To reach the sustainable use of aquatic ecosystems, we must first understand the interrelationship between different physical and biological components controlling the functioning and dynamics that regulate the systems. This ecosystem approach is especially applicable in coastal environments because they are the final destination of all drainage basins regardless of whether the basins are superficial or underground; the hydrological connectivity between inland and coastal marine ecosystems is strong. This connectivity must be acknowledged in all coastal environments analyzed using the ecosystem approach.

In contrast, coastal environments, in addition to the human problem of drinking water supply, have other problems such as rapid urbanization, destruction of wetlands (including salt marshes, sandy beaches, and mangroves), and health issues caused by pollution, collapsing artisanal and industrial fisheries, salinization and pollution of aquifers, siltation and hindrance navigation, increasing muddiness of waters, and decreased biological productivity. All these problems result in coasts that are inhospitable and where sustainable activities are impossible, especially tourism and enjoyment of life.

Because of the multitude of factors involved for accomplishing sustainable use and conservation of coastal areas, a multidisciplinary and holistic approach is necessary, including different spatial (regional and local; from river underground basins to estuarine and coastal areas) and temporal scales (short and long-term; pulse events, seasonal, and interannual). These must be integrated with human population dynamics to provide holistic management and enhance the capacity of coastal ecosystems, for example, to resist human impacts, maintain resilience to natural events such as hurricanes, and improve ecosystem resistance to sea-level rise. The coastal zone of Yucatan is a typical example of rapid development generated by both domestic and foreign activities, which have produced considerable negative environmental changes, some of them irreversible (Herrera-Silveira et al. 2004).

The Yucatan Peninsula, a region of the Gulf of Mexico, is a great calcareous mass located in the tropical zone, and despite it having been described as a unit, this region has different geomorphology, ecosystem processes, and human impact within its 3 subregions (Caribbean, north, and west coasts). Therefore, up-to-date knowledge regarding the ecosystem characteristics, human dynamics, and usage trends of the Yucatan Peninsula is important for promoting the realization of the local, state, and federal policies on the coastal resources management of this region of the Gulf of Mexico, under the integrated coastal zone management framework. The objective of this chapter is to present an overview of the ecological characteristics at a regional and subregional level, human dynamics, various management strategies, and environmental consequences, and to suggest alternative strategies for future use.
System Description

The Yucatan Peninsula is a 400,000 km² flat, limestone terrace, located in southeastern Mexico, with a 1250 km-long coastline; the eastern side faces the Caribbean and the northern and western parts face the Gulf of Mexico (Fig. 12.1). This region, including its submarine shelf, Campeche Bank, is susceptible to rapid and constant disintegration by chemical erosion through carbonate rock dissolution, which gives rise to large caves, such as sinkholes (cenotes), and submarine caves; therefore, it is a karst province. The soil is very thin and has no rivers only groundwater flows that discharge mostly in the northeastern, north-central, and northwestern coastal areas of the peninsula to wetlands and coastal waters (Fig. 12.2).

Because of its geographic tropical location, the atmospheric climate of the peninsula varies little with an average annual temperature of 26 °C, a dry season (January–May) and a rainy season (May–October), and strong northern winds (nortes, November–January) that are a milder version of extratropical storms. Climate ranges from humid in the south (precipitation of 2000–3000 mm/yr) to arid in the north (400 mm/yr).

The Yucatan Peninsula is an excellent region for comparing characteristics and processes among coastal lagoons, coastal seas, mangroves, seagrasses, and coral reefs. This is because: (1) coastal lagoons of a spectrum of sizes and shapes; (2) different effects of regional forcing functions on the east, north, and west coasts; (3) different sea connections, freshwater inputs, and human activities of the coastal ecosystems; (4) the tropical climate that ranges from arid to humid; and (5) areas that could be affected differently by natural events such as hurricanes.

The structure and functioning of the coastal ecosystems of the Yucatan Peninsula are controlled through interactions among regional (i.e., Yucatan Current) and local forcing functions (i.e., Cabo Catoche upwelling and groundwater discharges), as well as pulsing events ranging from high-frequency low-intensity events (i.e., tides) to low-frequency high-intensity events (i.e., hurricanes).

