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History of Water and Habitat Improvement in the Nueces Estuary, Texas, USA

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Abstract: Reservoir impoundments in the Nueces watershed (Texas, USA) have reduced Nueces River flows to the coast by more than 50% since the 1980s. Reductions in freshwater inflows prompted state and local managers, along with scientists, to embark on a 3-decade process of ecosystem-based restoration and habitat improvement in the Nueces Estuary. Current management efforts in the estuary have increased freshwater flow to the Rincon Bayou and habitat has been protected from land acquisition in the Nueces Delta. Restoring freshwater flow and acquiring land in the Nueces Delta was not easily accomplished but has been successful through the efforts of federal, state, local agencies, and nongovernmental organizations. This paper also describes mitigation activities that have taken place in the Nueces Estuary.

Keywords: Coastal conservation, habitat sustainability, freshwater inflow, ecosystem-based management

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INTRODUCTION

According to archaeological and geological records dating back to 6000 B.C., drought and water shortages in the lower Nueces River affected early inhabitants and explorers of the lower Texas Gulf Coast. Cunningham (1999) states that human appearance and disappearance coincided with drought periods for the Aransas group (2000 B.C.–1300 A.D.) and the Rockport group, also known as the Karankawas (1400 A.D.–1848). Water shortages were likely one of several factors that affected initial population growth of early settlers. Corpus Christi, Texas began as trading post in 1838 and from 1845–1846 the area was occupied by US troops under General Zachary Taylor in preparation for war with Mexico before becoming officially incorporated in 1852 (Table 1). To meet human demands for water, reservoirs were built on

Table 1. Chronology of population of Corpus Christi, Texas, and impoundments constructed on the Nueces River. Data compiled from the US Census and Cunningham (1519–2010).

Year	Population	Water Supply Availability	Remarks
1519	Undocumented census of Native Americans	Undocumented water supply.	Spanish explorer Alonzo Alvarez de Pineda discovered what is now Corpus Christi, Texas.
1845	6000	Artesian well, 116 m deep, determined non-potable because of high sulfide.	Of the population, 4000 were temporary Army soldiers.
1850	689	1852: Water shortage. \$1.50/ barrel of river water. 1853: Artesian well drilling begins.	City of Corpus Christi incorporated. Supply of water for emergencies.
1860	175	Artesian	
1870	2140	Artesian	
1880	3257	Artesian	
1890	4387	1893: City builds water system from Nueces River. 1898:Calallen diversion dam constructed.	Saltwater intrusion from Nueces Bay in public water supply. Decided to build Calallen saltwater diversion dam. Height of Calallen dam was 0.46 m above high tide and reservoir was 1.1 x 10^6 m^3.
1900	4703		
1910	8222	1915: Replacement dam built for Calallen diversion dam that increased the size of Calallen Reservoir.	Increased height of Calallen dam to 0.76 m above high tide and reservoir to1.2 x 10^6 m^3.
1920	10,522	1929: La Fruta Dam built.	Created Lovenskiold Reservoir with 74 x 10^6 m^3 storage capacity; Dam was rebuilt in 1935.
1930	27,741	1931: Increased the Calallen Reservoir.	Increased height of Calallen dam to 1.07 m above high tide and reservoir to 1.4 x 10^6 m^3.
1940	57,301		
1950	108,287	1951: Increased the Calallen Reservoir. 1958: Wesley Seale Dam built.	Increased height of Calallen dam to 1.37 m above high tide and reservoir to 1.6 x 10^6 m^3. Lake Corpus Christi with 317 x 10^6 m^3 storage capacity.
1960	167,690		
1970	204,525		
1980	231,999	1982: Choke Canyon Dam built.	Choke Canyon Reservoir with 857 x 10^6 m^3 storage capacity.
1990	257,453	1998: 163 km Mary Rhodes Pipeline built. Transports water from Lake Texana to the City's O.N. Stevens Water Treatment Plant; State approved the Garwood transbasin diversion for another water source.	Mary Rhodes Pipeline delivers 66.4 x 10^6 m^3 of water per year to the city of Corpus Christi but is capable of delivering 138.1 x 10^6 m^3. Six wastewater treatment plants with combined capacity of 135,503 m^3 d^{-1}.
2000	277,454		
2010	305,215		

the Nueces River (Cunningham 1999). These impoundments have resulted in reduced inflows affecting nutrient loads to the coast and biological productivity of the Nueces Delta (BOR 2000). Reduced inflows coupled with drought conditions have resulted in periods of hypersalinity, creating a negative or reverse estuary (Palmer et al. 2002, Ward et al. 2002).

The Nueces River is the main freshwater inflow source for the Nueces Delta and the Nueces Estuary, which is one of 7 major estuarine systems in Texas (Fig. 1) (Matthews and Mueller 1987; Weaver 1985; Longley 1994). The Nueces River provides water for urban, agriculture, and industry use for the City of Corpus Christi (City) and surrounding region (Anderson 1960).

The Calallen Diversion Dam, constructed in 1898, was the first impoundment on the lower Nueces River tidal segment developed for surface water storage (Norwine et al. 2005). Located 24 km west of Corpus Christi, this small rock-filled dam created a barrier restricting Nueces Bay saltwater from entering the Calallen Pool (Henley and Rauschuber 1981; Cunningham 1999). The Calallen Diversion Dam has been raised several times to meet the City's water demands and is currently 1.63 m above mean sea level (msl) with an average storage capacity of 1.45 x 10^6 m^3 (1175 acre-ft) (Cunningham 1999).

As population and economic growth increased in Corpus Christi, water demands were met by construction of the La Fruta Dam in 1929 (rebuilt in 1935), which created the Lovenskiold Reservoir located approximately 56 river km upstream of the Calallen Dam with an approximate storage capacity of 68 x 10^6 m^3 (55,000 acre-ft) (Cunningham 1999). In 1958, the Wesley Seale Dam replaced the La Fruta Dam and created Lake Corpus Christi with a storage capacity of 317 x 10^6 m^3 (257,260 acre-ft). The most recent impoundment, Choke Canyon Reservoir, was constructed in 1982 and is located 80 river km upstream of Lake Corpus Christi on the Frio River with a current storage capacity of 857 x 10^6 m^3 (695,271 acre-ft) (Corpus Christi Water Department, Lake Corpus Christi and Choke Canyon Reservoir 2011). An additional potable water source is also supplied to Corpus Christi from Lake Texana via the Mary Rhodes Pipeline. The 163 km pipeline was built in 1998 and delivers between 36% to 44% of the drinking water to the City (Corpus Christi Water Department, Lake Texana 2011).

