Issues

There will be considerable challenges and consequences involving climate change, particularly sea-level rise, during the next century along the South Texas coast. A rising global sea-level will have a disproportionate effect in South Texas due to the flat topography (Twilley et al. 2001). As shorelines move landward, marine and estuarine habitats will change or migrate also. Other probable climate change impacts will include: alterations in freshwater inflows from rivers; changes in estuarine ecosystem functioning; more frequent or longer-lasting droughts; increased incidence of extreme salt concentrations in some coastal ecosystems; changes in various kinds of habitats (increases in some, and decreases in others); and, further reductions in certain estuarine-dependent species: e.g. oysters, blue crabs, shrimp.

Scientists have two primary methods for forecasting these future changes or impacts. One method is to analyze and study similar conditions in the past and projecting those conditions on future coastal landscapes. For example, when conditions in South Texas were considerably wetter as evidenced by Rangia clams on the Nueces Delta or worm tube rocks in Baffin Bay; or when conditions were drier, like the 1950s, when vast sand dunes occupied large portions of the back side of barrier islands. Another method is in analyzing large data sets of the past and projecting those into the future using conceptual models or scenarios of future conditions. Neither of these approaches can predict exact conditions, but people living in the area, particularly those responsible for future planning (city, county, state, and federal managers or trustees), should be aware of future possible consequences.

An increasing body of literature is available to evaluate potential climatic changes and sea-level rise impacts on the Texas coast:

- sea-level rise impacts on salt marsh and bay productivity (Zimmerman et al. 1991);
- estuarine habitats and freshwater inflow (Longley 1995);
- hypoxia in coastal waters (Justic 1996);
- potential risks of climate change to Gulf Coast ecosystems and the goods and services they provide (Twilley et al. 2001; Ning et al. 2003 a and b);
- status and historical trends in seagrass habitats (Pulich and Blair 1997);
- wind-tidal flats (Withers and Tunnell 1998),
- other estuarine and coastal habitats (White et al. 1998);
- status and trends of wetlands and aquatic habitats on Texas barrier islands and adjacent bay systems (White et al. 2002, and 2006); and,
- impacts to ecosystems and social systems (Alvarez et al. 2006).
Chapter 3

Current Coastal Landscape

There are seven major estuarine systems along 600 kilometers (373 miles) of coastline (Figure 1, Longley 1994). All seven Texas estuaries have similar geomorphic structure and physiography. Barrier islands are parallel to the mainland along the coast, and lagoons are found between the islands and mainland. The lagoons are interrupted with drowned river valleys that form the bay and estuarine systems. There are Gulf inlets through the barrier islands, which connect the sea with the lagoon behind the island. The lagoon opens to a large primary bay, and there is a constriction between the primary bay and the smaller secondary bay. Most bays are fed by just one or two rivers draining watersheds. The river generally flows into the secondary bay. Primary bays have greater marine influence and secondary bays have greater freshwater influence.

The Texas coast is bounded by Sabine River (border to Louisiana) in the northeast and the Rio Grande (border with Mexico) in the southwest. The major bay-estuarine systems are the Sabine-Neches Estuary, Trinity-San Jacinto Estuary, Lavaca-Colorado Estuary, Guadalupe Estuary, Mission-Aransas Estuary, Nueces Estuary, and Laguna Madre Estuary. Laguna Madre is actually two different systems: Upper Laguna Madre/Baffin Bay and Lower Laguna Madre. Texas follows the traditional system of naming an estuary for the river(s) that dilute sea water (Longely 1994). In NOAA publications (e.g., Orlando et al. 1993), these systems are named after the primary bay: Sabine Lake, Galveston Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, and Laguna Madre, respectively. There are also three riverine estuaries, the Brazos River, San Bernard River, and the Rio Grande, which flow directly into the Gulf of Mexico.

Freshwater wetlands and lower salinity brackish-salt marshes and oyster reefs are common in the north and higher salinity seagrass beds and wind-tidal flats are common to the south. In the Texas Coastal Bend, Corpus Christi lies at the approximate boundary where precipitation exceeds evaporation to the north and evaporation exceeds precipitation to the south (Table 1). Hence, Laguna Madre is a higher salinity lagoon, containing over 80% of Texas seagrasses (Pulich and Blair 1997) and over 80% of Texas wind-tidal flats (Withers and Tunnell 1998).