Regional Forcing Functions

To understand the relative importance of the regional and local forcing functions in the coastal zone of the Yucatan Peninsula, a general description of these functions according to their spatial and temporal influence follows.

Yucatan Current

The Yucatan Current is the main source of water and other inputs to the Gulf of Mexico and enters through the Yucatan Strait. This current has a south–north direction with an average speed of 1.5 m/s (Fig. 12.3). Its waters are warm and very clear, which favors development of fringe reefs in the Mexican Caribbean, which are part of the second largest barrier reef in the world—the Mesoamerican Barrier Reef System. The current moves sediments from south to north, as shown by sand accumulation in the barrier island and sand beaches as a response to the coastal circulation patterns generated by coral reef distribution and bottom relief. This forcing function is continuous; it contributes to functioning of the Yucatan coastal ecosystem by the transport and dispersion of chemical (salinity, nutrients, and dissolved organic matter) and biological (transport of larvae) materials and pollutants (hydrocarbons, heavy metals, and pesticides) that can come from river basins in Central America (Monreal-Gómez et al. 2004; Enriquez et al. 2010).

Littoral Yucatan Current

At least 2 currents result from the Yucatan Current: the Lazo Current, which is the origin of the Gulf Stream, and the littoral current of Yucatan, which later enters the Gulf of Mexico with a mean temperature of 25 °C and a mean salinity of 35. This current flows east-to-west at an average speed of 0.12 m/s (I. Mariño, CINVESTAV, personal communication, 2004) (Fig. 12.3). Breaking waves are weak but generate beach currents that move considerable amounts of sediments, which can be observed as
sand accumulations that form a barrier island parallel to
the coast that separates the sea from coastal lagoons and
other water bodies. The Yucatan Current is continuous
and its contribution to the ecosystem functioning of the
Yucatan Peninsula is related to the transport and disper-
sion of chemical (salinity, nutrients, and dissolved organic
matter) and biological variables (transport of larvae), and
pollutants (hydrocarbons, heavy metals, and pesticides).
These can enter the Gulf of Mexico through the Yucatan
Current and submarine groundwater discharges (Troccoli
et al. 2004).

Influence from the Gulf of Mexico
This forcing function originates in the water mass that
is formed in the Gulf of Mexico during winter, when
passing cold fronts produce a convective mixed layer at
200-m depth that reduces water temperature (22 °C) and
increases salinity (36.4) (Monreal-Gómez et al. 2004) and
produces a northeasterly current (Fig. 12.3). In the coastal
marine area, this forcing function significantly reduces
water temperature and transparency through turbulence generated by strong winds and increases chlorophyll-a concentration through resuspension of the microphytobenthos (Troccoli et al. 2004). This forcing function is seasonally important during the nortes fronts, which last between 3 and 5 days, and should be considered as a pulsing event. Its contribution to the coastal ecosystem functioning of the Yucatan Peninsula could be related to nutrient recycling and dispersion of organic matter that accumulated during the previous growing season of the primary producers (phytoplankton and submerged aquatic vegetation) (Aguayo 2004; Herrera-Silveira et al. 2004; Herrera-Silveira and Morales-Ojeda 2009).

**Submarine Groundwater Discharges (SGD)**

The Yucatan Peninsula, as a karstic province, has characteristics of an almost free infiltration of rainwater to the aquifer, which is why it has an important net of underground water. The final destination of this underground water is the coastal water through point (springs) or diffuse sources (seeps). Therefore, the main freshwater inputs to the coastal ecosystems in the Yucatan Peninsula are through submerged groundwater discharges. The volume of water discharged in the coastal zone has been estimated between $8.6 \times 10^6$ and $12 \times 10^6 \text{ m}^3 \text{ km}^{-1} \text{ yr}^{-1}$ (Hanshaw and Back 1980).

Low water temperatures and high nitrate and silica concentrations (Table 12.1) suggest that the quality of SGD is relatively poor (Herrera-Silveira 1994). The aquifer is polluted because 92% of the urban areas use septic tanks for wastewater, agriculture uses fertilizers and agrochemicals with no appropriate regulation, and during the last 10 years, cattle activity has increased (poultry, pig, and shrimp farms) without wastewater treatment systems. Human activities in the inland region of the Yucatan Peninsula are responsible for the groundwater pollution that reaches the coastal ecosystems (Aranda-Cirerol 2004). The spatial distribution of SGD is not homogeneous. At a regional level, satellite image analyses of surface-water temperature show that the north coast of the Yucatan Peninsula receives the largest quantities of these discharges and has lower mean temperatures (Paat 2005).