Precipitation is a key factor in determining surface flow in

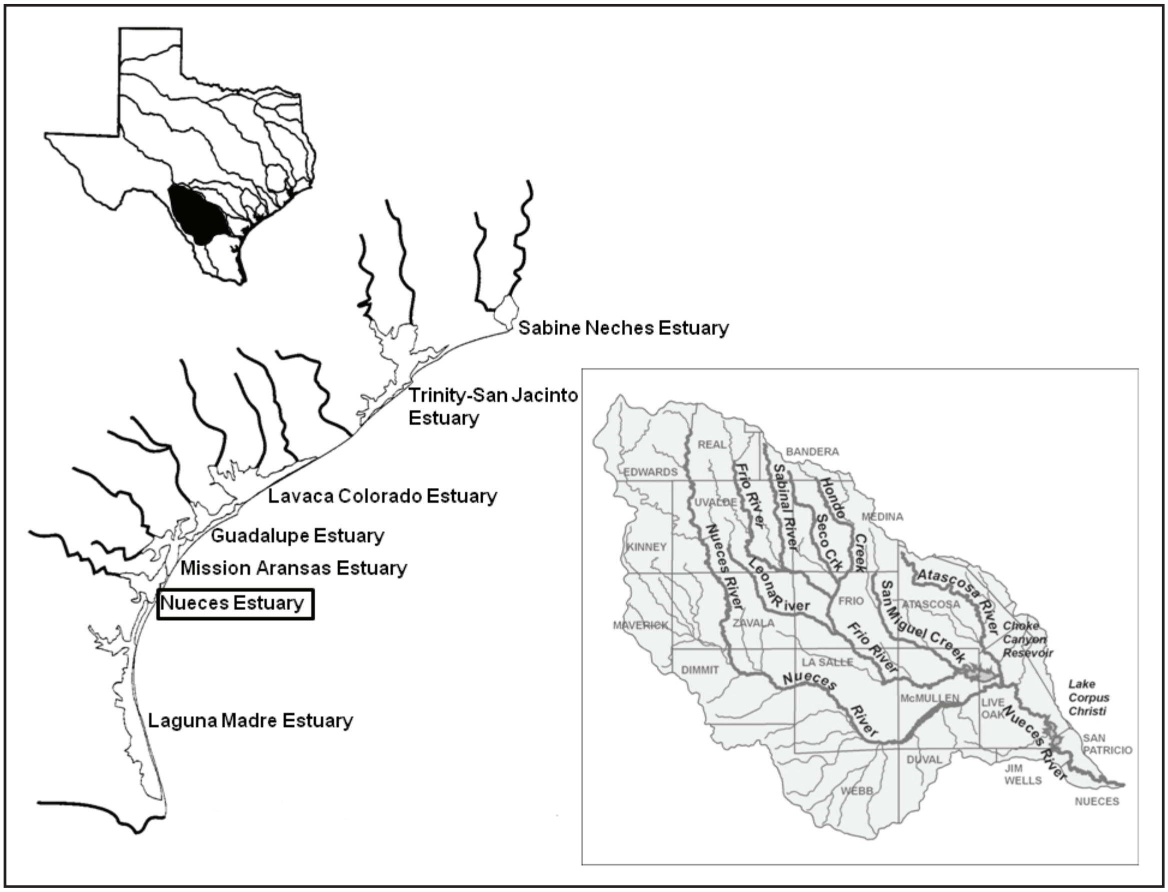

Fig. 1. Map of the 7 estuaries located along the Texas coast. Shaded area identifies the Nueces River Basin.

rivers. In the Nueces Estuary, precipitation is variable and can be influenced by El Niño and La Niña years. From 1948–2010, precipitation has increased slightly, especially during El Niño years (Fig. 2). Along with precipitation, the 2 existing reservoirs on the Nueces River control inflow into the Nueces Estuary. Using Asquith et al.(1997) in determining the mean annual flow into the Nueces Estuary, comparison of pre-construction (1940–1957) to post-construction of dams (1983–2010), shows a 39% decrease of inflow into the estuary (USGS gage 08211000, Nueces River near Mathis, Texas) (Fig. 3).

Estuaries need varying degrees of freshwater inflow to trigger cyclical patterns in salinity and other physicochemical variables essential to flora and fauna (Ritter et al. 2005). Reduced inflows to the Nueces Delta combined with low and variable precipitation and high evaporation rates, results in periods of hypersaline conditions. Negative ecological effects of hypersaline conditions, particularly to the shrimping industry (Matthews and Mueller 1987; Whitledge and Stockwell 1995), prompted the state of Texas to develop inflow criteria for freshwater inflows for the Nueces Estuary in 1990 (reviewed in Montagna et al. 2009). US Geological Survey data from 1941–1974 showed average annual inflow to the Nueces Delta prior to construction of the 2 dams was 774 x 10^6 m^3 yr^{-1} (627,492 acre-ft yr^{-1}) (Henley and Rauschuber 1981). Lack of inflow into the Nueces Estuary prompted several mandates from the Texas Commission on Environmental Quality over the years. The current Agreed Order mandated in 2001 that the Nueces Estuary receive no less than 186 x 10^6 m^3 yr^{-1} (151,000 acre-ft yr^{-1}) of freshwater inflow per year. While restoring some flow, this mandate represented a 76% decrease in historical annual (1941–1974) inflows into the Nueces Estuary.

The intent of this paper is to describe the Nueces Estuary region, document recent activities and research projects designed to improve, restore, and enhance habitat by use of alternative freshwater sources, river diversions, and land acquisition to meet biological and hydrological inflow requirements to the Nueces Delta.

REGIONAL DESCRIPTION

Nueces River Watershed

The Nueces River Basin covers 4.3 million ha and encompasses 5 ecoregions: the Edwards Plateau, Southern Texas

