 mm s^{-1}), and lowest in between net structures (75 mm s^{-1}). There was no difference in flow treatments between the two replicate plots.

Turbidity did not vary significantly among flow treatments, indicating flow manipulations did not alter the concentration of suspended sediment. Turbidity differences were found among dates ($p = 0.0001$). No interaction effects were detected. Turbidity samples for 23 April were not included in ANOVA because sediment was resuspended during sample collection.

TREATMENT EFFECTS

Macroinfauna community structure response over all sampling dates was clear, because there were no significant treatment interactions for diversity (N1), and evenness (E1). There was no significant differences among flow treatments for diversity, and evenness. There were significant differences for disturbance frequency levels for diversity ($p = 0.0001$), and evenness ($p = 0.005$). Significant differences (0.0001) among dates were detected for diversity and evenness. Diversity was highest for biweekly samples (1.82) and lowest for undisturbed samples (1.31); both of which were significantly different from monthly (1.59) and bimonthly (1.62) samples, which were the same (Table 1, Tukey test). Biweekly (0.59) samples had the highest average evenness, which was different from monthly (0.44), bimonthly (0.37), and undisturbed levels (0.28) (Table 1, Tukey test). Evenness in monthly and bimonthly samples were the same, and bimonthly and undisturbed sample means were the same (Tukey test).

Macroinfauna standing stock (i.e., abundance and biomass) response to the experimental treatments was analyzed three ways: by all sample dates, by initiation dates, and by ending dates (Table 2). Regardless of the design or analysis used, there were many significant interactions obscuring interpretation of main treatment effects (Table 1). Total biomass and abundance did not have similar results in regard to which interactions existed. The two main experimental treatments (flow and disturbance frequency) contributed very little variance components regardless of the analysis technique, ranging from 0 % to 12.7 %.

In general, the full-rank analysis for two ending dates yielded similar results to the incomplete factorial design for all sampling dates for both abundance and biomass (Table 1). The difference between the contribution of the date effect is particularly striking. Sampling date contributed the largest percentage of variance for abundance and biomass for the incomplete factorial analysis and the full-rank analysis of ending dates, ranging from 35.4 % - 86.9 %. In contrast, date contributed no variance to the full-rank analysis of initiating dates, and nearly all the variance was contributed by the frequency*date interaction for abundance (91.9 %) and biomass (57.7 %). The similarity between analyses of p-values and variance components for all dates and ending dates indicates macrobenthic response is similar among all treatments on given dates. Similarly, significant frequency*date interactions found in the initial date analysis indicates that community change is different for each experimental treatment due to samples being taken on different dates.

Regardless of the analysis method, the flow*frequency interaction was always significant (Table 2). The nature of the interaction is different responses to flow variation in frequent disturbances (at biweekly and monthly scales) compared to less frequent disturbances at longer times scales (bimonthly and undisturbed) (Fig. 6). Abundance was very similar in flow treatments during short-term disturbance, but the increased flow treatment had much higher abundances in the samples that had recovered the longest or were undisturbed (Fig. 6a). The trend for biomass was similar, except that biomass was higher in the decreased flow treatment than in the control or increased flow treatment over the short-term disturbances (Fig. 6b).

SIMPLE MAIN EFFECTS

Analysis of the full rank model yielded many significant interaction effects (Table 2), so simple main effects models were run (Tables 3 and 4). Flow treatment effects were determined with separate analyses by each disturbance frequency level (Table 3) and frequency treatment effects were determined with separate analyses by each flow level (Table 4).

Flow Effects

The flow treatment tests are generally valid because of non-significant interactions with date, except for the undisturbed samples (Table 3). No significant abundance differences were found among flow treatments. The biomass differences among flow treatments for biweekly and monthly levels (Fig. 6.) were significant (Table 3). At the biweekly and monthly frequency levels, decreased flow yielded significantly greater biomass than control and increased flow levels (Tukey test). Abundance changed over collection dates for all frequency levels. Biomass changed over the long-term, but over short-term (biweekly) time intervals.

The flow*date interaction was significant for abundance and biomass for the undisturbed treatment (Table 3). This interaction is especially interesting because it represents how undisturbed sediment changed over time as a result of the flow treatments alone (Fig. 7). In undisturbed sediment, highest abundance and biomass values were found within structures that altered flow. Except for the first collection date, the abundance and biomass in the control plots were always lower than the altered flow plots indicating a possible structure effect. So, the interaction was due to the first collection date (when all flow levels were similar) and the similarity of flow alteration structures (which alternated between highest and second highest values).

Frequency Effects

Disturbance frequency tests were affected by significant frequency*date interaction effects, except in decreased flow structures (Table 4). At the decreased flow level, average biomass of monthly (1.20 g m^{-2}), bimonthly (1.15 g m^{-2}), and weekly (0.90 g m^{-2}) frequencies were similar to each other, but were significantly different from undisturbed average biomass (0.69 g m^{-2}).

Effects of the disturbance frequency experiment on the natural community is represented by changes in the undisturbed sediment community in control level of flow treatments. There was a significant frequency*date interaction for control flow levels for both abundance and biomass (Table 4). Average abundance and biomass was lower in undisturbed sediment than in all disturbance treatment levels except for biweekly samples collected on 07 May (Fig. 8). The lower abundance and biomass in undisturbed samples may indicate disturbance enhances community productivity. On most dates, average abundance and biomass in bimonthly-frequency, control-flow, samples were greater than other disturbance frequency samples. In general, there was a trend of increasing abundance and biomass from biweekly, to monthly, to bimonthly disturbance frequencies, indicating growth or recruitment with time.

COMMUNITY STRUCTURE

Ten taxa were found during the experiment. Streblospio benedicti and Laeoneris culveri were present on each sampling date. Chironomid larvae were observed 23 April and 7 May, but appeared in abundance 20 June, persisting through 1 August. Polydora cornuta Bosc was present between 4 June and 2 July, but was most abundant on 20 June. Polydora cornuta was observed only once in 31 observations at the control-flow plot indicating a possible positive structure effect. Mysidopsis almyra Bowman was present between 23 April and 22 May, and was found only in undisturbed samples. Nermerteans were found on 20 June and 02 July in undisturbed and monthly samples. Mulinia lateralis (Say) was found infrequently between 23 April and 20 June in undisturbed sediment of decreased and control flow treatments. Mediomastus ambiseta (Hartman) was found infrequently between 4 June and 1 August. Amphipods and oligochaetes were each present in a single sample during the course of the study.

Average abundance and biomass were greatest for samples collected on 20 June 1997 (Figs. 7 and 8). Average abundance was 422,000 m^{-2} and average biomass was 5.62 g m^{-2}. Streblospio benedicti accounted for 96 % of abundance and 76 % of biomass in these samples on average. The bimonthly-frequency, increased-flow plots contained the greatest average abundance and biomass of all samples in the study. For example, one sample contained 4,730 organisms (1,342,000 m^{-2}), of which 4,667 (1,324,000 m^{-2}) were S. benedicti. Many S. benedicti were very small, presumably lecithotrophic larvae or post larval juveniles, but sizes were not measured.

Principal component analysis (PCA) yielded three distinct collection date groups (Fig. 9a), but no flow or disturbance frequency effects. PC1 separated samples collected 20 June and 02 July from those collected 17 July and 01 August. PC2 separated samples collected 23 April - 04 June from those collected 20 June - 01 August. Chironomid larvae (CL) loaded 0.97 on PC2 (Fig. 9b) indicating their importance to characterizing communities sampled 20 June and later. Streblospio benedicti and Laeoneris culveri loaded positively for both

PC1 and PC2 indicating their importance to characterizing samples collected 20 June and 02 July. PCA of each date group separated in the first PCA also failed to segregate flow treatments or disturbance frequency treatments.