The contribution of SGD to the coastal ecosystem functioning of the Yucatan Peninsula is related to nutrient dynamics. The composition and abundance of organisms such as phytoplankton and submerged aquatic vegetation, risk of eutrophication, and the increasing frequency, extension, and duration of harmful algal blooms are related to these freshwater sources (Troccoli 2001; Aguayo 2004; Hererra-Silveria et al. 2004; Carruthers et al. 2005; Alvarez-Góngora and Herrera-Silveira 2006). Due to the aforementioned issues, a priority for sustainable development of the coastal area of the Yucatan Peninsula is a program to reduce wastewater discharges to the aquifer. According to the land conditions and current technologies, the natural and constructed wetlands are a viable alternative, as demonstrated in other regions of the world (Kadlec and Knight 1996; Day et al. 2004).

**Local Forcing Functions**

To understand the relative importance of the regional and local forcing functions in the functioning of the coastal zone of the Yucatan Peninsula, local forcing functions are described as follows according to their spatial and temporal influence.

**Cabo Catoche Upwelling**

This upwelling appears to follow a seasonal cycle. During spring and summer, when the Yucatan Current is more intense, upwelled water intrudes onto the Yucatan Shelf to create a 2-layered water column. Strong stratification between Caribbean surface water and the Yucatan upwelling water layer on the shelf is likely to prevent mixing among them, except during the winter periods of northern winds. Field observations suggest that this upwelling is probably caused by bottom friction or other topographical mechanisms (Merino 1997). Due to the high aquatic productivity in the upwelling area, abundant marine
fauna such as dolphins and sea turtles is common in spring and summer. This area is probably the most important zone for whale shark (Rhincodon typus) aggregations in the Caribbean region, and it is possible to observe up to 300 whale sharks in the summer.

Subzones of the Littoral Yucatan Current

The Littoral Yucatan Current that runs along the north coast can be divided into 2 subzones (Z-I and Z-II) according to the water masses mixing. The first subzone (Z-I) mainly has waters from the Yucatan Current, though during spring and summer it is possible to observe a mixture of waters from the Yucatan Current and the Cabo Catoche Upwelling that has an influence from Holbox to Dzilam de Bravo (Fig. 12.1). This area’s contribution to the coastal ecosystem functioning of the Yucatan Peninsula is related to nutrient dynamics and productivity because the area has high salinities (35–37) and low silicate concentrations (5–15 μmol/L). Regardless of the high water transparency, phytoplankton biomass is low (Chl-a < 2 mg/m³) and is dominated by species such as Lyngbia sp., Pseudonitzchia seriata, Striatella interrupta, Gyrodinium fusiforme, and Heterocapsa circularisquama, and the submerged aquatic vegetation (SAV) is composed of seagrasses and macroalgae, the latter being dominant.

The second subzone (Z-II) is a mixture of the Yucatan Current and submarine groundwater discharges from point sources such as marine springs (ojos de agua) or from diffuse sources like seeps (Herrera-Silveira 1994; Herrera-Silveira and Comin 2000; Troccoli 2001; Aranda-Cícerol 2004). The subzone influences the area from Dzilam to Celestún on the northwestern coast (Fig. 12.1). Its contribution to the coastal ecosystem functioning of the Yucatan Peninsula is related to nutrient dynamics and productivity and is characterized by lower salinities (25–35) and higher nitrate and silicate concentrations that come from the underground water (Herrera-Silveira et al. 2004). The phytoplankton biomass is higher (Chl-a 2–7 mg/m³) and is dominated by species such as Chaetoceros debilis, Cylindrotheca closterium, Rhizosolenia setigera, Prorocentrum mexicanum, and Scripsiella trochoidea; the SAV is dominated by seagrasses (Thalassia testudinum, Halodule wrightii, and Syringodium filiforme) (Troccoli 2001; Aguayo 2004; Alvarez-Góngora and Herrera-Silveira 2006). The frequency of harmful algal blooms has been increasing along the coast in this zone during the summer.