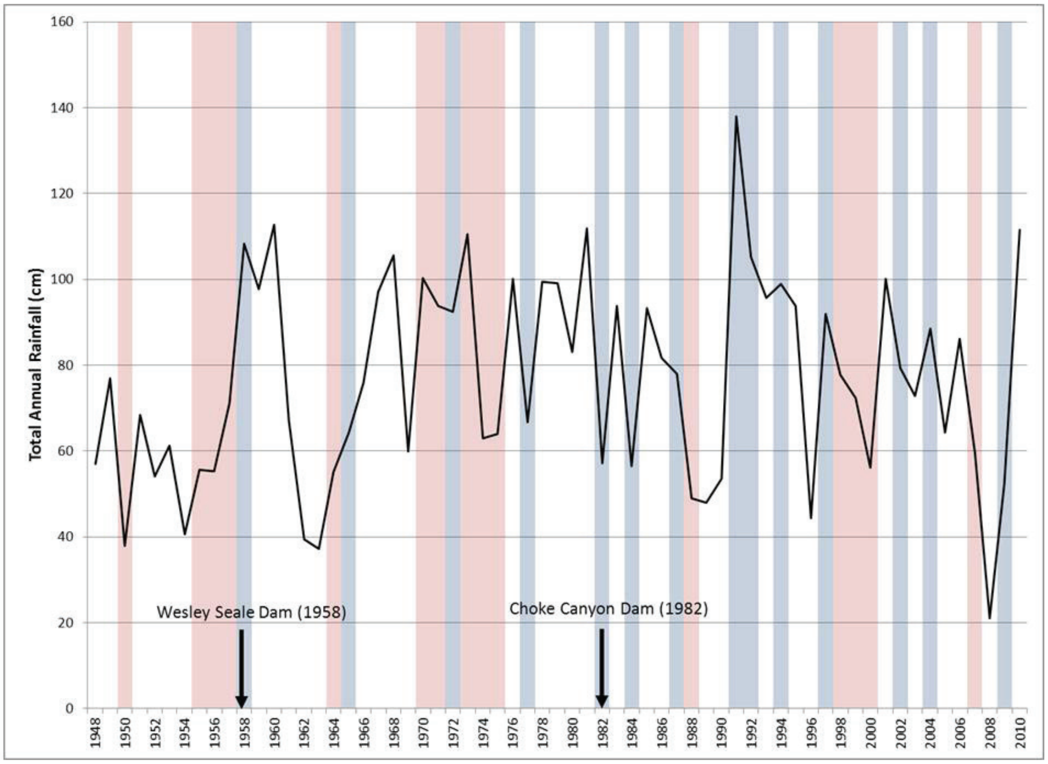

Fig. 2. Total annual precipitation recorded from the Corpus Christi International Airport from 1948–2010 and historical record of El Niño (blue) and La Niña (Red) years. (Precipitation data from National Climatic Data Center station 20024190 and El Niño-Southern Oscillation data from NOAA Climate Prediction Center.)

Plains, East Central Texas Plains, Western Gulf Coastal Plains, and the Texas Blackland Prairies (Griffith and Omernik 2009). Tributaries of the Nueces River include the Frio, Sabinal, Leona, and Atascosa rivers, and the Seco, Hondo, and San Miguel creeks (see Fig. 1). All rivers and creeks originate from seeps and springs in the Edwards Plateau (Henley and Rauschuber 1981). From 1934 through 2009 the streams crossing the Balcones Fault Zone contributed approximately 885 x 10^6 $m^3 yr^{-1}$ (717,481 acre-ft yr^{-1}) of flow into the Edwards aquifer; recharge varies from year to year based on precipitation (Eckhardt 2011). The Nueces is the only river that regularly maintains some surface flow beyond the recharge zone in the basin. In the lower reaches of the river, rainfall provides much of the stream flow for the Nueces and its tributaries south of the Balcones Fault Zone.

Originating in Real County at an elevation of around 730 m (TPWD 1974; Benke and Cushing 2005) the Nueces River flows for approximately 507 km in a southeasterly direction to its mouth at Nueces Bay (TPWD 1974). After passing the Calallen Diversion Dam, the Nueces River flows along the southern edge of the Nueces Delta and empties into Nueces Bay, bypassing the delta except during periods of flooding. Historical data (1940–2000) show Nueces River reservoir operations have reduced freshwater inundation frequencies to the Nueces Delta from 2.3 flood events to 1.2 events annually (BOR 2000). The Nueces Overflow Channel, a river modification located east of Interstate Highway 37, was built in 1995 as part of a demonstration project to divert freshwater into the delta interior. The overflow channel lowered the minimum flood threshold of the upper delta from 1.64 m above sea level to sea level increasing the probability for freshwater inflows to the upper delta (BOR 2000; Palmer et al. 2002).

Nueces Delta

The Nueces Delta is one component of the Nueces Estuary. The estuary includes 20 km of the Nueces River tidal segment below the Calallen Diversion Dam; one primary bay, Corpus Christi Bay; one secondary bay, Nueces Bay; and 2 tertiary bays, Oso Bay and Redfish Bay (Henley and Rauschuber 1981) (Fig. 4). The Nueces Delta is 75 km^2 and consists of approximately 58.5 km^2 of middle and high marsh and 0.35 km^2 of low marsh. Middle and high marsh vegetation of the Nueces Delta includes species such as *Borrichia frutescens, Limonium nashi, Lycium carolinianum, Rayjacksonia phyllocephala, Opuntia engelmannii* var. *lindheimeri,* and *Spartina spartinae*. The low marsh includes species such as *Batis maritima, Distichlis spicata, Monanthochloe littoralis, Salicornia bigelovii, Salicornia*

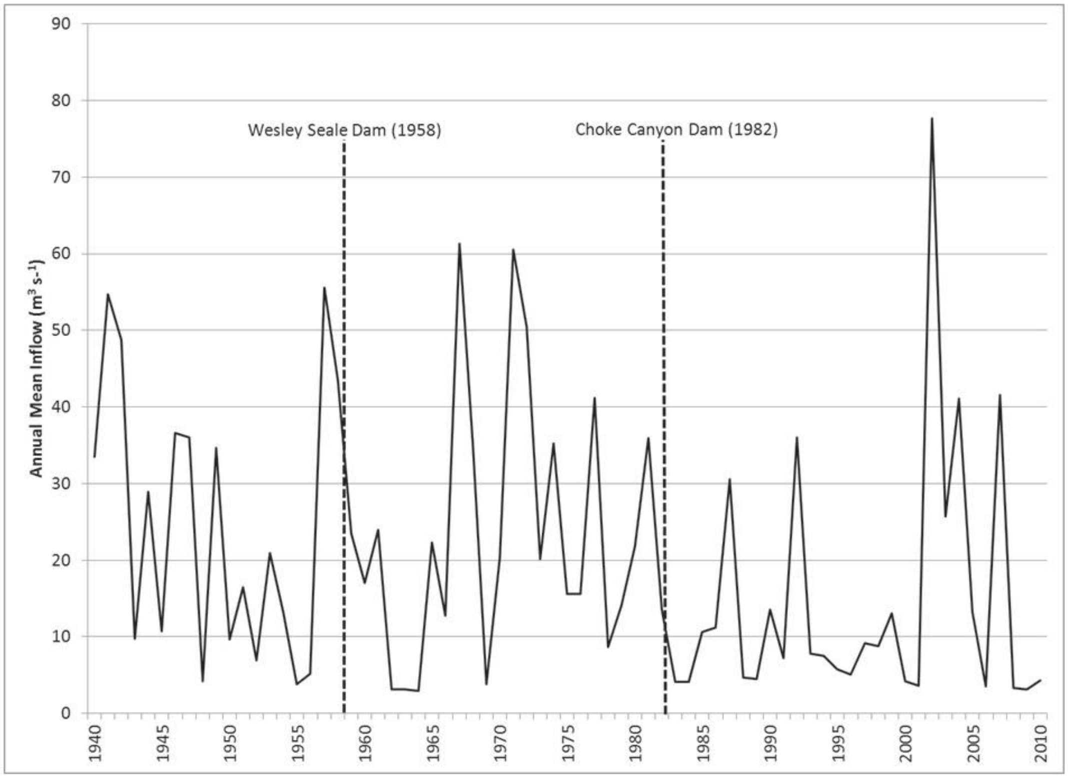

Fig. 3. Average annual Nueces River inflow ($m^3 s^{-1}$) into Nueces Bay from 1940–2010. (Data from US Geologic Survey gauge 08211000, Nueces River at Mathis, Texas, USA.)