<table>
<thead>
<tr>
<th>Habitat</th>
<th>Laguna Madre</th>
<th>Nueces</th>
<th>Mission- Aransas</th>
<th>Guadalupe</th>
<th>Lavaca - Colorado</th>
<th>Trinity - San Jacinto</th>
<th>Sabine - Neches</th>
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<tbody>
<tr>
<td>Fresh Marsh</td>
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<td>9</td>
<td>5.7</td>
<td>17.7</td>
<td>21.4</td>
<td>19.4</td>
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<td>1.5</td>
<td>0.1</td>
<td>34.6</td>
<td>36.3</td>
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<td>25.2</td>
<td>27.9</td>
<td>29.6</td>
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<td>118</td>
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<td>Wind- Tidal Flat</td>
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<td>12.4</td>
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<td>9.5</td>
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<td>27.9</td>
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<td>366.1</td>
<td>493.6</td>
<td>49</td>
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<tr>
<td>Dredge Material</td>
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<td>9.7</td>
<td>3.9</td>
<td>4.7</td>
<td>10.7</td>
<td>11.2</td>
<td>16.7</td>
</tr>
</tbody>
</table>


Sea-Level and Shoreline Change

Past and Ongoing Shoreline Change

Most of the sandy Gulf of Mexico shoreline of South Texas has probably been retreating for several thousand years and definitely since the mid to late 1800s when sufficiently accurate shoreline maps were constructed for comparison with today’s maps. An analysis of multiple Gulf of Mexico shorelines from 1930 to 2000 and from the Colorado River to the US–Mexico border shows that 56% of the shoreline retreated at a mean rate of 2.2 meters/year (7.22 feet/year), 36% remained essentially stable, and only 8% advanced seaward. Advancing shoreline sections were associated with impoundment of sand by jetties or spit progradation caused by engineering alterations affecting Pass Cavallo. A section a few miles long in the central Padre Island area also advanced because of the natural convergence of littoral drift.
Bay shorelines have been retreating for at least ten thousand years as sea level rose from the lowstand of eighteen thousand years ago and flooded paleoriver channels running through the bays. Inundation, waves, and tidal action eroded river banks, and the resulting shoreline retreat largely shaped the bays as they exist today. Generally these bay shorelines continue to retreat with the erosion of marshes and flats, clay bluffs, sandy slopes, and sand and shell beaches. In some areas, extensive shore-protection structures such as rip rap and bulkheads have been installed. Paine and Morton (1993) determined an average retreat rate for the Copano, Aransas, and Redfish Bay systems of 0.24 m/yr (0.79 ft/yr) from 1930 through 1982. In Baffin Bay, most of the shoreline retreated from 1941 through 1995 (Gibeaut and Tremblay 2003).

Changing sea level relative to the land (relative sea-level change) and the increase and decrease in sand supply to the coast causes shorelines to retreat or advance over a period of a hundred years or more (Bruun 1962; Gibeaut and Tremblay 2003). The rise in relative sea level during the last one hundred years along the South Texas coast has moved the Gulf and bay shorelines by inundation and by shifting the erosive energy of waves and currents landward. This has happened because, overall the rate of new sediment delivered to the littoral zone has not been sufficient to stem the effects of relative sea-level
rise. Localized exceptions to this are where rivers form deltas at the heads of the bays, such as the Nueces and Mission Deltas; and where creeks erode bluffs and enter the bays (Morton and Paine 1984; Paine and Morton 1993); and where dunes have migrated and advanced the shoreline (Prouty and Prouty 1989; Gibeaut and Tremblay 2003). Because of this sediment deficit and the low-lying and gently sloping shores of much of the South Texas coast, relative sea-level rise has had and will continue to have a profound effect on coastal habitats. Increases in the rate of global sea-level rise, as projected by global climate modeling (Intergovernmental Panel on Climate Change [IPCC 2007]), and coastal development will very likely result in further decreases of coastal wetland habitats.

Relative Sea-Level Change

Relative sea-level rise along the South Texas coast is caused by natural and human-induced land surface-subsidence and a global rise in ocean level. Global sea level is rising primarily through addition of water to the oceans by melting continental ice and to a lesser degree, through thermal expansion of ocean water (Miller and Douglas 2004), both of which are caused by global warming. Tide-gauge records in South Texas, which include the effects of land subsidence, show that relative sea level has risen at a rate of 4.6 mm/yr (0.18 in/yr) at Rockport since 1948, 2.05 mm/yr (0.08 in/yr) at Port Mansfield since 1963, and 3.44 mm/yr (0.14 in/yr) at South Padre Island since 1958 (Zervas 2001). Douglas (1991) considered tide gauges from around the world and, after accounting for vertical land movements, determined that global sea level from the late nineteenth through the late twentieth century rose at a rate of only 1.8 mm/yr (0.07 in/yr). Land subsidence rates can be estimated for tide gauge locations by subtracting 1.8 mm/yr (0.07 in/yr) from the relative sea-level rise rate recorded by the gauge. This calculation illustrates that land subsidence is an important component of relative sea-level rise in South Texas.