DISCUSSION

FLOW EFFECTS

The structures used to manipulate flow significantly altered flow velocity in the expected manner (Fig. 5), but they did not significantly affect turbidity or macrobenthos overall (Table 2, Fig. 6). Flow treatments accounted for only a small fraction of the total variance in abundance and biomass (<1.9 %). Significant interactions with sampling date and disturbance frequency treatments indicate that altered flow affected macrobenthos only in certain instances (Table 2). The strongest flow effects were found in undisturbed samples only (Table 3). In undisturbed sediments, average abundance and biomass were greater at increased and decreased flow levels than in control plots for all sampling dates except the first (Fig. 7). Increased abundance and biomass in increased and decreased flow plots relative to control plots indicate the physical presence of experimental structures may have affected macrobenthos. It is possible structure proximity afforded the community a refuge from predation or increased food supply by increasing sedimentation rate. The difference may also explain the flow*frequency interaction, because frequently disturbed (biweekly and monthly) samples had low abundance and biomass due to recent defaunation.

At the species level, Polydora cornuta was found only at increased and decreased flow plots with one exception, indicating a possible attraction to structures. Between 1994 and 1997, P. cornuta was not observed at Rincon Bayou (Montagna and Ritter unpublished data). The present study is the only report of its presence at station C.

Failure to detect significant abundance and biomass differences among flow treatments may arise from inadequacy of the manipulations. Flow treatments did not alter flow velocity enough to significantly affect resuspended sediment. Average flow velocities of weir treatment plots ranged between 10.1 and 16.4 cm s^{-1}. These velocities may not have reached critical erosion velocities of the natural cohesive sediment of Rincon Bayou. For example, critical erosion velocities of the Skeffling intertidal mud flat on the Humber Estuary, U.K. ranged between 21.8 cm s^{-1} and 30.8 cm s^{-1} (Widdows et al. 1998). Community change driven by altered resuspension rates would not be detected by the manipulations in the present study.

Changes in flow velocity affects growth of some species. For example, growth of some macrobenthic suspension feeders, such as Membranipora membranacea, Balanus crenatus, and Pseudochitinopoma occidentalis, are inhibited by flow velocities 12 - 30 cm s^{-1} (Wildish and Kristmanson 1979; Eckman and Duggins 1993). In contrast, growth rates of spionid polychaetes common to Rincon Bayou increase with increasing flow. Polydora cornuta and Streblospio benedicti increase growth rates with flow velocities between 9 and 18 cm s^{-1} (Hentschel 1999a; 1999b). For example, P. cornuta grew at a rate of 1.4 volumetric doublings per day, reaching sexual maturity within 1 week at 18 cm s^{-1} velocity (Hentschel 1999a; 1999b). Because the response by the two spionid polychaetes common to the study area increased over the range of measured flow velocities, inhibition probably did not occur near structures. It is more likely slight enhancement occurred, explaining the small increase of abundance and biomass in increased flow plots (Fig. 7).

The increase of abundance and biomass in increased flow (weir structure) plots is due to changes in population size of Streblospio benedicti. Population growth of S. benedicti appears to have been enhanced at increased flow plots prior to the flood of 22 June 1997. On 20 June, S. benedicti populations at increased flow plots were twice that of decreased flow and control plots. Streblospio benedicti grows faster under higher flow conditions (Hentschel 1999a; 1999b). The unique life history of S. benedicti could also be partly responsible for the rapid population growth. Colonists could have been adults carrying a full brood (Levin 1984).

DISTURBANCE FREQUENCY EFFECTS

Disturbance frequency treatments appear to demonstrate succession. Longer periods between disturbances (i.e., biweekly to monthly to bimonthly) were associated with increasing abundance and biomass and decreasing evenness (Table 1, Fig. 8). The trend demonstrates early colonization and successively greater abundance, biomass, and less dominance with longer periods between disturbance. Lower evenness and abundance in more frequently disturbed communities indicates greater disturbance frequency maintains the community at a earlier stage of succession (Pearson and Rosenberg 1976; 1978; Dauer 1993; Trueblood et al. 1994; Weisberg et al. 1997). If a community is disturbed every two weeks, it cannot proceed beyond the colonization stage. Thus, the length of time since the last disturbance regulates the community (Connell 1978). In addition, communities subjected to altered flow disturbance (i.e., increased or decreased) had higher abundance and biomass than natural (control) communities (Fig. 7) explaining the frequency*flow interaction (Fig. 6). These results indicate disturbance may play an important role in regulating macrobenthic community dynamics and increase secondary production as suggested by Rhoads et al. (1978).

All disturbance frequency levels, including undisturbed ambient samples, were dominated by the polychaete Streblospio benedicti. Streblospio benedicti is an opportunistic species (Grassle and Grassle 1974). Dominance by opportunists is a key characteristic indicating early succession, or highly disturbed, estuarine macrobenthic communities (Pearson and Rosenberg 1976; 1978; Thistle 1981; Dauer 1993; McCook 1994; Weisberg et al. 1997). Dominance of S. benedicti in the current study may indicate the community of station C is highly disturbed by natural environmental variation, e.g., as the broad salinity ranges and flow conditions found during this study (Fig. 4).

Community abundance, biomass, and diversity of undisturbed sediments were lower than that of all disturbance treatments after the first (7 May) biweekly samples (Fig.). The undisturbed sediment community is the ambient, reference community against which colonization of defaunated (disturbed) sediment was compared. Increasing abundance, biomass, and diversity were expected in defaunated sediment until disturbed and undisturbed communities were similar. In contrast, abundance of the bimonthly disturbance frequency level was 8 times that of the undisturbed community; biomass of bimonthly level was twice that of undisturbed sediment; and diversity of bimonthly level was higher than that of undisturbed sediment.

There are three possible explanations for the differences between undisturbed and defaunated communities. The structure of experimental trays may attract organisms as a refuge or alter water flow affecting deposition and recruitment (Butman 1986b; Snelgrove et al. 1993). The defaunated sediment may attract macrobenthos or promote macrobenthic reproduction. Macrobenthic succession of defaunated sediment may be initiated by a population burst of opportunistic species. The population burst may exceed late succession community abundance and biomass, but return to normal levels after a period longer than 8 weeks. One, two, or all three explanations may be responsible for the observed differences.

TEMPORALITY

Temporality, "the quality or state of being temporal (Mish 1985, p.1214)", is a property of communities that arises in all studies from the complexity of ecological interactions in the natural environment. Community variation through time is not in itself a new finding. Temporality, however, is the unexplained temporal component of community variation that may exceed that of experimental treatments. Examples of temporality can be found in benthic communities of the Savin Hill mudflat, Boston Harbor (Trueblood et al. 1994), microbial communities of the Parker River salt marsh, Rowley, MA (Montagna and Ruber 1980), and epifaunal communities at Beaufort, NC (Sutherland and Karlson 1977; Holm et al. 1997). In all these cases, natural community variation over time (i.e., temporality) exceeded the effects of experimental manipulations.

In the present study, collection date had the strongest effect on macrobenthic abundance (Figs. 7 and 8; Tables 2 - 4), biomass (Figs. 7 and 8; Tables 1 - 4), diversity, and community structure (Fig. 9). Thus, natural temporal variation of salinity, temperature, and dissolved oxygen (Fig. 4), which may be associated with seasonality and flooding, played a greater role in determining community structure than flow or disturbance frequency treatments (Tables 2 - 4). There were three community states through time (Fig. 9). The first group, representing 23 April - 4 June 1997, was dominant when average salinity varied between 11 and 18 ‰, average dissolved oxygen declined from 11.22 mg l^{-1} to 3.89 mg l^{-1}, and temperature varied between 24.5 and 26.5 °C (Fig. 4). The low abundance and biomass estimates of 4 June, compared with previous dates (Figs. 7 and 8) is probably related to overnight hypoxia that likely occurred under low-flow conditions observed that day (Fig.4). After 4 June, the community state shifted because of increased abundances of chironomid larvae, Streblospio benedicti and Laeoneris culveri (Fig. 9b). Streblospio benedicti appears to have had a recruitment event between 4 June and 20 June when total average S. benedicti abundance increased from 11,000 to 94,000 m^{-2}. The recruitment event appeared to be greatest under increased flow conditions. This indicates a possible flow treatment and sampling date interaction whereby flow velocity may have affected active substrate selection, passive organisms deposition (Butman 1986a; 1989), or spionid organismal growth (Hentschel 1999a; 1999b). The third community state is related to the flood event that began 22 June 1997. Salinity dropped to 0 ‰ by 02 July and had increased to only 2 ‰ by 01 August. The persistence of low salinity over a period of more than one month probably led to declines in total abundance and biomass following the flood (Figs. 7 and 8). For example, when salinity was reduced from 19.9 ‰ to 3.19 ‰, S. benedict survived up to 11.5 h, whereas P. cornuta expired within 7 hours, and Leptocheirus plumulosus remained active and normal (Sanders et al. 1965). Differential salinity tolerance explains persistence and species changes, and is one component of temporality.