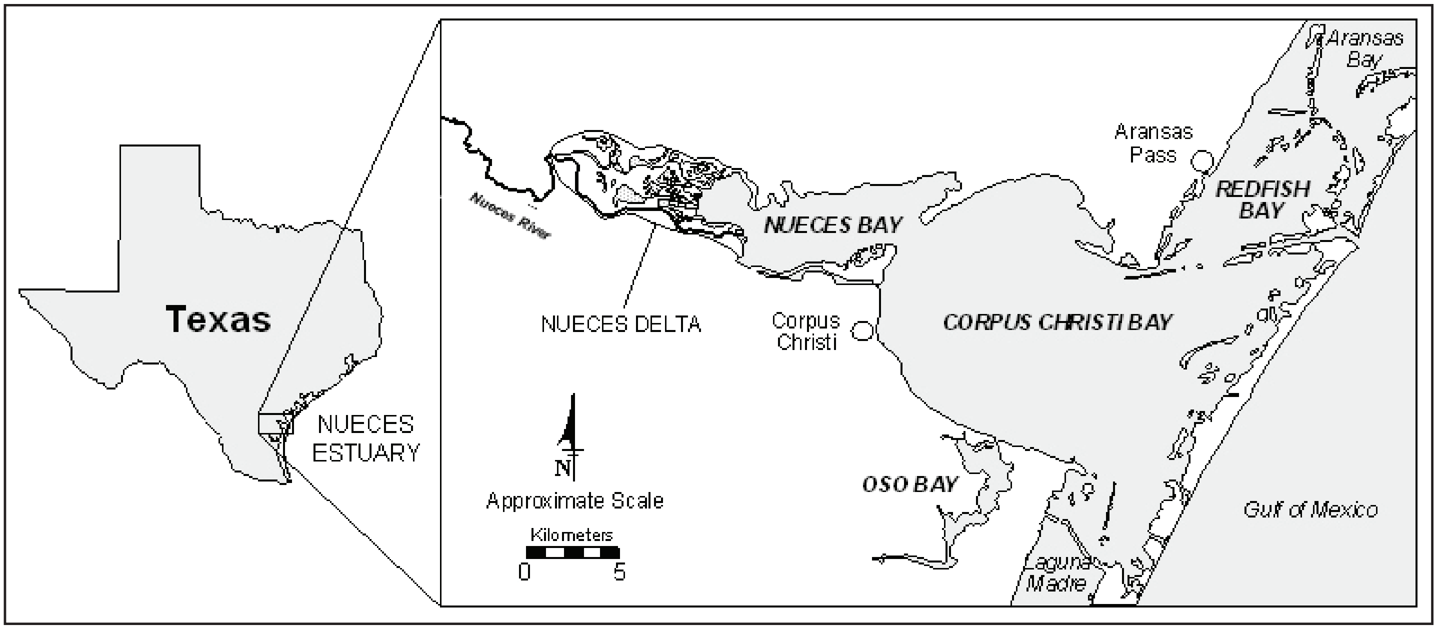

Fig. 4. Map detailing location of the Nueces Estuary (map modified after the BOR 2000).

virginica, Schoenoplectus maritimus with *Spartina alterniflora* scattered along the periphery of tidal channels (Ockerman 2005; Henley and Rauschuber 1981; Espey, Huston & Associates 1981). Seagrasses, *Halodule wrightii* and *Ruppia maritima*, and relic and extant oyster reefs of *Crassostrea virginica* are scattered throughout Nueces Bay and cover approximately 2.94 km^2 (Tunnell et al. 1996; Pulich and White 1997).

Located between a humid subtropical region to the northeast and a semiarid region to the west and southwest, the area has a net annual moisture loss of approximately 31 cm yr^{-1} (TWC 1991). Summers are hot and humid, and moderate winters produce an occasional freeze following strong northerly frontal passages (Jones 1975; Chabreck 1990). Mean annual precipitation is approximately 77.6 cm yr^{-1} (NOAA 2010). However, this is offset by evaporation rates that typically range from 90 to 115 cm yr^{-1} but may reach as high as 150 cm yr^{-1} (TWC 1991). Southeasterly prevailing winds serve as a primary source of atmospheric moisture with tropical storms and hurricanes occasionally yielding substantial amounts of rainfall during late summer and early fall (Armstrong 1987).

NUECES DELTA PROJECTS

While many estuarine organisms tolerate hypersaline conditions, extended periods of hypersalinity resulting from reduced inflow in the Nueces Delta have impacted biological productivity, vegetation cover, species richness, and species diversity over the past 6 decades (Alexander and Dunton 2002; Montagna et al. 2002; Palmer et al. 2002). Hypersaline conditions have reduced populations of commercially and recreationally important faunal species, particularly shrimp and oysters (Murray and Jinnette 1974; Longley 1994; Montagna et al. 2002; Palmer et al. 2002). In response to negative environmental and economic impacts from reduced flows, management projects were initiated to increase biological productivity of the Nueces Delta by restoring freshwater flow. The water rights permit issued in October 1976 stated that following the completion and filling of Choke Canyon Reservoir scheduled water releases from Lake Corpus Christi would be no less than 186 x 10^6 m^3 yr^{-1} (151,000 acre-ft) into the Nueces Estuary via reservoir spills, releases, or return flows. At that time, flow in the Nueces River bypassed the interior delta and flowed directly into Nueces Bay. Mandated water releases from the city's municipal water supply, Lake Corpus Christi, raised concern from residents especially during drought conditions when water restrictions were in place. These concerns of human needs versus environmental needs resulted in management evaluation of alternative water resources to meet estuarine freshwater requirements of the delta.