The South Texas coastal plain was built by an accumulation of alluvial, estuarine, coastal, and deeper marine sediments over the last hundred and fifty million years. This stack of mud and sand is 10- to 15-km thick (6.21 to 9.32 mi) (Antoine and Gilmore 1970) and is compacting under its own weight at a long-term (hundred thousand years) rate of about 0.05 mm/yr (0.001 in/yr) (Paine 1993). Higher rates of natural compaction, however, are likely occurring over the last ten thousand years as the sediments deposited during the latest transgression of the sea compact. Areas along the South Texas coast with these relatively thick and unconsolidated Holocene sediments are the barrier islands, bay margins, and estuarine deltas, which contain important habitats highly sensitive to sea-level fluctuations. Meckel et al. (2006) used a sediment compaction model to show statistically that the amount of compaction is generally greater in areas with thicker and more rapidly deposited sediments. Using Meckel’s results and stratigraphy of Mustang Island (Simms et al. 2006) and the Nueces Delta (Brown et al. 1976), the likely natural rate of subsidence of South Texas barrier islands and modern deltas ranges from 1 to 5 mm/yr (0.04 to 0.20 in/yr).

Additional land subsidence is caused by groundwater withdrawal and oil and gas production, which decrease pore pressures in underlying sediments, allowing further compaction. Ratzlaff (1980) compared releveling surveys for various periods from 1917 through 1975 and observed locally high land subsidence rates of as much as 49 mm/yr (1.93 in/yr), such as at the Saxet oil and gas field southwest of Nueces Bay. Highest rates correlated with oil, gas, and groundwater production. By combining tide-gauge and releveling data, Paine (1993) estimated Texas coastal subsidence rates of 3 to 7 mm/yr (0.12 to 0.28 in/yr). Sharp et al. (1991) and Paine (1993) hypothesized that regional depressurization of petroleum reservoirs was the cause of historical subsidence rates being much higher than geologically long-term rates. Morton et al. (2006) provided evidence of hydrocarbon production causing regional land subsidence and associated wetland loss in the Mississippi Delta and the upper Texas coast regions. It is clear that the rate of relative sea-level rise has and will continue to vary along the South Texas coast because of natural and human-induced land subsidence. It is also clear that the magnitude of the subsidence will continue to contribute a significant portion of relative sea-level rise, even with projected increases in global sea-level rise caused by global warming. Furthermore, just as the rate of global sea-level rise is expected to increase with further global warming, we can expect to experience at least local increases in land subsidence as more hydrocarbon and groundwater extraction occurs. Because of the implications for the sustainability of coastal habitats, determining the patterns, causes, and possible mitigation strategies of natural and man-induced coastal land subsidence should be a priority for future research.

Relative Sea-Level and Shoreline Change Projections

The IPCC (2007) report provides model projections for global sea-level rise based on six greenhouse-gas and aerosol-emission scenarios. The range in the amount of projected global sea-level rise by 2099 relative to the average from
1980 through 1999 is 0.18 to 0.59 m (0.59 to 1.93 ft). After adding estimates for local land subsidence, the amount of projected relative sea-level rise by the year 2100 is 0.46 to 0.87 m (1.51 to 2.85 ft) at Rockport, 0.20 to 0.61 m (0.66 to 2.00 ft) at Port Mansfield, and 0.34 to 0.75 m (1.12 to 2.46 ft) at South Padre Island. These amounts will likely be greater in areas with relatively thick Holocene deposits filling paleoriver channels and tidal inlets, such as along barrier islands and modern deltas at the heads of bays (e.g. Nueces River Delta), and they may be much higher where subsidence caused by groundwater and hydrocarbon extraction occurs.

Depositional subenvironments of barrier islands and bay margins are the substrates for various types of aquatic, wetland, and upland habitats. These subenvironments and associated habitats are closely linked to elevation relative to sea level through the processes that form and maintain them. On the low-lying, sandy, barrier islands of the microtidal (tide range 0.6 m (1.97 ft) on the open coast and less than 0.3 m (0.98 ft) in the bays) South Texas coast, a rise of just 0.1 m (0.32 ft) in relative sea level can cause conversion of fringing low marshes and flats to open water and seagrass beds, and usually dry high marshes and flats to usually wet low marshes and flats (Gibeaut et al. 2003).

Mustang Island is a barrier island at the mouth of Corpus Christi Bay (Figure 1). Most of the island, except for the tallest foredunes, is less than 3 m (9.84 ft) above sea level, which is typical for the barrier islands along the South Texas coast. Inundation of Mustang Island by relative sea-level-rise amounts projected for 2100 are depicted in Figure 2. Even a rise of just 0.46 m (1.51 ft) will cause lateral shifts of 1 to 2 km (0.62 to 1.24 mi) of bay-side wetland environments. The upper bound rise amount of 0.87 m (2.85 ft) will narrow the upland areas of the island to a width less than 200 m (656.17 ft) in places and flood central portions of the City of Port Aransas on the north end of the island.

Actual shoreline retreat and loss of wetland areas on South Texas barrier islands will depend not just on relative sea-level rise but also on
1) whether vertical sediment accretion can keep up with the rise,
2) whether adjacent upland slopes are gentle enough for wetlands to migrate landward,
3) whether development obstructs the upward/landward migration of wetlands, and
4) the severity of erosion by waves and currents at the edge of marshes and flats.