The strong response of macroinfauna to temporally variable, ambient, environmental conditions rather than to experimental manipulations indicates experimental effects were less important than temporal community response to natural environmental fluctuations. This is almost certainly true for flow treatment manipulations for which no significant effects on macrobenthos were found. Flow effects probably exist, but are barely detectable due to environmental variation. Though significant disturbance frequency effects were found, community structure differences were masked by community composition similarities in all treatments within collection dates.

Temporality is the controlling feature of the Rincon Bayou benthic community, explaining most of the variance in abundance and biomass (Table 2). Rincon Bayou is an extreme environment, ranging from hypersalinity in droughts and freshwater in floods. From 1994 - 1997, salinity at station C ranged between 0 and 160 ‰. The present study unintentionally captured a flood event that led to a sudden drop of salinity from 18 to 0 ‰, which persisted for more than a month (Fig. 4). Such a salinity change exceeds the tolerances of most euryhaline species (Sanders et al. 1965), and led to an increased populations of chironomid larvae and decreased populations of Streblospio benedicti and Laeoneris culveri (Fig. 9). In Rincon Bayou, community change occurring in response to physical disturbance appears to be limited by natural environmental variation through time, which we call temporality. Temporality is simply the short-term analogy to longer-term seasonality.

SUMMARY

Succession is controlled more by the natural tempo of environmental variation (e.g., availability of recruits, and coincidence of rainfall) than by small-scale events (e.g., patch defaunation and water flow). Flow appears to be a less important determinant of community structure for Rincon Bayou station C compared to natural variation of background environmental characteristics (e.g., salinity), but appears to influence abundance, biomass, and diversity. Rincon Bayou is generally a low-inflow, microtidal, shallow water habitat subject to broad salinity fluctuations concomitant with periodic drought and flood events. During the period of the present study, sample collection date was the most important factor in determining community structure indicating experimental effects were overwhelmed by natural environmental variation arising from recruitment and flood events. Within the context of natural temporal variation, significant differences were found among disturbance frequency treatments. Community abundance, biomass, diversity, and evenness decreased with increasing disturbance frequency indicating the importance of post-disturbance community persistence in determining community structure and succession state, and possible tray effects. Disturbance in the form of flow alteration or defaunated sediment increased community abundance and biomass, indicating disturbance may increase production of early succession macrobenthic communities in estuaries.

Acknowledgments

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Table 1: Summary of mean community characteristics over all sampling dates for disturbance frequency and flow treatments.

Treatment Level	Abundance $\log(n\ m^{-2}+1)$	Biomass $\log(g\ m^{-2}+1)$	Diversity (N1)	Evenness (E1)
Frequency				
Biweekly	9.33	0.64	1.82	0.59
Monthly	10.37	1.00	1.59	0.37
Bimonthly	10.98	1.27	1.62	0.28
Undisturbed	9.87	0.66	1.31	0.44
Flow				
Increased	10.12	0.85	1.54	0.39
Decreased	10.16	0.90	1.51	0.37
Control	9.78	0.66	1.46	0.38

Table 2: Analysis of three replications of the flow-disturbance frequency experiment. Analyses for total experimental data including all dates (3-way incomplete design), when experiments were initiated on two dates (3-way factorial design), and when experiments ended on two dates (3-way factorial design) (Fig. 3). Results for a) abundance and b) biomass. Table finds degrees of freedom (df), probability level (p), and variance component percentage (%) for each main effect. Freq = disturbance frequency, * = interaction, and - = does not exit.

Treatment	All Dates Incomplete design			Initiating Dates 3-way factorial design			Ending Dates 3-way factorial design		
	df	p	%	df	p	%	df	p	%
a) Abundance									
Flow	2	0.9548	0.5	2	0.1061	0	2	0.0003	0.2
Freq	3	0.0001	4.3	3	0.0001	0	3	0.0001	5.0
Flow*Freq	6	0.0001	2.2	6	0.0001	1.4	6	0.0005	1.4
Date	7	0.0001	76.5	1	0.0001	0	1	0.0001	86.9
Flow*Date	14	0.0026	2.0	2	0.4542	0	2	0.0033	1.1
Freq*Date	-	-	-	3	0.0001	91.9	3	0.1339	0.2
Flow*Freq*Date	-	-	-	6	0.0171	1.5	6	0.3368	0.1
Plot	1	0.2443	0	1	0.5136	0	1	0.9747	0
Error	271	-	14.5	118	-	5.3	118	-	5.2
b) Biomass									
Flow	2	0.0672	1.2	2	0.0172	1.9	2	0.0872	0
Freq	3	0.0001	12.7	3	0.0001	0	3	0.0001	8.0
Flow*Freq	6	0.0001	4.6	6	0.0001	3.2	6	0.0149	1.8
Date	7	0.0001	35.4	1	0.1490	0	1	0.0001	46.8
Flow*Date	14	0.0132	3.4	2	0.9475	0	2	0.0006	6.6
Freq*Date	-	-	-	3	0.0001	57.7	3	0.0002	7.5
Flow*Freq*Date	-	-	-	6	0.0042	10.2	6	0.1015	3.5
Plot	1	0.1170	0.1	1	0.0275	1.4	1	0.8423	0
Error	271	-	42.7	118	-	25.6	118	-	25.8

Table 3: Simple main effects for the flow*frequency interaction over all sampling dates. Two-way, randomized block ANOVA calculated for each disturbance level for a) abundance and b) biomass. Abbreviations as in Table 2.

Treatment	Disturbance Frequency Level							
	Biweekly		Monthly		Bimonthly		Undisturbed	
	df	p	df	p	df	p	df	p
a) Abundance								
Flow	2	0.1373	2	0.2861	2	0.0511	2	0.0001
Date	2	0.0001	3	0.0001	1	0.0001	7	0.0001
Flow*Date	4	0.4825	6	0.0538	2	0.1522	14	0.0001
Plot	1	0.4240	1	0.9244	1	0.4019	1	0.0195
Error	44		59		28		119	
b) Biomass								
Flow	2	0.0238	2	0.0090	2	0.3416	2	0.0001
Date	2	0.1138	2	0.0001	2	0.0001	2	0.0001
Flow*Date	4	0.3841	4	0.5400	4	0.0168	4	0.0001
Plot	1	0.7145	1	0.3949	1	0.1490	1	0.0645
Error	44		44		44		44	

Table 4: Simple main effects for the flow*frequency interaction over all sampling dates. Two-way, randomized block ANOVA calculated for each flow level for a) abundance and b) biomass. Abbreviations as in Table 2.