Nueces Delta Mitigation Project 1989–1997

The first project in the Nueces Delta was a mitigation plan that involved aquatic and marsh habitat creation. In March 1987, the US Army Corps of Engineers and the Port of Corpus Christi Authority excavated an 0.81 km^2 upland borrow area in the Nueces Delta to create salt marsh habitat to offset habitat losses from the Corpus Christi Ship Channel 45-Foot Dredging Project. Nueces Delta Mitigation Project participants included the US Fish and Wildlife Service, National Marine Fisheries Service, US Environmental Protection Agency, Texas Parks and Wildlife, and the Texas General Land Office (FWS 1984).

Marsh habitat was created by constructing a series of channels and ponds that maximized circulation and edge effect by planting smooth cordgrass, *S. alterniflora* (Fig. 5). The US Army Corps of Engineers and US Fish and Wildlife Service implemented a 5-year monitoring program in June 1989 to evaluate success of *S. alterniflora* establishment and the biological response to the created marsh using biometrics based on monitoring of benthic infauna, epifaunal invertebrates, nekton, avian usage, and hydrological data (Nicolau and Tunnell 1999).

The initial planting failed within 6 months because 1) a construction design failure resulted in complete marsh submergence during low tide (when plants should have been emergent) and 2) higher than optimum salinity that was too stressful for the *S. alterniflora* transplants (Nicolau and Tunnell 1999). The salinity in the Nueces Delta during planting exceeded 40 practical salinity units (PSU) for over 6 months, and exceeded the optimum salinity for *S. alterniflora* of 10-20 PSU (Ruth 1990; Linthurst and Seneca 1981; Webb 1983).

A multi-agency planning conference in May 1993 discussed the design failure and reconstruction alternatives to satisfy mitigation requirements. The discussions resulted in a design to build a smaller marsh at 0.04 km^2 within the mitigation area before attempting the full-scale site modification (Fig. 6). Because of time and monetary constraints, construction was postponed to February 1994 and the test area decreased from 0.04 km^2 to 0.024 km^2. Two weeks before completion, with approximately 75% of the area elevated to grade, a wind-driven high tide event breached all levees and completely inundated the area. When the waters receded, a more natural design appeared than originally planned and construction was stopped. The planting area now included several small islands for birds to nest on and a network of channels and ponds for aquatic species to take refuge in during low tides. When the 5-year study concluded in August 1994, birds were utilizing the area for nesting and new plant growth was established within the Nueces Delta Mitigation Project area (Nicolau and Tunnell 1999). The 0.024 km^2 test marsh was considered a success and plans to move forward and build the full-scale mitigation site were initiated. In August 1995, a plan was designed after a successful US Fish and Wildlife Service project in the Sabine National Wildlife Refuge in Louisiana. The Sabine National Wildlife Refuge used *in situ* material to construct low levees or islands in a grid pattern to maximize inter-tidal habitat for *S. alterniflora*. After the US Army Corp of Engineers completed plans and specifications for the Nueces Delta Mitigation Project, construction began in January 1997. Construction ended in late February 1997, followed by planting of *S. alterniflora* in March 1997 (Fig. 7). Wind-driven tidal events soon after planting resulted in high tides, which destroyed some *S. alterniflora*, but by August 1997, new growth was established at many new levee locations and the US Army Corp of Engineers declared the project a success. Through management efforts of multiple agencies, the Nueces Delta Mitigation Project created new aquatic and marsh habitat.

Rincon Bayou Overflow Channel Demonstration Project 1993–1999

The US Bureau of Reclamation initiated and funded the Rincon Bayou Overflow Channel Demonstration Project in 1993 to increase freshwater inflows to the upper Nueces Delta. Two main project objectives were: 1) to increase the probability of freshwater inflow events to reach the upper Nueces Delta and 2) to monitor subsequent changes in biological productivity within the delta. Baseline monitoring took place from October 1994 through October 1995 (BOR 2000). Two channels, the Nueces Overflow Channel and the Rincon Overflow Channel, were excavated to divert river water to the Upper Rincon Bayou and were completed October 1995 (Fig. 8). The Nueces Overflow Channel, excavated to 0.6 m msl, connected the Nueces River to the delta and increased flow exchange during periods of river flood and high tide conditions. The Rincon Overflow Channel, excavated to 1.22 m msl upstream (south) and 0.91 m msl downstream (north), was constructed to increase the exchange of water from the Rincon Bayou to the northernmost reaches of the Nueces Delta (BOR 2000).

Changes in water column productivity, benthic macrofauna (species composition, density and biomass), and vegetation communities were used to evaluate biological productivity in response to the overflow channels from October 1994 to December 1999. During the 50-month demonstration project, the amount of freshwater diverted from the Nueces River to the upper Rincon Bayou increased approximately 732% when comparing inflow data from 1982 to 1995. Five significant freshwater inflow events occurred resulting in flow through the Rincon Overflow Channel and inundation of the marsh and tidal flats in the northern part of the delta (BOR 2000). These events were substantial enough to lower the salinity gradient in the upper delta below hypersaline conditions. Data collected during the study period showed the diversion channels significantly lowered the minimum flooding threshold of the upper Nueces Delta. Positive responses to the increased freshwater were identified in the water column, benthic infauna, and vegetation (BOR 2000). However, in September 2000, in accordance with project guidelines and due to failed attempts to purchase the land on which the channel was constructed, the Bureau of Reclamation filled in the Nueces Overflow Channel. Then, in October 2001, the City reopened the Nueces

Fig. 5. Aerial photograph showing the first stage of the Nueces Delta Mitigation Project site (Lanmon Aerial 991-B5, 9 February 1991).

Fig. 6. Aerial photograph showing the second stage of the Nueces Delta Mitigation Project site (Lanmon Aerial 3295-1, 11 February 1995).

Fig. 7. Aerial photograph showing the completed cells of the Nueces Delta Mitigation Project site (Lanmon Aerial 9497-1, 3 May 1997).