Campeche Bank Circulation

The Campeche Bank circulation is the result of the Yucatan Current penetrating the Campeche Bank in a southerly direction with low speeds of 0.05 m/s, and the coastal countercurrent in a northerly direction, generating a cyclonic gyre that can be observed in Campeche Bay (Monreal-Gómez at al. 2004). This coastal zone has a stagnation zone from Celestún to Ciudad Campeche. The contribution of this circulation to the coastal ecosystem functioning of the Yucatan Peninsula is related to the nutrient dynamics and productivity, as well as to pollutant transport from oil exploitation platforms in the Gulf of Mexico. The cyclonic circulation and stagnation zone probably contribute to an increase in the residence time of water on the west coast of the Yucatan Peninsula because high chlorophyll-a concentrations (3–7 mg/m³) have been observed that are not related to the observed nutrient concentrations, suggesting that they could result from Langmuir circulation, which favors phytoplankton concentration. The decrease in current speed (from 1.5 to 0.05 m/s) favors high stability of sediments, and extensive areas of seagrass dominated by Thalassia testudinum have been observed.

Historical records indicate that during the Ixtoc1 oil spill in 1979, hydrocarbons were observed on the Celestún coast, east of the spill. This transport of pollutants was evidence of the coastal countercurrent and cyclonic circulation that was later described by Monreal-Gómez and Salas-de-León (1990).

Subregions of the Yucatan Peninsula

According to different classification criteria of the subregions of Gulf of Mexico, the Yucatan Peninsula is usually recognized as a characteristic unit with its own subregions (Yañez-Arancibia and Day 2004; Yañez-Arancibia et al. 2004). Two subregions are recognized in the Yucatan Peninsula. The first is the Caribbean coastline and including the Rio Hondo–Chetumal Bay area corresponding to the state of Quintana Roo. The second includes the northern and western plains of the Yucatan Peninsula, corresponding to the central and northern state of Campeche and the entire state of Yucatan (Fig. 12.1).

A characteristic profile from land to sea is low deciduous forest, mangrove forest, brackish wetlands with freshwater springs, coastal lagoon, sand-dune barrier, beach, coastal sea including sand banks in the Gulf of Mexico,
rent over Campeche Bank when entering the Gulf of Mexico; the speed of the currents depends on the volume of water flowing into the Gulf, which varies between 25 and 35 million cubic meters per second.

Regardless of the above description, from different studies on several components of the ecosystems in the Yucatan Peninsula, we propose the following subregions and descriptions of their main characteristics.

Caribbean Coast Subregion

This region covers the area from the Yalahau Lagoon in the northeast to the mouth of the Rio Hondo in Chetumal Bay. On the Caribbean side, a 200-km coral reef barrier is located 200–1000 m from the coastline. A few carbonate islands are also located near the coast in the northeastern Yucatan Peninsula. The central part of the coastline of the eastern littoral has small rocky cliffs (maximum altitude 40 m). The profile from land to sea (Fig. 12.4) is mangrove forest, coastal lagoons, sand barrier–dune-beach system, coastal sea (reef lagoon), and coral reefs.

The mangrove zone is permanently isolated from any surface connection to the sea, although it is connected to the sea through groundwater. The dominant species are Rhizophora mangle (red mangrove) and Avicennia germinans (black mangrove). The structural development of the forest is characteristic of the scrub and basin mangrove (Lara-Domínguez et al. 2005).
The coastal lagoons are shallow and are covered by seagrass meadows, mainly *Thalassia testudinum*, *Halodule wrightii*, and *Ruppia maritima*. Depending on human influence in these lagoons, the condition of the ecosystem health was based on water quality, seagrasses, and phytoplankton community indicators (Table 12.2).

The sand-dune beach zone is covered by scrub mangrove and sand-dune vegetation with many endemic and endangered species such *Mamillaria gaumeri*, *Nopalea inaperta*, *Cakile lanceolata*, and *Chamaesyce yucatanensis* (Durán et al. 1988). It provides habitat for waterfowl and wildlife, and massive tourist activities have been developed there, mainly in the northern area.