Treatment		Flow Treatment Levels		
		Control	Increased	Decreased
	df	p	p	p
a) Abundance				
Frequency	3	0.0001	0.0001	0.0001
Date	4	0.0001	0.0001	0.0001
Freq*Date	6	0.0001	0.0001	0.0001
Plot	1	0.4117	0.5310	0.5807
Error	69			
b) Biomass				
Frequency	3	0.0001	0.0001	0.0033
Date	4	0.0001	0.0001	0.0006
Freq*Date	6	0.0505	0.0001	0.1453
Plot	1	0.0593	0.9175	0.9739
Error	69			

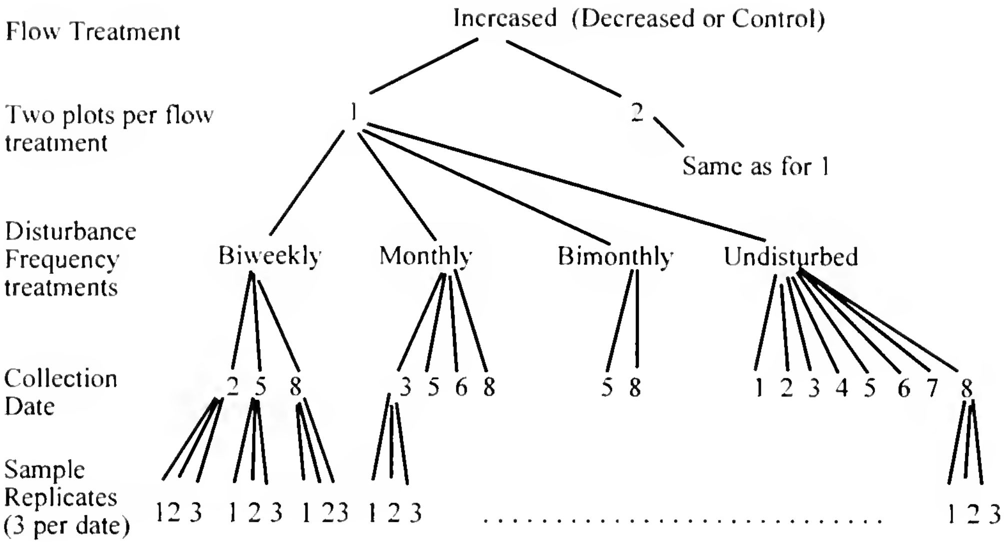

Figure 1: Experimental design of the study. The experiment was a three-way, randomized block, incomplete factorial design to evaluate effects of flow regime and disturbance frequency on macrobenthos over time. Flow treatment levels were: increased by weirs and decreased by nets relative to controls with no structure. Disturbance frequency treatment levels were: biweekly = every 2 weeks, monthly = every 4 weeks, bimonthly = every 8 weeks, and undisturbed. Collection dates were: 1 = 23 April 1997, 2 = 07 May 1997, 3 = 22 May 1997, 4 = 04 June 1997, 5 = 20 June 1997, 6 = 02 July 1997, 7 = 17 July 1997, and 8 = 01 August 1997.

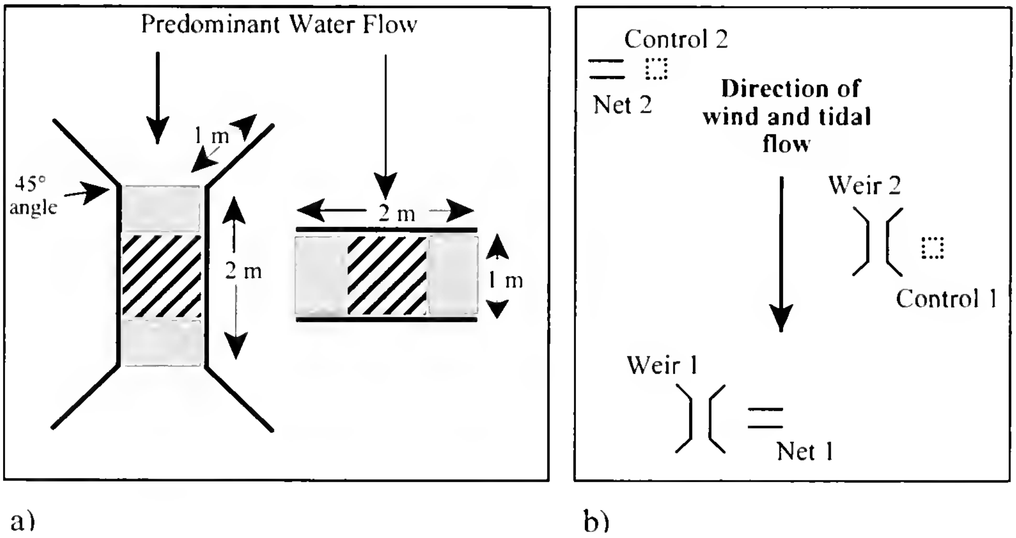

Figure 2: Flow alteration treatments for a) weir and net structure designs and b) field emplacement. Trays of defaunated sediment were randomly placed in hatched center regions. Undisturbed core samples were obtained in the shaded regions. Control plots were defined by corner posts (dotted lines).

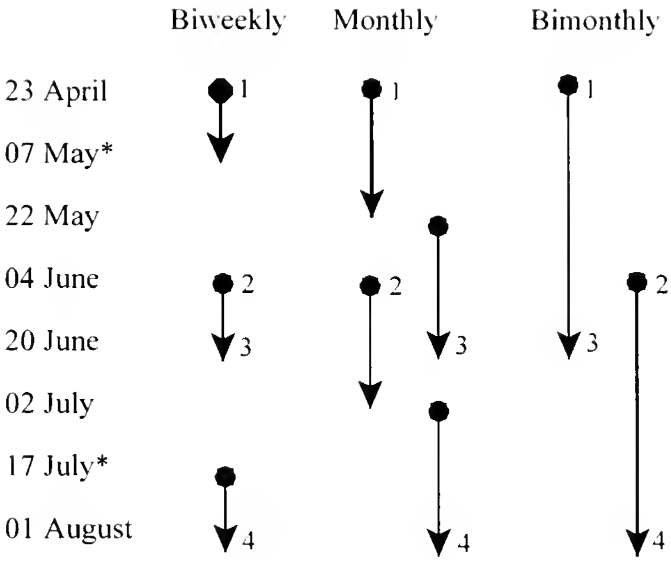

Figure 3: Time line for sample collection dates in 1997. Tray placement indicated by dots (●) and sample collection indicated by arrow heads (➤). Date flow velocity measurements were taken indicated by asterisk (*). Beginning of the flood event (22 June) indicated by dashed (-) line. Disturbance frequency treatments were replicated twice, two different ways: by same initial dates (dots 1 and 2) and same ending dates (dots 3 and 4). Undisturbed samples were collected on every date.

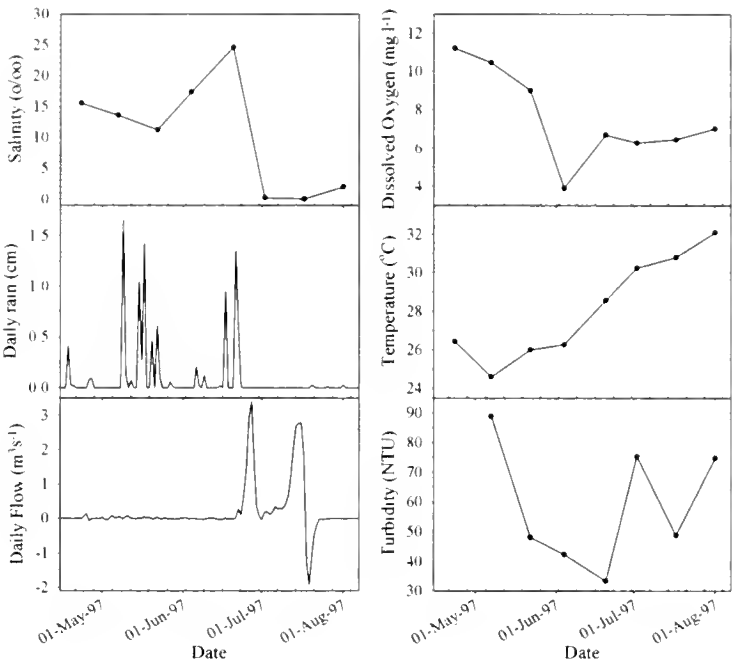

Figure 4: Hydrographic conditions over sampling period. Average salinity, dissolved oxygen, water temperature, and turbidity measured each sampling date. Standard error bars are smaller than symbols. Minor ticks placed every Monday. Daily rain fall and inflow from gage (USGS 1997).