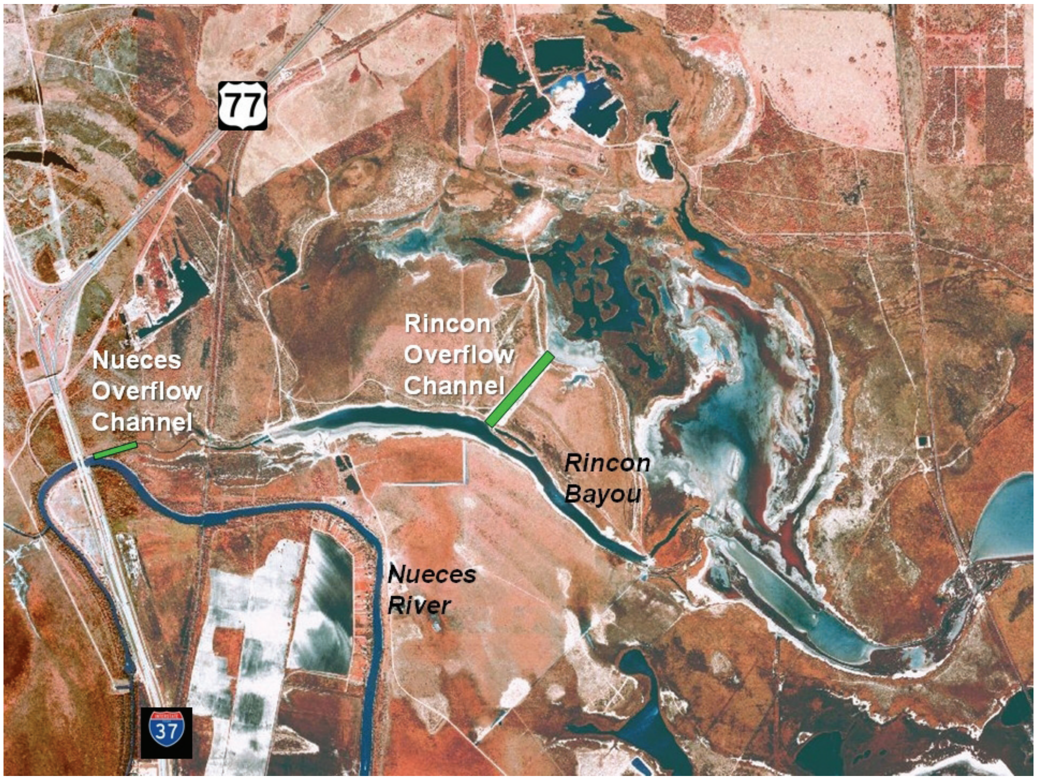

Fig. 8. Map showing placement of the Nueces Overflow Channel and Rincon Overflow Channel on the Nueces River (BOR 2000).

Overflow Channel (excavated to a depth of 0.3 m msl) as part of a permanent diversion to restore flows to the Nueces Delta.

Effluent Diversion Demonstration Project 1998–2003

Based on recommendations in the Regional Wastewater Planning Study-Phase II Nueces Estuary (HDR 1993), the City developed a full-scale demonstration project in the lower Nueces Delta that used treated municipal effluent as an alternative freshwater source (Dunton and Hill 2006). The diversion provided a supply of nutrient-rich freshwater that also facilitated reductions in hypersalinity.

In June 1997 three 0.013 km^2 earthen cells were built at the Effluent Diversion Demonstration Project site to receive treated effluent from the Allison Wastewater Treatment Plant. The project site is located 900 m northeast of the Allison Wastewater Treatment Plant, 300 m north of the Nueces River, and approximately 3.5 km west of Nueces Bay (Fig. 9). Once the pipeline and cells were determined to be fully functional, 7570 $m^3\ d^{-1}$ (6.14 acre-ft d^{-1}) of effluent began to be pumped to the diversion site.

One project goal was to assess the feasibility of enhancing productivity in the Nueces Delta using treated effluent discharges. Specific objectives were 1) to determine if "no harm" occurred because of the diversion and 2) to assess changes in the marsh ecosystem due to the diversion. To measure ecological changes occurring in response to the discharge, the City established a comprehensive monitoring program that met the requirements of the Texas Natural Resource Conservation Commission permit (now Texas Commission on Environmental Quality). Monitoring of productivity focused on 1) phytoplankton primary production and biomass, 2) zooplankton and mesozooplankton biomass and species abundance, 3) emergent vegetation biomass, species composition, percent cover, and plant canopy structure, 4) benthic density, biomass, and diversity, 5) nekton catch per unit effort, biomass, and diversity, 6) avifauna species abundance, diversity, and habitat usage and, 7) physiochemical effects including sediment porewater salinity and inorganic nitrogen levels (Dunton and Hill 2006).

The volume of effluent diverted into South Lake decreased salinity at the diversion site and created a 0.07 km^2 emergent vegetation marsh that attracted many species of birds (Dunton and Hill 2006). Birds used the area for feeding, resting, and breeding and as a freshwater source and refuge during times of drought. The high inorganic nitrogen and phosphorus at the diversion site was rapidly assimilated (50%–80% reduction) by the vegetation within 325 m downstream of the site (Alexander and Dunton 2002). In meeting the permit requirements established by the Texas Natural Resource Conservation Commission for this diversion project, the City began initial development of a comprehensive regional water resources management program that integrated local water supply and effluent treatment facilities to manage water resources in the most environmentally productive, dependable, and affordable approach.

Rincon Bayou Nueces Delta Study 2003–2010

The Rincon Bayou Nueces Delta study was funded by the City and followed the 2001 Texas Commission on Environmental Quality Agreed Order requiring the City to construct and operate a 1.5 m diameter water pipeline to deliver up to 3.7×10^6 m^3 d^{-1} (3000 acre-ft) of freshwater to the Rincon Bayou in accordance with the 1995 Texas Commission on Environmental Quality pass-through order. To facilitate the objective, in October 2001 the City reopened the Nueces Overflow Channel (0.3 m msl) making the diversion channel a permanent feature of the Nueces Delta (see Fig. 8). This project, like the Effluent Diversion Demonstration Project, required the City to implement a monitoring program to facilitate a management program for freshwater inflows into the estuary and determine if “no harm” resulted from the diversions.

Field studies began October 2003 at 9 stations recommended in the 2002 Nueces Estuary Advisory Council Monitoring Plan. Monitoring objectives for the Rincon Bayou Diversion Project focused on biological effects related to the Nueces Overflow Channel, Rincon Overflow Channel, and the Rincon Bayou pipeline diversions to the Nueces Delta (see Fig. 8 and Fig. 9). Original project recommendations called for a 5 year monitoring plan; 2 year pre-pipeline, 2 year post-pipeline, with 1 year for data analysis and final report. Delays in pipeline construction (completed in 2008) extended the monitoring timeline to 7 years. Data parameters collected included 1) emergent vegetation biomass, species composition, percent cover and plant canopy structure, 2) benthic invertebrate density, biomass, and diversity, 3) nekton catch per unit effort, biomass and diversity, 4) avifauna species abundance, diversity, and habitat usage. and 5) physiochemical effects resulting from the diversion.