Given the observed conversion of tidal flats to open water and seagrass beds and the migration of marshes into higher areas since the 1950s on Mustang and adjacent islands (White et al. 2006), it is unlikely that vertical accretion will offset the effects of an increase in the rate of relative sea-level rise. Upland slopes increase toward the core of the islands, tempering the amount of new marsh that can develop. It is very likely that future development will obstruct new marsh creation, such as occurred at the Padre Isles development beginning in the 1970s (White et al. 2006). Erosion of the outer edges of marshes and flats since the 1930s has caused shoreline retreat in the range of 0.5 to 2.5 m/yr (1.64 to 8.20 ft/yr) along most of the Mustang Island bay shoreline (Morton and Paine 1984; Williams 1999). Erosion by waves may increase as higher water level decreases the amount of wave shoaling and extends wave energy farther landward.

As sealevel rises and barrier islands become narrower, large storms will eventually breach, washover, and transport sand landward into the bays. This process is already happening along low and narrow portions of the South Texas coast, such as Corpus Christi and Newport Passes during Hurricane Beulah in 1967 (Davis et al. 1973) (Figure 2) and along South Padre Island during Hurricane Bret in 1999 (Figure 3). Furthermore, increasing aridity, which climate models predict for this region, has the potential to reduce stabilizing dune vegetation and cause more active dune migration and blowouts, as were observed on north Padre Island and Mustang Island during the drought period of the 1950s (White et al. 1978; Prouty and Prouty 1989). Hurricane intensities have increased recently and may continue to increase with warming of sea-surface temperatures (Emanuel 2005). Hence, rising sea level, increasing aridity, and increasing storm intensity will drive the South Texas barrier islands toward narrower, lower-lying islands that are more frequently washed over and severed by tropical storms similar to present-day Matagorda Peninsula, Texas (Figure 4). Eventually, depending on the actual rate of relative sea-level rise, portions of the South Texas barrier island chain will be destroyed, a scenario similar to the near demise of the Chandeleur Islands in Louisiana following recent hurricanes.
Figure 2. Inundation of Mustang Island. The amounts of sea-level rise depicted here (darker blue color) are expected in 100 years when combining local subsidence estimates with the lower and upper ranges of global sea-level rise projections presented in the IPCC (2007) report. This map was created using aerial photography draped on a high-resolution, lidar-derived digital elevation model. Lidar data acquisition and processing were performed by the Bureau of Economic Geology, The University of Texas at Austin in 2005.
**Figure 3.** Looking towards Laguna Madre at hurricane washover channels on Padre Island, Texas about 4 km (2.49 mi) north of Mansfield Pass. Hurricane Bret formed these channels when it struck on August 22, 1999. More than a dozen other former washover channels were reactivated by Bret. Darker blue indicates sea-level rise flooded areas.

**Figure 4.** Rising sea level, increased storm intensity, and increased aridity will drive the South Texas barrier islands towards narrower, lower-lying islands that are completely washed over and severed by tropical storms as shown here by present-day Matagorda Peninsula, Texas.
Figure 5. Perspective view of inundation of the Corpus Christi Bay area by sea-level rise. These scenarios are reflective of polar ice sheet melting and destabilization triggered by global warming. Topographic relief is vertically exaggerated six times.
The IPCC (2007) climate projections for global sea-level rise discussed previously do not include the full effects of potential changes in polar ice-sheet flow as global warming proceeds. Recent observations of ice-sheet changes suggest the possibility of large contributions to sea-level rise from the flow of Greenland and Antarctic glaciers into the oceans (Rignot and Kanagaratnam 2006; Shepherd and Wingham 2007). Overpeck et al. (2006) compared hundred-year global temperature projections in the IPCC Third Assessment Report (2001) with climatic and sea-level conditions during the last interglacial period about 130,000 years ago. During that time, polar temperatures were 3 to 5°C (5.4 to 9°F) higher than now, causing polar ice to retreat and contribute to sea-level 4 to more than 6 m (13.12 to more than 19.69 ft) higher than today. This amount of warming is within the range projected during the next hundred years by IPCC modeling studies. Therefore, increases in sea-level caused by melting polar ice may be expected to proceed for centuries resulting in sea-level rise of several meters and sea-level rise rates twice those projected in the IPCC (2007) report (Overpeck et al. 2006).

Figure 5 illustrates how a sea-level rise of 2, 4, and 6 m (6.56, 13.12, and 19.69 ft) would each inundate the Corpus Christi Bay area. Today’s barrier islands would be completely submerged with a rise of less than 4 m (13.12 ft). The lower Nueces Delta would be submerged with a 2-m rise (6.56 ft), and the entire delta and lower river valley would be submerged with a 6-m rise (19.69 ft). Pleistocene bluffs and the relict Pleistocene delta-plain surface more than 6 m (19.69 ft) high confine the sea around the upper portions of Corpus Christi and Nueces bays and the Nueces River Valley. The Ingleside Barrier (Figure 5) is a relict barrier-strandplain system deposited about 120,000 years ago during the last interglacial period when sea level was 5 to 8 m (16.40 to 26.25 ft) higher than today (Wilkinson et al. 1975; Brown et al. 1976; Paine 1993). Even though the Ingleside Barrier has probably subsided several meters since its formation (Paine 1993), it is still emergent at elevated sea levels and may serve as the core for a future barrier-island system. It is important to note that simply raising the ocean level, as in Figures 5 and 6, does not reveal a realistic shape for the future shoreline because waves and currents will redistribute the sediments during the rise and constantly reshape the shoreline, with a tendency to smooth it.