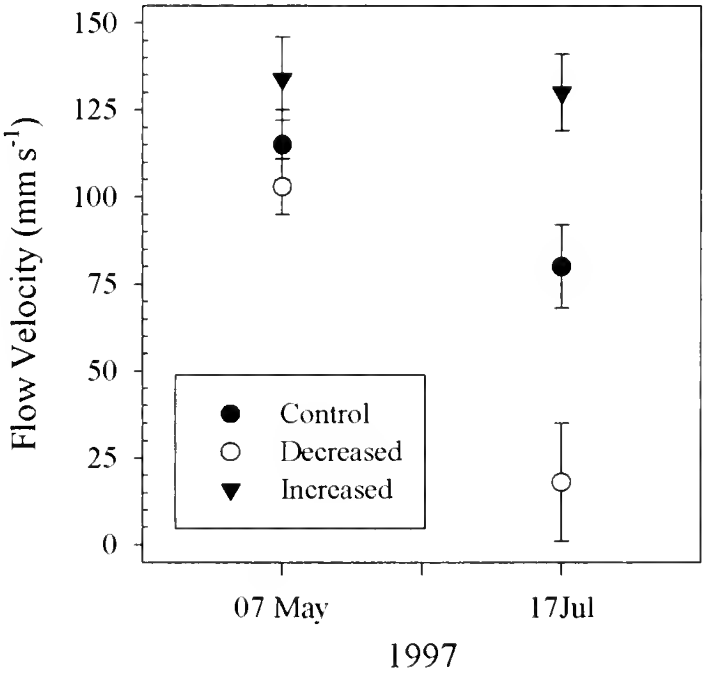

Figure 5: Average flow velocity measurements from flow treatments on two dates (7 May and 17 July 1997). Tukey minimum significant difference is 26.45 for flow regimes, and 18.29 for dates.

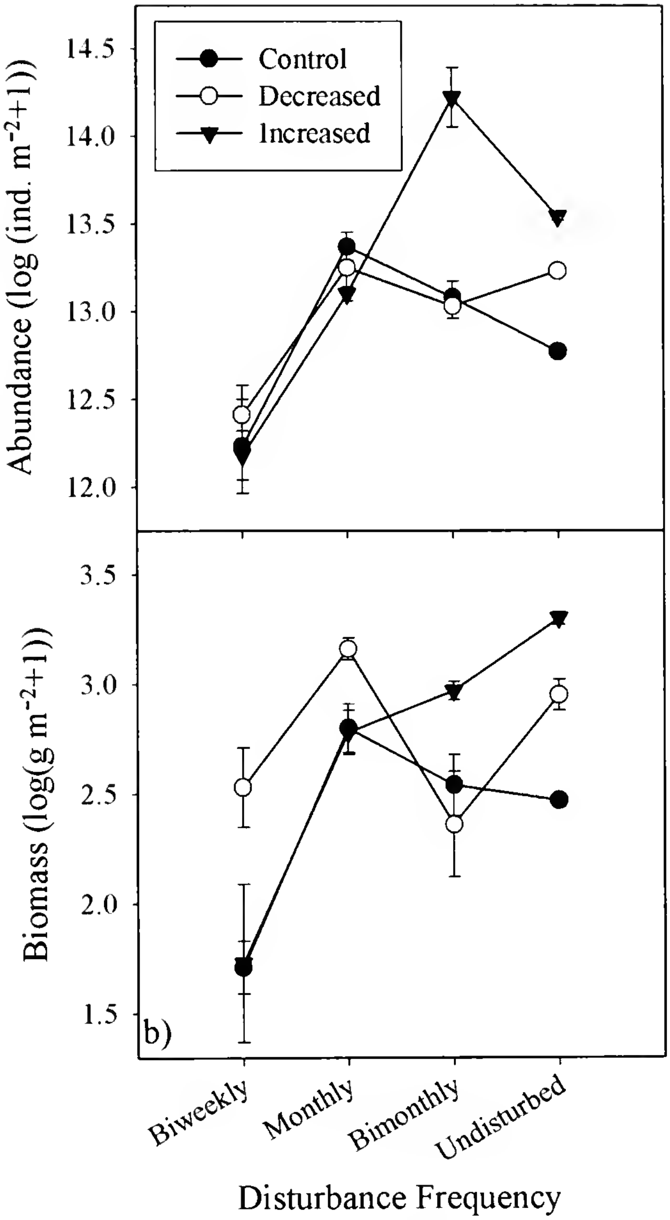

Figure 6: Disturbance frequency*flow interaction for average a) abundance and b) biomass.

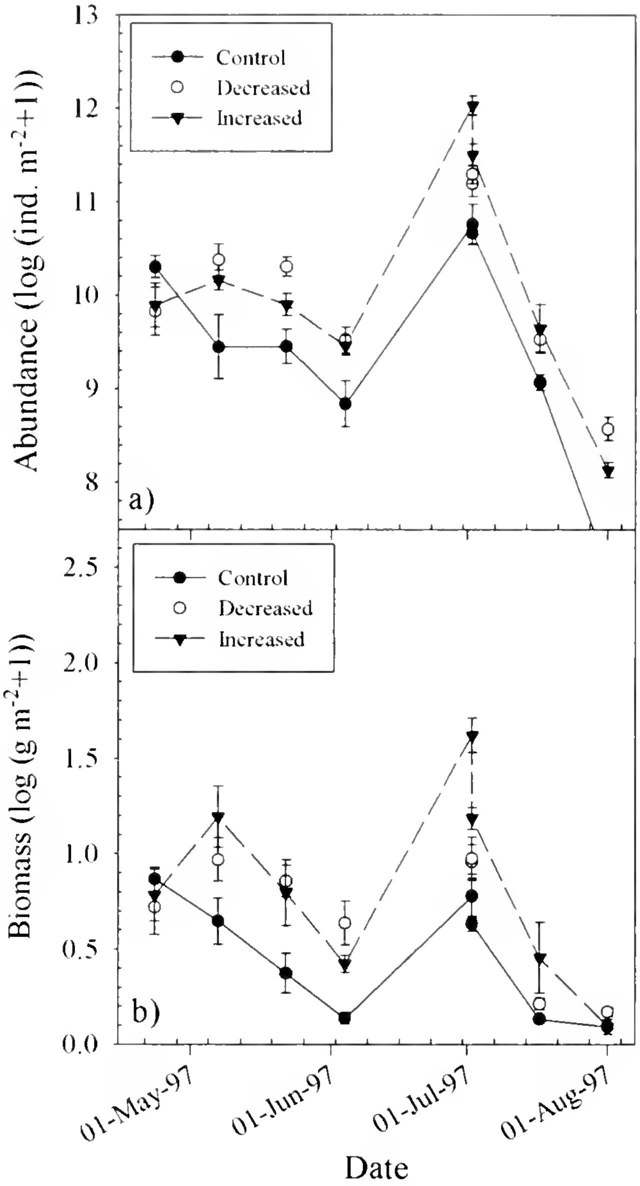

Figure 7: Flow*date interaction for average a) abundance and b) biomass (b) in undisturbed sediment. Minor ticks placed every Monday. Tukey minimum significant difference is 0.20 for abundance and 0.12 for biomass.