The monitoring program was intended to assess benefits of the diversion on productivity in Rincon Bayou and assist in development of an optimal operation management plan for the pipeline. Once the monitoring requirements were

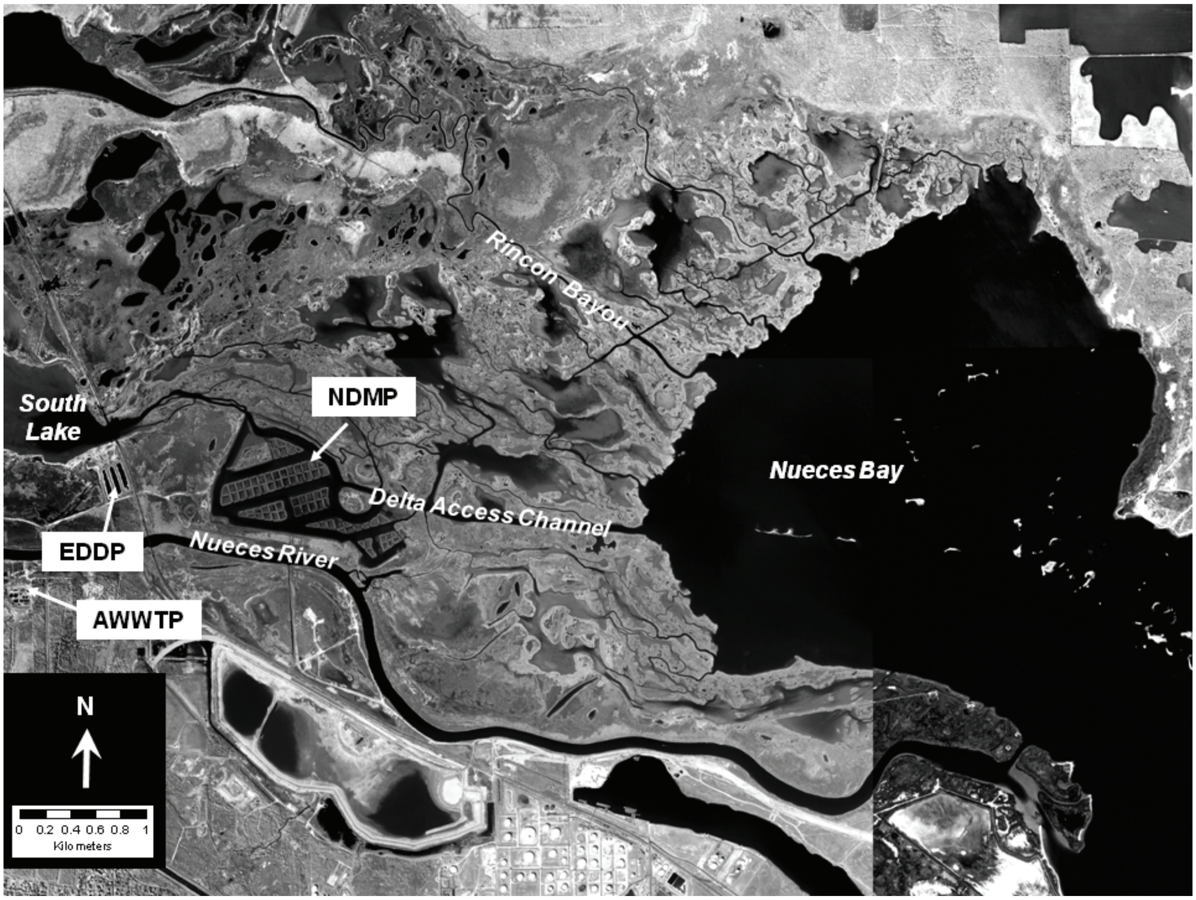

Fig. 9. Lower Nueces Delta showing locations of the Nueces Delta Mitigation Project (NDMP), Effluent Diversion Demonstration Project (EDDP), and Alison Wastewater Treatment Plant (AWWTP).

met, biological monitoring was stopped with only 3 pipeline releases occurring during the study (September 2009, January 2010, and May 2010). Since the completion of the project in September 2010, 3 more releases have occurred: March 2011, May 2011, and June 2011. Salinity monitoring is still active and is the parameter being measured to determine the spatial effects of freshwater into the delta via the pipeline (Adams and Tunnell 2010). Salinity gauges are maintained by the Conrad Blucher Institute at Texas A&M University–Corpus Christi (Conrad Blucher Institute 2011).

Nueces Delta Preserve Land Acquisition (2004–2011)

The Nueces Delta Preserve was established in 2003 when approximately 5.7 km^2 of Nueces River Delta property was acquired by the Coastal Bend Bays & Estuaries Program with funds from US Environmental Protection Agency Supplemental Environmental Project Settlements and the US Department of Interior's Coastal Impact Assistance Program (Fig. 10). Along with the $1.5 million Supplemental Environmental Project funds, the Coastal Bend Bays & Estuaries Program also received an additional $2.5 million in matching funds and completed 3 land acquisitions and habitat protection projects. The Coastal Bend Bays & Estuaries Program worked with The Nature Conservancy of Texas, Texas Commission on Environmental Quality, the City, the US Department of Agriculture Natural Resources Conservation Service, and the US Fish and Wildlife Service to acquire lands and conservation easements on delta property with high ecological value and/or subject to high development pressure.

The Coastal Bend Bays & Estuaries Program has protected 6 rookery islands and approximately 0.024 km^2 of colonial waterbird rookery island habitat in Nueces Bay and planted *S. alterniflora* along eroding shorelines in Nueces Bay to help reduce erosion and create habitat. In total, the Coastal Bend Bays & Estuaries Program has acquired approximately 21.85 km^2 and is currently working to add another 20.64 km$^{2.}$

DISCUSSION

Freshwater is a valuable environmental resource and its accessibility is less than 1% (11 million km^3) of the total volume of water on Earth (Batchelor 1999). Many factors affect freshwater availability including population growth, pollution, economics, land usage, and climate change (Davies and Simonovic 2011). Finding the balance between human and environmental freshwater needs within a river basin is complex but has been possible in other management efforts. Using an adaptive approach in management plans to protect this resource is essential. Most policy makers and scientists now accept this new methodology allowing modifications to plans when objectives are not being met (Rammel et al. 2007; Cundill and Fabricius 2009; Wilby et al. 2010).

As done in the Nueces Estuary, the Australian government passed laws to improve water quality resources after river dam construction and drought conditions had detrimental effects on the Murray Darling Basin located in southeastern Australia (Kingsford 2000). The basin drains Australia's 3 longest rivers—the Murray 2530 km, the Darling 2740 km, and the Murrumbidgee 1690 km (Kingsford 2000; McNamara 2007)—and covers 1,061,469 km^2, equal to 14% of Australia's land area (Walker 1985; Kingsford 2000). Since 1920 there has been a 5-fold increase in water diverted from the Murray Darling system (irrigation being the largest at 95% of diversion volume), which has resulted in hypersaline water, increased algal blooms, habitat alteration, and increased water temperature, all which have adversely affected native plants and animals (Walker 1985; Kingsford 2000). Since the 1980s Australia's government has implemented laws to restore inflows and restore water quality of the Murray Darling Basin. These efforts culminated in 2008 when the Murray-Darling Basin Authority assumed sole responsibility for planning integrated management of the basin water resources in an effort to ensure that future sustainable water use provides sufficient water for a healthy environment as well as agriculture, industries, and human use. Success in managing the Murray Darling Basin is a result of strong relationships among state and local organizations, agriculture, industry, and the public. Comparable efforts for the Nueces Delta brought independent stakeholders together in establishing objectives for the Nueces Delta and Nueces Estuary. These efforts were critical in instituting ecosystem management practices for the delta's habitats and restoring freshwater inflows to the Nueces Delta. The partnerships between scientists, resource managers, and stakeholders were necessary in determining environmental and economic needs to maintain this ecosystem, while also fulfilling residential, agricultural, economic, and industrial demands of the coastal bend.