The reef lagoon is shallow (< 10 m depth), covered by seagrass meadows that are dominated by *Thalassia testudinum*, *Syringodium filiforme*, and *Halodule wrightii*. This zone is influenced by groundwater discharges, which may affect nutrient dynamics, salinity, and seagrass structure (Carruthers et al. 2005).

The coral reef is a fringe-type reef located along the eastern coast of the Yucatan Peninsula, close and parallel to the coast for about 400 km. Reefs are distributed in a semi-continuous barrier along the coast, with an intermediate, flat, karstified floor between reef formations. From the central area toward the Belize border, reef structures have what is commonly called a “spur and groove” system. According to geomorphologic criteria (Weidie 1985), the reef presents 3 major zones in profile, from the littoral to the open sea: a reef lagoon (back reef), a crest, and a reef front; these zones can be subdivided into subzones (Gutiérrez-Carbonell et al. 1993).

**North Coast Subregion**

This zone is characterized by a barrier island enclosing shallow, coastal lagoons with no coral reefs, except for Alacranes Reef located 120 km to the north. A profile from land to sea (Fig. 12.5) shows flooded lowland forest, mangrove forest, coastal lagoons, sand-dune beach zone, and coastal sea where submerged aquatic vegetation is an important component (Aguayo 2004).

In the mangrove zone, monospecific or mixed forests of *Rhizophora mangle*, *Avicennia germinans*, and *Laguncularia racemosa* are common, depending on hydrological and sediment variables. Average tree height, density, diameter at breast height, and complexity indices were used to characterize riverine, basin, fringe, dwarf, and hammock mangrove habitat types within this zone. Because this is a hurricane-prone region, areas with vigorous seedling recruitment or mangrove stems growing out of fallen trunks are commonly observed.

The coastal lagoons are shallow; their bottoms are covered with submerged aquatic vegetation and the lagoons are recognized as ecosystems that are important to local fisheries, tourism activities, and waterfowl. Depending on the balance between freshwater (from groundwater) and seawater, we found estuarine, marine and hyperhaline systems, along the salinity gradient. The ecosystem health assessment, including water quality, seagrasses, and phytoplankton community indicators, identified a spectrum of conditions ranging from healthy systems (Dzilam) to lagoons in poor condition (Chelem) (Table 12.2).

The sand-dune beach zone, in several portions of the coast’s endemic dune vegetation (Rico-Gray 1982; Espejel 1987; Durán 1987), provides habitat for waterfowl, and local populations develop tourist activities there. However, foreign tourist activity is growing rapidly.

The coastal sea zone is relatively shallow (10 m deep at 10 km from the coast), and 10–80% is covered by submerged aquatic vegetation. In the eastern region, macroalgae is dominant, but seagrasses are dominant in the central and western regions. This zone is strongly influenced by groundwater discharges that are rich in nitrates and silicates (and possibly other substances), which, in more urbanized areas, like in Progreso and Sisal, water-quality, seagrass, and phytoplankton indicators suggest a eutrophic condition (Troccoli 2001; Aranda-Cirerol 2004; Herrera-Silveira and Morales-Ojeda 2009).

**West Coast Subregion**

The profile from land to sea is grass vegetation mixed with mangrove hammocks, hyperhaline swamp, mangrove forest, and coastal sea with areas of extensive submerged aquatic vegetation (Fig. 12.6). The zone where shrub vegetation and hammocks are mixed is a wetland area. The hammock is a special vegetation type that can only be found in this region, in Cuba, and in some areas in south Florida. Hammocks are dense stands of hardwood trees that grow on natural rises only a few inches in elevation. They appear as teardrop-shaped islands shaped by the flow of water in the middle of the slough. Because of their slight elevation, hammocks rarely flood. Acids from decaying plants dissolve the limestone around each tree island, creating a natural moat that protects the hammock plants from fire. Shaded from the sun by the tall trees, ferns and airplants thrive in the moisture-laden air inside the hammock. This subregion is characterized...
Table 12.2. Hydrobiological characteristics of the coastal lagoon in the Yucatan Peninsula and their water quality, phytoplankton biomass, and submerged aquatic vegetation (SAV) coverage. Ranges of residence time of water are calculated according to LOICZ model (Smith et al. 1999). Nutrients, Chl-α, and SAV (coverage) from Herrera-Silveira et al. 1998; Herrera-Silveira, Jiménez Zaldívar et al. 2002; Herrera-Silveira, Silva-Casarín et al. 2002; Tran et al. 2002; Medina-Gómez and Herrera-Silveira 2003; Arellano 2004; Sima 2004.