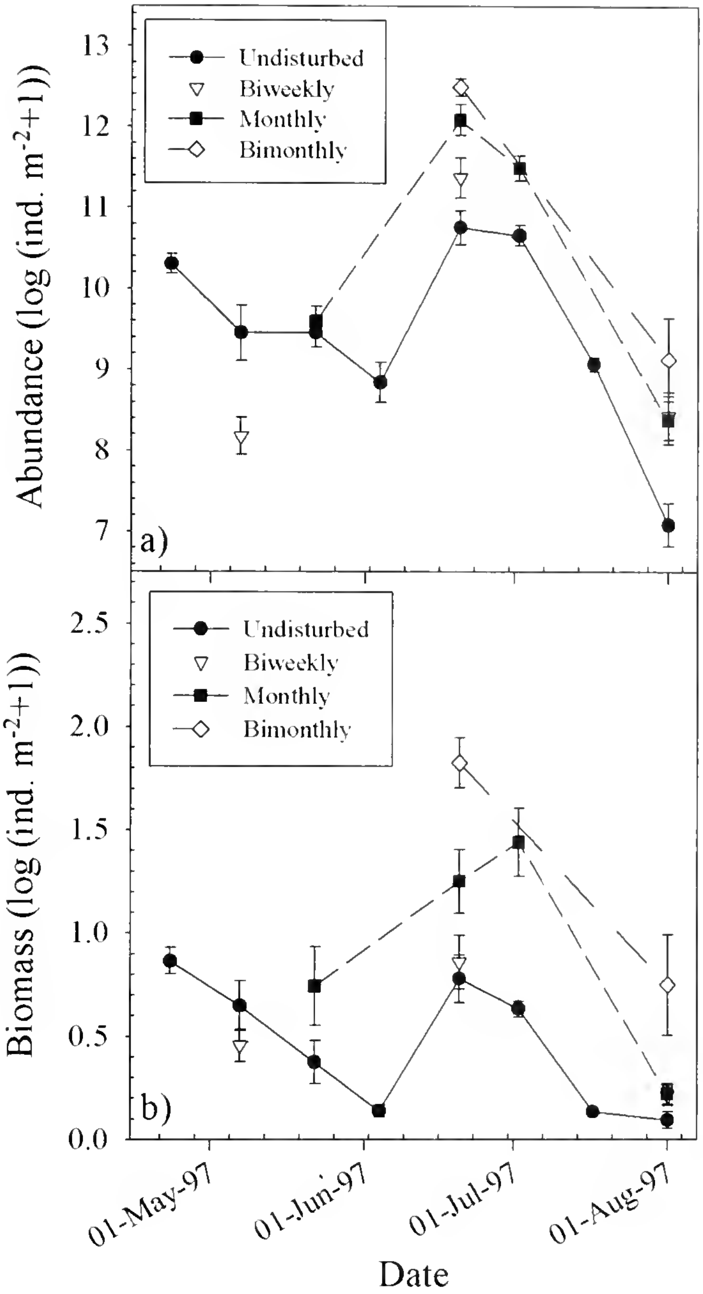

Figure 8: Disturbance frequency*date interaction for average a) abundance and b) biomass from control flow plots. Minor ticks placed every Monday. Tukey minimum significant difference is 0.59 for abundance and 0.25 for biomass.

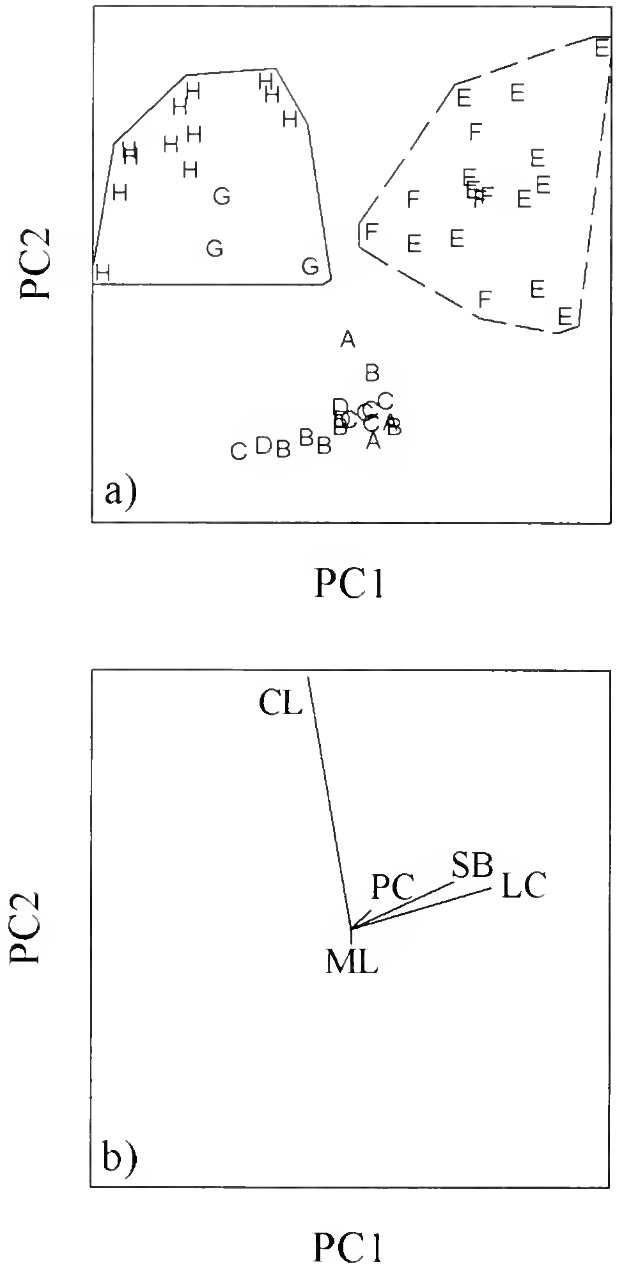

Figure 9: Principal component (PC) analysis for all species data. A) Plot of PC scores for dates: A = 23 April 1997, B = 07 May 1997, C = 22 May 1997, D = 04 June 1997, E = 20 June 1997, F = 02 July 1997, G = 17 July 1997, and H = 01 August 1997. B) Plot of standardized PC loadings for species: CL = chironomid larvae, LC = Laeoneris culveri, ML = Mulinia lateralis, PC = Polydora cornuta, and SB = Streblospio benedicti.

APPENDIX G

Field Notes and Observations from Benthic Sampling Trips: October 1994 - December 1999

In early October 1994 Paul Montagna, Rick Kalke, Terry Whitledge, Dean Stockwell and Ken Dunton met with Mike Irlbeck at Rincon Bayou to discuss station locations. The road and the pasture to Stations A & B were very wet and the water level was near the top of the culverts and flowing from A to B. The secondary diversion channel was not finished but a ditch cut through the road in its place restricting travel.

SAMPLING DATES

28 Oct. 94. First benthic sampling trip. Salinity was low from previous inflow event, *Ruppia* was noted in the reference sites A & B. High D. O. at A & B associated with the *Ruppia*. Roads were muddy.

Note: Reference sites A & B don't appear to be affected by daily tidal movement as are sites. C, D, E and F in Rincon Bayou.

11 Jan 95. Benthic samples. Low tides at stations in Rincon Bayou. Salinity normal, no signs of increase with low water.

12 Apr. 95. Benthic samples. Salinity normal. *Ruppia* very short and sparse at A & B. We used push-net at Station C for isotope samples. Lot of mysids, grass shrimp, and some brown shrimp. Water level up with spring high tides.

12 July 95. Benthic samples. Summer low tides, hot dry conditions with high evaporation. Road and pond at Stations A & B covered with white pelicans, Ibis, Stilts and mottled ducks. Lot of terns skimming surface. Low oxygen levels. Some dead Cyprinodon variegatas and a few blue crabs along shoreline. Some live crabs along shore at air/water interface, fish appear to be gulping for air, and numerous corixids (water boatmen) at A & B. Salinities high at all stations. Water levels down in Rincon Bayou at Stations C, D, E and F. Dead crab and Cyprinodon at Stations C & D. Station E, mud wet but no standing water. Approximately 40 yards out water 0.01 m deep , dug hole for hydros, cores from wet mud. Saw a live *Laeonereis culveri* on surface of mud. 80.5‰ pore water and same on surface water. Salt crystals on surface of adjacent algae flat. Station F, sure is hot, water low 15-20 ft. from shoreline. Station G (Railroad Trestle) salinity was 43.5‰.

3 Oct 95. Benthic samples. Water level was high due to Hurricane Opal in Gulf of Mexico. Tidal flushing lowered salinities. Stations A & B water level up, oxygen OK, salinity down a little. Stations C, D, E & F flushed from high tides. Isotope sample from Station G.

31 Oct. 95. Exploratory trip, Dean Stockwell and Rick Kalke. Nueces River Diversion Channel just completed. On 29 Oct. 95 Corpus Christi received 3rd highest record rainfall, 10+ inches over-night. We were able to motor with the jet boat from Nueces River to C-5 the culvert between the river and Station C. Mike Irlbeck had hiked in from the road and we gave him a ride out. Salinity at the culvert was 0.57‰. We drove to Stations A & B by vehicle. High water due to run-off and tides. Surface water was flowing from B to A because of the wind and the salinity was 10.16‰. Large mats of blue-green algae were on the surface and along the shore. Took slides. Roads too wet to go to other stations.