Given as an example, the success of the Murray Darling Basin efforts have shown adaptive management programs work and are increasingly becoming a management tool in much of the United States and other countries (Becu et al. 2003; Schlüter and Rüger 2007; Cundill and Fabricius 2009; Kallis et al. 2009; Allen et al. 2011; Fontaine 2011; Moore et al. 2011). To some extent, an "adaptive" approach is currently being practiced in managing the Rincon Bayou Pipeline in the Nueces Delta, in terms of timing, volume, and duration of flow. This "adaptive" approach in managing diverted freshwater gives flexibility to resource decision makers during drought or flood conditions and the ability to increase or decrease volume depending on water availability. However, as of now, no biological monitoring is required to evaluate the spatial and

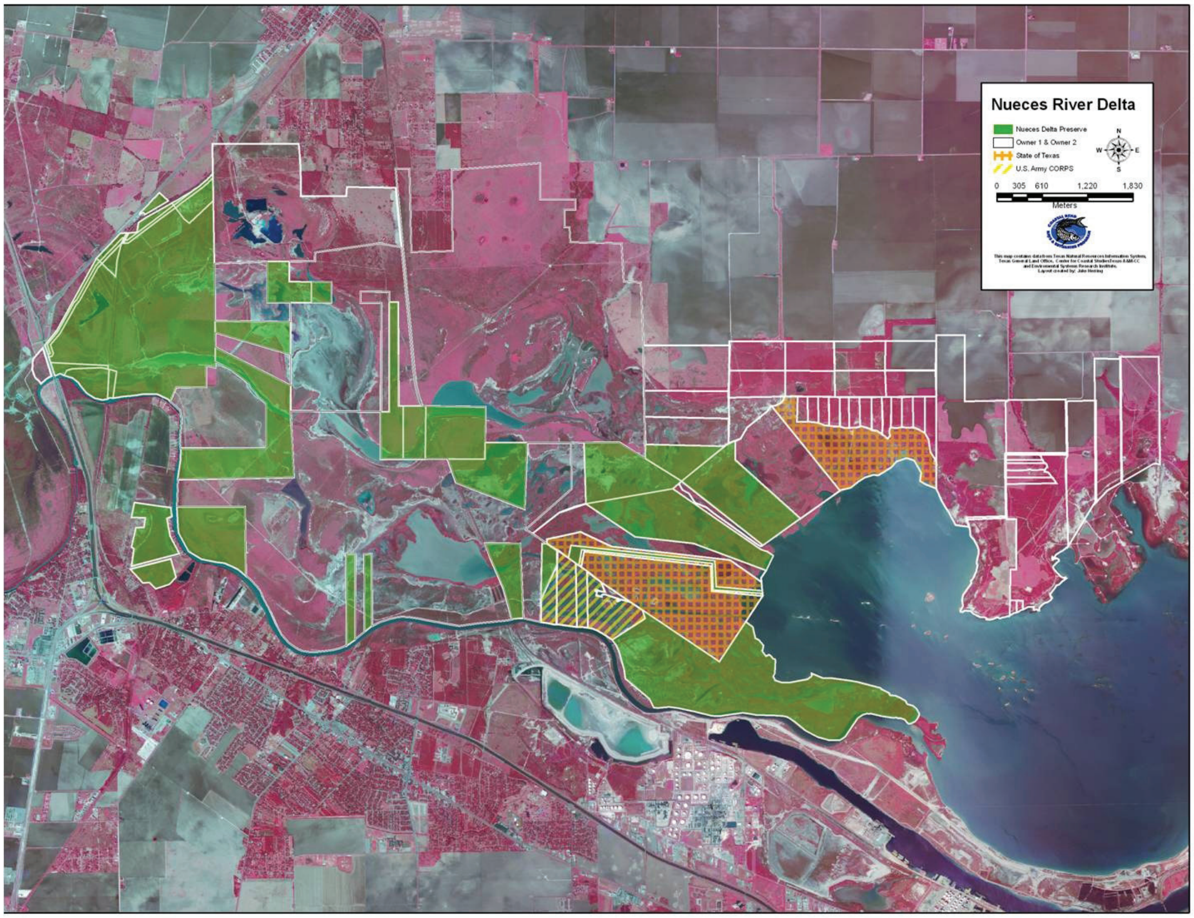

Fig. 10. Nueces Delta land acquisition: Coastal Bend Bays & Estuary Program (green shaded area), State of Texas (orange checked), and US Army Corps of Engineers. (Photo courtesy of Coastal Bend Bays & Estuary Program).

temporal effects of the Rincon Bayou Pipeline and to determine if the current plan optimizes ecosystem benefits. Without those data, this management plan cannot (1) be evaluated for ecological effectiveness, (2) ascertain ecosystem benefits from the plan, and (3) identify if plan objectives have been met other than salinity changes. When only one parameter or scale is used to determine system change, in this case salinity, processes occurring at different scales and rates may be masked (Cundill and Fabricius 2009). This is why it is important to have both biological and physio-chemical data collected at different scales since communities and chemicals react to change at different rates.

Monitoring provides the data tools for effective decision making when using an adaptive approach to manage resources (Steyer and Llewellyn 2000; Fontaine 2011; McFadden et al. 2011; Williams 2011b; Cundill and Fabricius 2009). Both biological and chemical data are needed to justify changes to environmental plans and identify if the objectives have been met (McFadden et al. 2011; Williams 2011a). The current effort in restoring and maintaining existing connectivity between river, delta, and bay in the Nueces Estuary with freshwater flow enhances chemodiversity (i.e. salinity gradient, pH), which in turn supports a variety of habitats essential to fauna and flora. These valuable delta habitats (i.e. uplands, high marsh, low marsh, wetlands, and mudflat) are now being protected from commercial and agricultural development through the efforts of the Coastal Bend Bays & Estuary Program land acquisition program. Protecting the delta's habitats and implementing adaptive management practices in future environmental projects provides natural resource managers with the tools required to make the decisions necessary to maintain a functional estuary.

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