**Figure 6.** Inundation of land if the level of the sea were to rise 6 m (19.69 ft) above present level. Lighter blue shows the present bays and lagoons and the darker blue depicts inundated areas. This scenario is reflective of polar ice sheet melting and destabilization triggered by global warming during the next 100 years resulting in sea level rise rates of 10 mm/yr or more for centuries. Constant redistribution of sediments by waves and currents during sea-level rise would tend to smooth the shoreline, but that process is not reflected in this map.
Figure 6 depicts inundation of the South Texas coast if sea level were to rise 6 m (19.69 ft). In this scenario, the barrier islands are completely inundated, and the sea advances about 20 km (12.43 mi) inland from the bay margins except where sufficiently high Pleistocene bluffs and uplands exist. River valleys and deltas at the heads of secondary bays are flooded. White et al. (2002) showed that vertical accretion rates on the Nueces Delta are less than the rate of relative sea-level rise today. It is unlikely that vertical accretion rates will be sufficient to maintain wetlands on the South Texas deltas if relative sea-level rise rates increase to 10 mm/yr (0.39 in/yr) or more, as would happen in the Figure 6 scenario. If polar ice-sheet destabilization should occur, therefore, we can expect massive losses of critical wetland habitat in the bays.

**Ecosystem Changes**

**Freshwater Inflow and Estuarine Functioning**

The estuaries of Texas are remarkably hydrologically diverse in spite of similar geomorphology. This is due to a climatic gradient, which influences freshwater inflow to estuaries. The gradient of decreasing rainfall, and concomitant freshwater inflow, from northeast to southwest, is the most distinctive feature of the coastline (Table 2). Along this gradient, rainfall decreases by a factor of two, but inflow balance decreases by almost two orders of magnitude. Inflow balance is the sum of freshwater inputs (gaged, modeled runoff, direct precipitation, plus return flows) minus the outputs (diversions and evaporation). The net effect is a gradient with estuaries with similar physical characteristics but a declining salinity gradient.


<table>
<thead>
<tr>
<th>Estuary</th>
<th>Area (km²)</th>
<th>Rainfall (cm y⁻¹)</th>
<th>Inflow (10⁶ m³ y⁻¹)</th>
<th>Salinity (ppt)</th>
<th>Commercial Harvest</th>
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<tbody>
<tr>
<td>Sabine-Neches</td>
<td>183</td>
<td>142</td>
<td>16,897</td>
<td>8</td>
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<td></td>
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<td></td>
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<td></td>
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Freshwater inflow patterns appear to group into four distinct climatic subregions, which vary by about an order of magnitude each (Figure 7). The northeastern most subregion is composed of the Sabine-Neches Estuary (containing Sabine Lake) and the Trinity-San Jacinto Estuary (containing Galveston Bay). This northeastern subregion has the highest rainfall and inflow balance greater than 10¹⁰ m³ y⁻¹. The next three climatic subregions form the largest area and contain five estuaries linked by large lagoons, extending from the Colorado River to the Rio Grande. The most well known lagoonal estuary is Laguna Madre. The climatic subregions are distinct in several ways. Most important is a lack of connection between the watersheds, thus each bay system is fed by different rivers. The Intracoastal Water Way provides a man-made, dredged channel linking all subregions. The Lavaca-Colorado Estuary (containing Matagorda Bay) and Guadalupe Estuary (containing San Antonio Bay) have an average inflow rate of about 10⁶ m³ y⁻¹. The Mission-Aransas Estuary (containing Aransas Bay) and Nueces Estuary (containing Corpus Christi Bay) have an average inflow rate of about 10⁸ m³ y⁻¹. Laguna Madre is a negative estuary because evaporation exceeds inputs and has an average negative inflow rate of about 10⁸ m³ y⁻¹. Thus the region spans positive, neutral and negative estuaries.
There is also a concomitant gradient of different timing of peak inflow events (Figure 8). The northern estuaries receive peak inflow during the spring, the central estuaries are bimodal receiving peak inflows during the spring and fall, and the southern most estuaries receive peak inflows during the fall. These distinct patterns are very important ecologically, because growth, reproduction, and migration of many species is keyed to seasonal events. The timing and magnitude of inundation is believed to regulate finfish and shellfish production (Texas Department Water Resources 1982). The differences within and among the subregions and estuaries of Texas provides a sufficiently broad scale to examine effects of climate change and variability on ecological processes.