13 Dec. 95. Isotope samples from the mouth of Rincon Bayou (L=50, C, F, H = 68).

8 Jan, 96. Benthic samples. Winter low tides evident at Stations E & F. Salinities in Rincon Bayou in the 30's to 39.0‰ at station F.

21 Feb. 96. Isotope samples. Water very low. Stations A & B. .1 m deep, salinity 33.3‰. Rincon Bayou Station C ~ .05 m deep 81‰, D & E no water. Station F only puddles, refractometer 122‰. Highest salinities, beginning of 1996 drought?

19 Mar. 96. Isotope samples. No water at Stations A, B, C, D & E. ~ .05 m water at Sta. F, 68.6‰.

9 Apr. 96. Benthic and Isotope samples. At Station G- Railroad Trestle. Water still low, sampled lake east of railroad tracks ~4" deep, very turbid, collected some post larval brown shrimp for isotopes. Station A- dry, only a puddle in center ~1"deep, algae layer on top of mud. Station B, sample area dry except for water between cracks in mud (water from rain fall from previous week) 50‰. Station C, dry, only damp mud, only water was in cracks and in wash-out area around posts, 98‰. Station D, no standing water, a little water in cracks and animal tracks, 100‰. Station E, 1/4 inch water from where cores were taken, foot tracks from Jan. 98 still there, 82‰. Station E, removed mud from same depression as Jan. 96 for Hydrolab, very low water 2-3" deep, 59.3‰. Station H=68 Nueces River Bridge, 6.8‰.

13 May 96. Isotope samples. Water level back up again but salinity levels still high. Station C, water very clear, bottom covered with blue green algae mat (very green) - sampled with push-net - no sign of any shrimp only a few *Cyprinodon,* 59.3‰. Sta. F, 51.8‰, water very turbid, lot of small swirls from fish and shrimp, some port-larval brown shrimp collected. Station G, (Trestle) 51.7%, water turbid, brown shrimp numerous, saw redfish feeding so shallow its back was out of the water. Station H = 68-river 8.9‰, collected brown shrimp and blue crabs with push-net.

1 June 96. Isotope samples. Station H=68, 9.9‰ collected brown shrimp, spot and Rangia. Station C, 70.4‰, water from high tide was flowing through upper culverts C-5 & C-4 through diversion channel to the Nueces River.

12 July 96. Benthic samples. Stations A & B, no water, took cores on dry land, very little moisture in sediment. Stations C & D. Small amount of water, salinity C=159.2‰, D=120‰. Stations E & F water shallow, 85.86‰, no shrimp, picture of algal mats on slides. Station G=Trestle, 84‰ no shrimp. Station H=68 River, 2.1‰, push-net for shrimp, caught 1 brown shrimp, saw a couple of large shrimp avoiding net.

22 Oct. 96. Benthic samples. Stations A & B - water back ~.1 m, 40‰. Stations C, D, E and F - water back, evidence of lower salinity input from the River Diversion Channel 25.1‰ at C→ 46.4‰ at F.

6 Jan. 97. Benthic samples. Stations A & B, bottom covered with dense bed of *Ruppia.* 52.4‰, Salinity gradient from C to F = 25.0‰ to 56.4‰. Stations E and F sediment surface with layer of algal mat. Station H = 68 River 0‰. Low flow coming over dam.

23 Apr. 97. Benthic samples. Stations A & B, low oxygen, water a thick green color, *Ruppia* seems to be declining, not as thick as Jan. 97. Stations C, D, E, and F, salinity down to 15-16‰. Station D, lot of medium to large blue crabs and some reds and drum. Station E, water shallow 2-3 in., slight outgoing current 1045, algal mat over most of bottom, took benthic samples from bare bottom.

2 July 97. Benthic samples. Stations A & B, salinity down to 4.8‰, water up, *Ruppia* covering most of bottom, very healthy, to surface of water. Station C, water ~ 1 ft deep at shoreline, evidence of being higher, Christine's experimental plot completely under water. Salinity from C to F was 0.2 to 4.4‰. Station H=68 at river 0‰. Station 62 Whitledge station in flats north of secondary diversion channel, puddle at culvert was 0‰, water in flat on way to 62 was 4‰ and at 62 stake 2‰ Station D, washout in culvert on road.

28 Oct. 97. Benthic samples. Light rain, low salinity at all stations. Stations A & B, 4‰ C to F, 0.3 to 4.1‰. Water level down from the flood event in July 97.

16 Jan. 98. Benthic samples. Stations A & B hydrographic conditions good. The area between Stations C & D seems to pond during low tides. In the summer long term ponding will sometimes evaporate and dry up. Station C was 0.1 m deep and Station D was 0.04 m deep. Water level was low, only small ditch of water form culvert between upper and lower Rincon Bayou. Hole in road covered with pile of fill. Station E, no water, only damp mud with numerous worm casts. Station F, dry, only wet mud with occasional puddles, 35‰.

8 April 98. Benthic samples. Station A, short *Ruppia*. Station B, surface of sediment with ~ 4cm loose flock (mud), 16‰. Station D, water level up, C-5- water just to culverts with small channel or trickle of water moving. Station D, large number of black drum feeding in area around D, water flowing out toward bay. Salinity from C to F was 12.9 to 30.2‰.

9 July 98. Benthic samples. Salinity, high 104‰. Station A & B, very low water, oxygen low, lot of wading birds and sea-gulls apparently feeding on *Cyprinodon variegatas*, etc. Stations C-F, water level normal, not low. Station D, lot of larger fish, reds and drums. Salinity high C to D, 60‰.

5. Aug. 98. Primary production. Rick Kalke with Kevin Neely. Stations A & B, dry, no water. Station C, salt deposits on surface, only sheen of water on mud surface. Station D, basically dry, only narrow strip of water. Stations 67 & 62, dry, Station F=61, 94.93‰, Station 83, 50.2‰, Station 60, 70.24‰.

Starting in September 1998, I (Rick Kalke) began sampling with Lynn Tinnin and Terry Whitledge's primary production processes.

29 Sept. 98. Primary production. Station A & B, water level up, 28.2 - 28.4‰. Stations C & D, salinities indicate inflow event, 2.3 to 5.6‰, current going out of Rincon through culvert toward bay to Stations E & F, 22.1 and 20.8‰. Station H=68; river 0‰.

28 Oct. 98. Benthic samples and collected water for Lynn Tinnin, not able to get water for primary production samples. Major flood occurred on 17 Oct. 98. Water level had been high enough to wash out culverts and road at the secondary diversion channel and washed a large portion of road out at Station D. We had to hike in from the secondary wash-out to collect benthic and water samples from Stations D, E and F. Stations A & B, water up, running from A to B, 2 & 1.5‰. Stations C-F , major freshwater flushing 0 to 0.8‰.

Due to road wash-outs and/or wet conditions we were unable to sample some of the lower Rincon Bayou Stations, i.e. Station D, E, and F until 24 Feb. 99.

18 Nov. 98. Primary Production. Stations A & B, water flowing from A to B, salinity 3.8 to 3.7‰. Station C, water high, up to grass line along shore, about same in Oct. 98. Road real wet in spots, maybe a little drier than Oct. Station H=68, river up over sides of boat ramp to shoreline, 0‰.

17 Dec. 98. Primary Production. Stations A & B, current from A to B, 14.6 and 14.7‰. Station C, 11.7‰, roads still washed out. Station H=68, river level back down to bottom of boat ramp.

12 Jan. 99. Benthic samples. Stations A & B, 10.1 to 13.8‰, lot of water boatmen (corixidae) Stations C & D, water in upper Rincon ponding 19.3‰ & 19.9‰. Station E & F, had to hike in from Station D, low water in their area, salinity 25 & 23.8‰.