The latitudinal gradient of decreasing inflow into estuaries regulates salinity. As well as a latitudinal climatic gradient, there is a longitudinal salinity gradient within each estuary. The salinity gradient within and among the estuaries has already been demonstrated to regulate the infaunal molluscan community (Montagna and Kalke 1995). There are also salinity gradients within the estuaries from the river mouth to the sea, which influences the zonation of communities found within the estuaries (Kalke and Montagna 1991; Montagna and Kalke 1992; 1995). The interactions among the geophysical factors of climate, estuarine physiography and diversity of habitat types in the Gulf of Mexico are factors that influence diversity of the region.

Another characteristic of Texas estuaries is the extreme year-to-year variability in inflow\(^1\) (Figure 9). Consequently, salinity gradients within estuaries vary from year-to-year. The southwestern estuaries in particular appear to be in a nearly desert climate that is punctuated by flood events. The floods are caused by tropical storms or larger global climate patterns. The El Niño Southern Oscillation (ENSO) has a strong influence on inflow to Texas estuaries. The Southern Oscillation Index (SOI)\(^2\) is negative during El Niño events. There is an inverse correlation between SOI and total inflow to the Texas coast (-0.14, \(p = 0.004\)). The inverse correlation between smoothed SOI and smoothed total inflow to the Texas coast is strong (-0.47, \(p < 0.001\)), but inflow is always highest when the SOI is negative (Figure 10). The ENSO phenomenon is only one climactic factor affecting inflow. Inflow is also influenced by tropical waves, which affect the coast from the east.

The importance of ENSO events on driving regional-scale climatic variability and salinity structure in Texas estuaries is now

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\(^{1}\) http://hyper20.twdb.state.tx.us/data/bays_estuaries/hydrologypage.html

\(^{2}\) http://www.cgd.ucar.edu/cas/catalog/climind/soi.html
reasonable well understood (Tolan 2007). The ENSO signals are correlated to salinity structure within Texas estuaries within four to six months. During El Niño events, salinities in Texas estuaries decrease because of increased freshwater flows to the coasts. During La Niña periods, salinities increase because of the drier climatic conditions. These cycles occur with a periodicity of 3.55, 5.33, and 10.67 years. The ENSO is dominated by the 3.55- and 5.33-year periods and the 10.67-year period is defined by the Pacific Decadal Oscillation.

![Figure 9](image)

**Figure 9.** Total inflow of Texas Coast and Southern Oscillation Index (SOI). Bottom panel contains trends smoothed (using polynomial regression and weights computed from the Gaussian density).

The Texas coast is likely an ideal area to study climate change effects on estuaries, because it already is a natural experiment. There is physical similarity among Texas estuaries, each is simple draining only one or two watersheds, and they lie in a climatic gradient that is influenced by large-scale climate patterns in the Pacific and Atlantic Oceans. Being semi-arid
and semi-tropical, small changes in global temperature will likely have large effects. For example, there has already been a 1.4°C (2.52°F) rise in surface temperatures of Corpus Christi Bay between 1982 and 2002, which correlates with a decrease in surface water oxygen content by 1.2 mg/L (Applebaum et al. 2005). Further, it is simple to pose hypotheses, e.g., drier conditions will result in estuaries more like the southwestern estuaries, and wetter conditions will result in estuaries more like those to the northeast. It will be possible to design stratified sampling programs where statistical control can be used on confounding factors, e.g., watershed drainage basins, anthropogenic inputs, Gulf of Mexico exchange, specific habitats, circulation patterns, and alterations by man.

**Habitat Change**

Several federal and state agencies are charged with tracking or monitoring the environment along the Texas coast.

- The National Oceanic and Atmospheric Administration (NOAA) monitors estuarine-dependent species and their habitats.
- Texas Parks and Wildlife Department (TPWD) monitors coastal fisheries and related species,
- Texas General Land Office (TGLO) maintains and operates many coastal programs and is in charge of all Texas coastal submerged lands,
- Texas Commission on Environmental Quality (TCEQ) monitors air and water quality along the coast,
- Texas Water Development Board (TWDB) conducts research on freshwater inflows and impacts to Texas estuaries, and
- the Bureau of Economic Geology (BEG) at the University of Texas at Austin conducts research on the status and the trends of coastal habitats as well as shoreline erosion and sea-level rise issues/impacts.

TPWD maintains and operates one of the longest-running coastal monitoring programs in the world (since late 1970s) on coastal living resources, and BEG has one of the strongest and most extensive mapping and coastal characterization programs in the United States. Both of these programs, and the others mentioned above, allow for accurate spatial and temporal tracking of Texas coastal natural resources.

Previous NOAA studies along the upper Texas coast provide a vision of future or predictive scenarios for South Texas coastal species, habitats, and productivity. During the 1980s, extensive studies on salt marshes revealed a glimpse of what might happen to species and secondary productivity when sea-level rise occurs (Zimmerman et al. 1991). Initial or slow flooding of these salt marshes will stimulate growth and abundance of algae, which in turn increases primary consumers and then secondary consumers. Large predatory species may also increase in size and abundance. However, these changes may be transitional or short term, and the benefits can disappear when drowning marshes convert to open-water habitats without plants (Zimmerman et al. 1991).

Subsidence of coastal land and salt marshes in the Houston-Galveston area actually revealed the above example, but it provides an excellent model of relative sea-level rise impacts on coastal marshes and associated species. Likewise, compilations of data prepared by the Texas BEG and analyzed by the TWDB show the potential changes and relationships between climate and estuaries along the Texas coast (Longley 1995). Under varying climatic scenarios, changes in climate drive changes in freshwater inflow, bay salinity, and sea-level rise. All of these, in turn, impact change or shifts in the distribution and coverage of certain coastal habitats.

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**Figure 10.** Linear regression relationship between average coast-wide inflow and the SIO index. Same data as plotted in Figure 9.
Figure 11. The area of habitat type as percent of total habitat area as a function of different freshwater inflow regimes within each Texas estuary (Table 1, Longley 1995). Freshwater inflow regime is represented as annual freshwater inflow/estuarine volume in units of year. A, B, and C fitted with exponential growth model; D and E fitted with exponential decay model; and F fitted with log normal model (Montagna et al. 2002).
Although, mapping of coastal habitats today is highly accurate with the use of digital aerial photography and Geographic Information Systems (GIS) software, comparisons to older maps and aerial photography less precise. Consequently, trends or directions of habitat change, rather than the actual aerial change or coverage, is more realistic. Longley (1995) gives the current trends in selected coastal habitats within estuaries with increasing freshwater inflow regimes (Figure 11). The inflow regime is represented as the freshwater replacement times per year (1/y), because it is calculated by dividing the freshwater inflow rate (ac-ft/y) by the estuary volume (ac-ft). The replacement rate is analogous to the inverse of the residence time, thus a value of one means that the once per year.

Each point in Figure 11 matches the established percent of habitat coverage within each of the seven estuaries along the Texas coast (Table 1). Long-term inflow changes, and thus habitat change, can occur as a result of increased water use due to human population increases, decreased run-off caused by increased evaporation due to higher temperatures, and increased or decreased run-off depending upon regional changes in precipitation (Longley 1995). Thus, if climate change causes the freshwater inflow regimes to change, then habitat composition within estuaries will change.

As freshwater regime increases, four habitats (freshwater marsh, swamp, saltwater marsh, and oyster reefs) increase by exponential growth models (Figure 11). However, if bays become too fresh because of very high inflow rates (as in Sabine Lake), then oyster populations plummet. The concept that there is an optimal flow and salinity range and maximum carrying capacity for bottom-dwelling organisms, such as oysters, has been shown to be true in the Nueces Delta where data fit a three-parameter log-normal model well (Montagna et al. 2002). Increasing freshwater is bad for some organisms. Seagrass and wind tidal flats decrease exponentially with increasing freshwater inflow regime (Figure 11).

Coupled with freshwater inflow increases or decreases affecting habitat change, sea-level rise is the other substantial driver. Estimates of sea-level rise vary greatly, making credible estimates of changes in habitats difficult. However, trends or direction of change can be predicted with some certainty and resultant consequences can be instructive for natural resource managers. Rising sea-level will cause more frequent and longer inundation of fresh marsh, swamp, and salt-brackish marshes. As fresh marshes and swamps are flooded by saline waters they will be converted to salt-brackish marshes, and eventually open water.

From the Coastal Bend throughout the Laguna Madre, wind-tidal flats could spread inland in low-lying areas. Former wind-tidal flats will convert to seagrass beds in many areas (e.g. land-cut, backside of South Padre Island) as the sea transgresses over this habitat. Seagrass beds will increase in shallow areas where they take over former wind-tidal flats, but they will be lost in deeper water (greater than 1 m) where sufficient light cannot penetrate.

Also, sea-level rise will increase the overall volume of the bays and lagoons, thereby decreasing the ability of freshwater inflows to maintain current salinity regimes (Longley 1995). The higher salinities found in South Texas bays and lagoons (Corpus Christi and Laguna Madre) would “migrate” up the Texas coast/in this scenario.

One critical element in the continued inundation of the coast would be when the sea-level “hits” the minor and major bluffs along shorelines. In addition to the erosion of the mainland, increasing water depth at this steep increase in shoreline elevation would cause termination of the shallow waters necessary for certain habitats (salt marshes, mangroves, wind-tidal flats, and seagrass beds).

Using the Texas Coastal Bend as an example of habitat trends over the past fifty years, we can see increases in estuarine marshes, mangroves, and seagrasses. Concomitantly, we see decreases in tidal flats and Gulf beach habitat, and palustrine marsh remains about the same (White et al. 2006) (Figure 12 and Table 3). The authors of this work stress that they are more confident in the direction of these trends than absolute magnitude (primarily due to the lack of accuracy in dealing with vintage aerial photos and subsequent maps). Their project, involving status and trends of wetlands and aquatic habitats on barrier islands and adjacent bays, covered the entire Texas coast and separate reports delineate changes by coastal region (White et al. 2002, 2004, and 2006).