13 Jan. 99. Primary production. Stations A & B, salinity 10.8‰ & 12.3‰. Station C, water golden brown in color, 19.9‰. Station H=68, river 0‰.

24 Feb. 99. Primary production. Stations A & B, water turbid, 15‰. Station C, salinity, 33.97, higher than Stations D, E, and F. Water at Station D turbid brown color, flowing into Rincon, 2" deep in culvert. Station E, algal flat dry, *Salicornia* patches show fresh growth. Station F water to edge of grass and clear. Station H=68 salinity 1.45, no flow over dam. First Nueces River Diversion Channel flow gage information.

18 Mar. 99. Primary production. Stations A & B, water turbid 20‰. Stations C & D, salinity down to 19.33 & 28.85. Station E, high water line was up to power poles but currently at shore line. Algal flat inactive. Station F, water turbid, up to grass line. Station H=68, river 1.25‰, no water over dam.

14 Apr. 99. Benthic samples. Stations A & B water up, .35m depth, salinity 13.78‰. Station C, salinity 4.84‰ from diversion channel. Station D, water very turbid, 15.78‰, some large fish swirls probably reds, drum and mullet. Stations E & F water .27 & .35 m, large school of redfish at Station F, tails out of water (see slide). Station G, trestle, 21.86‰ slight out-going tide.

15 Apr 99. Primary production. Conditions similar to 14 Apr. 99 except wind much stronger, NW-20 MPH. Water flowing over dam at Nueces River. Station H=68, 0.44‰.

24 May 99. Primary production. Stations A & B, dense beds of *Ruppia*, salinity, 16-18‰. Stations C & D, water muddy, lot of fish activity at both sites, redfish at Station D, caught some brown shrimp with push-net at Station C. Station E & F, lot of small fish, shrimp and redfish activity. Station H=68, river 2.02‰, water seeping over dam, no flow.

9 June 99. Primary production. Stations A & B, dense beds of *Ruppia* up to surface, low oxygen 1.95 to 1.49 ppm (mg/l), salinity 24-25‰. Stations C & D, 20 to 35‰. Station E, 39‰, at least 1 redfish and lot of bait-fish. A little water in algal flat was 110‰, dead Cyprinodon and brown shrimp 8 to 9.5 cm long in algal flat area. Probably trapped in evaporating pools left by low tides. Station F, lot of mullet and small bait swirls and a few redfish.

7 July. 99. Benthic samples. Stations A & B, salinity down to 8.3‰, oxygen low 1.59 to 1.7 ppm. (mg/l), *Ruppia* present but not as thick as it was in May and June. Freshwater inflow event, salinity down at Stations C-F, to 1.3 to 6.3‰. Rattlesnake at road right before Station D. Strong flow of freshwater from Station D to E & F. Station E, algal flat 10‰, algal mat green near shallow edges, gray and floating in deeper areas, no mats visible at Station E.

21 July 99. Primary productions. Stations A & B, oxygen low 1.6 ppm (mg/l) depth .21 to .27 m. Stations C to F, salinity still low 4.2 to 13.6‰. Station C oxygen 3.2 ppm. Station H=68, river, 0.6‰.

19 Aug, 99. Primary production. Stations A & B, water drying up, dead blue crabs in standing water, few live crabs along edges of bank out of water to get air, lot of shore birds in what little water left. No water where we normally sample, water taken by culvert for A & B. Stations C & D, water low, salinity 26 to 45‰, lot of wading birds, ~6 dead black drum carcasses on shore. Station E, no water ("I told you so!") says Ms, Tinnin. Station F, .05 m, 39‰. Station H=68 river, 0.48‰, barely flowing over dam.

16 Sept. 99. Primary production. Stations A & B, water back as result of rain and tides from hurricane Bret. *Ruppia* starting to grow along shorelines. Station C to F salinity 0.93 to 8.51‰. Station D current coming in from the bay, blue-green algal floating on surface, lot of fish activity, water turbid. Stations E and F, lot of fish and mullet, reds, shrimp. Algal flat at Station E, 2‰. Blue green algal floating at Stations E & F. Station H=68, river 0.43‰, flow over dam.

28 Oct.99. Benthic and primary production samples. Stations A & B, *Ruppia* growing along shoreline. Station C, lot of white shrimp, white pelicans and avocets. Station D, water real low, ponding between C & D, white shrimp jumping by culvert. Stations E & F, 16 & 15‰, Station H=68, river 1.22‰, no flow over dam.

17 Nov. 99. Primary production. Stations A & B water soupy green, 15 to 14‰, *Ruppia* along shoreline. Stations C & D, water clear 11 to 19‰, numerous bird tracks, no shrimp. Station E, water clear 25‰, Station F, SE wind began blowing and quickly stirred up sediment, now very turbid. Station H=68, river 0.85‰, no flow over dam.

8 Dec. 99. Primary production. YSI instrument not working. Only refractometer for salinity. Station A & B, 15 to 14‰. Station C, D, E and F, 10, 12 and 25‰. Station H=68 0‰, scattered showers.

Nueces River Diversion Channel Water Exchange

At the February, 1999 Rincon Bayou Demonstration Project team meeting there was some concern in the accuracy of the exchange rates of water moving through the diversion channel into and out of upper Rincon Bayou. During at least six sampling trips to Rincon Bayou we checked the hydrographic conditions, the flow patterns through the diversion channel, at the Rincon Bayou Station, 08211503, at the culverts above station C, station D and the culvert at this site, stations E and F and when available stations 50 and 51 at the mouth of Rincon Bayou in Nueces Bay. Observations at Station 08211503 verified with the gage data for this station indicate that the water exchange reported from this gage is accurate. The following is an example of the staff readings and the gage read-out for 6 observations.

DATE	TIME	GAGE	STAFF
24 Feb. 99	1230	1.14	1.1
18 Mar. 99	1200	2.15	2.04
14 Apr. 99	1410	No Data	1.78
15 Apr. 99	0800	1.57	1.54
24 May 99	1210	1.23	1.2
9 June 99	1205	1.69	1.67

The daily flow regime through the Nueces River Diversion Channel into Rincon Bayou is now established. The connection between the channel and upper Rincon Bayou where the ranch road crosses has resulted to a narrow ditch where water exchanged takes place. The ditch has vegetation growing up in both banks and seems to be maintained by almost daily tidal exchange into and back out of upper Rincon Bayou. Although no diel observations were made, the wet banks near low areas suggest tidal inundations moves water onto the flats occasionally. There is a split of tidal flow in the upper Rincon with tidal movement coming and going from both Nueces Bay and the Nueces River, resulting in higher salinity estuarine water from the bay meeting with lower salinity Nueces River water from the diversion channel in the upper Rincon Bayou. This exchange has helped alleviate the stagnated high salinity conditions observed when upper Rincon Bayou was a dead-end. High salinity conditions can still be expected during droughts and extreme low tides especially during the summer. The extent of water exchange in Rincon Bayou depends on the magnitude of the tidal of freshwater inflow event. A major event results in complete flushing and mixing of the system all the way to the bay while normal daily tidal movement may only move enough water to maintain some exchange with upper Rincon Bayou which is important.

Rincon Bayou Seasonal Observations

Hydrographic and environmental conditions at Rincon Bayou are dependent on annual tidal cycles and seasonal climatic conditions. Local weather events can dramatically effect these conditions. i.e. droughts, floods and tropical disturbances.

The typical annual cycle based on annual quarters:

January usually results in low winter tides and cool to cold temperatures. These conditions don't typically result in high evaporation and high salinities.

April conditions are associated with spring high tides which disperse brown shrimp post larvae and crab larvae throughout the delta and nursery areas. Many drum and redfish migrate into the area to feed on the growing shrimp population.

July often has periods of very low tides, low rainfall, associated with high temperatures and high evaporation. Rincon Bayou stations often dry up or the water becomes hypersaline.

October is the transition for summer to fall. The tides may be high especially with tropical storm activity and flooding may occur modifying typical high salinity conditions from summer. At the control stations A & B which are often dry in July and August the fall rainfall results in the germination and growth of Ruppia beds which are an important food source for waterfowl.

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MARCH 3, 1849