Mangroves are a good example of species that are likely to increase their range extension because of increased temperatures. For example, early maps of the distribution of black mangroves (*Avicennia germinans*) indicated there were only 65 acres (02.63 km²) of mangrove habitat in the Mission-Aransas estuary (NOAA 2006). However, it is likely that there are closer to 15,000 to 21,500 acres (60.70 to 87.01 km²) of mangroves in just the Mission-Aransas estuary alone. This change has occurred primarily within the last twenty years. At one time, the northern range limit of black mangrove was thought to be the Aransas Bay area. Mangroves are also sensitive to changes in elevation and thus would be greatly affected by sea-level rise and erosion. But other more dramatic changes may be in store. Since the hyperactive hurricane season of 2005, red mangroves (*Rhizophora mangle*) have started to take root in several sites along the Texas coast ranging from South Padre Island to Matagorda Island. These are still living as of this writing, and could become well established if winter
temperatures remain above freezing. In the recent past, red mangroves have been restricted to tropical climates in Mexico and south Florida. The mangroves can be a sentinel species for temperature change effects along the Texas coast.

Figure 12. Areal distribution of major habitats in the Texas Coastal Bend in the 1950s, 1979, and 2002-2004 (Table 2, White et al. 2006)
Species ranges are expected to change with changing climate. In some cases these will be extensions of tropical species northward due to increasing temperatures. In other cases, the changes will be related to salinity changes that limit the range of distribution of oligohaline and brackish species.

Table 3. Total area of major habitats in the 1950’s, 1979, and 2002-04 in the Texas Coastal Bend (from White et al. 2006)

<table>
<thead>
<tr>
<th>Habitat</th>
<th>1950s</th>
<th>1979</th>
<th>2002-2004</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ha</td>
<td>acres</td>
<td>ha</td>
</tr>
<tr>
<td>Estuarine Marsh</td>
<td>1,763</td>
<td>4,356</td>
<td>3,087</td>
</tr>
<tr>
<td>Mangrove</td>
<td>*</td>
<td>*</td>
<td>665</td>
</tr>
<tr>
<td>Tidal Flat</td>
<td>13,647</td>
<td>33,722</td>
<td>6,114</td>
</tr>
<tr>
<td>Seagrass</td>
<td>4,167</td>
<td>10,297</td>
<td>7,704</td>
</tr>
<tr>
<td>Palustrine Marsh</td>
<td>665</td>
<td>1,643</td>
<td>890</td>
</tr>
<tr>
<td>Gulf Beach</td>
<td>861</td>
<td>2,128</td>
<td>630</td>
</tr>
</tbody>
</table>

* = not mapped

Species Changes

Changes in abundance of oligohaline and brackish species are good examples of recent changes that are likely due to increased salinity in Texas estuaries. For example, in Gulf coast estuaries, the clam *Rangia cuneata* has long time been recognized as the dominant benthic animal in areas where salinity ranges from 0 - 15 ppt salinity. In recent studies of Rincon Bayou, in the Nueces Delta Texas, salinities now can be hypersaline, up to 100 ppt and *R. cuneata* is never found alive (Montagna et al. 2002). However, middens of *R. cuneata* were found in the Nueces Delta (Bureau of Reclamation 2000). Middens are piles of shells, which were created by local indigenous people as they feasted on the clams. Most of the clam shells exhibit brakes or marks consistent with those made to open the shell for the meat inside. The middens are composed of clams that are uniform in size 51 cm ± 1.6 cm. (20.08 ± 0.63) Based on published growth rates, these clams are likely five years old. The maximum life span of *Rangia* is fifteen to twenty years. *Rangia* shells this old (about five years) were most likely produced by a large, successfully recruiting population, existing in brackish water conditions for extended periods of time. This is in sharp contrast to current conditions in the Nueces Delta. Two dams were built and the sides of the Nueces River have been diked so fresh water does not spill into the delta. The delta is now hypersaline for extended periods of time and is a reverse estuary. The hypersaline conditions simply result from reduced inflows. The reverse estuary is caused by freshwater entering Nueces Bay below the delta and high tides flooding fresh water into the hypersaline delta. Thus, salinities typically decline toward the lower reaches, not the upper reaches of the delta. The presence of extensive middens indicates the delta benthic community has changed dramatically since dams were built and freshwater inflow has been reduced. The presence of hypersaline and reverse estuary conditions indicate wetland habitats no longer provide historical functions. Thus, if climate change alters inflow patterns such that salinities increase, then it can be expected that similar changes would be common.


McEachron, L. W. and B. Fuls. 1996. Trends in Relative Abundance and Size of Selected Finfishes and Shellfishes along the Texas Coast. *Coastal Fisheries Division, Management Data Series* Austin, Texas.


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Withers, K. and J. W. Tunnell, Jr. 1998. Identification of Tidal Flat Alterations and Determination of Effects on Biological Productivity of These Habitats Within the Coastal Bend. *CCBNEP* (26) Corpus Christi, Texas.