<table>
<thead>
<tr>
<th>Lagoon</th>
<th>Surface area (km²)</th>
<th>Residence time (τ; days)</th>
<th>Salinity</th>
<th>DIN (μmol/L)</th>
<th>SRP¹ (μmol/L)</th>
<th>SRSi² (μmol/L)</th>
<th>Chl-α (mg/m³)</th>
<th>SAV (%)</th>
<th>Ecosystem health</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laguna de Términos</td>
<td>1500</td>
<td>56–159</td>
<td>0–37</td>
<td>2–20</td>
<td>0.1–4.8</td>
<td>10–100</td>
<td>1–20</td>
<td>30</td>
<td>Poor in river inlets and surrounding Ciudad del Carmen</td>
</tr>
<tr>
<td>Celestún</td>
<td>28</td>
<td>3–150</td>
<td>5–38</td>
<td>2–58</td>
<td>0.05–2</td>
<td>5–450</td>
<td>0.2–13</td>
<td>70</td>
<td>Fair in inner and middle zones due to ecotourism and fisheries activities</td>
</tr>
<tr>
<td>Chelem</td>
<td>14</td>
<td>3–200</td>
<td>28–44</td>
<td>1–25</td>
<td>0.05–2</td>
<td>10–210</td>
<td>0.4–18</td>
<td>53</td>
<td>Poor in canoe track and east side (Progreso) due to groundwater discharges polluted with nutrients and toxic chemicals</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fair in middle and west side (Chelem) due to ecotourism and fisheries activities.</td>
</tr>
<tr>
<td>Dzilam</td>
<td>10</td>
<td>3–120</td>
<td>5–37</td>
<td>1–33</td>
<td>0.2–2</td>
<td>10–210</td>
<td>0.1–7</td>
<td>80</td>
<td>Despite location far from human activities, general condition is fair due to groundwater discharges polluted with nutrients and pesticides</td>
</tr>
<tr>
<td>Río Lagartos</td>
<td>91</td>
<td>3–350</td>
<td>22–130</td>
<td>1–56</td>
<td>0.05–2.6</td>
<td>5–90</td>
<td>0.1–15</td>
<td>22</td>
<td>Poor in inner zone due to groundwater discharges polluted with nutrients and pesticides</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fair in middle and seaward zone due to fisheries and boating</td>
</tr>
<tr>
<td>Holbox</td>
<td>275</td>
<td>3–185</td>
<td>32–44</td>
<td>2–20</td>
<td>0.05–2.2</td>
<td>5–110</td>
<td>2–9</td>
<td>45</td>
<td>Poor in surrounding Holbox and Chiquila due to groundwater discharges polluted with nutrients and toxic chemicals</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fair in inner zone due to groundwater discharges polluted with nutrients and toxic chemicals</td>
</tr>
<tr>
<td>Chacmochuk</td>
<td>122</td>
<td>3–150</td>
<td>28–40</td>
<td>2–25</td>
<td>0.6–2.4</td>
<td>5–95</td>
<td>0.5–11</td>
<td>70</td>
<td>Fair due to tourism activities and groundwater discharges polluted with nutrients and toxic chemicals</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Poor due to tourism activities and groundwater discharges polluted with nutrients and toxic chemicals</td>
</tr>
<tr>
<td>Nichupté</td>
<td>41</td>
<td>3–100</td>
<td>15–38</td>
<td>4–55</td>
<td>0.05–2.6</td>
<td>2–70</td>
<td>0.1–4</td>
<td>65</td>
<td>Fair due to ecotourism and groundwater discharges polluted with nutrients and toxic chemicals</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fair in inner zone due to groundwater discharges polluted with nutrients and toxic chemicals</td>
</tr>
<tr>
<td>Bojorquez</td>
<td>3</td>
<td>25–150</td>
<td>25–37</td>
<td>3–60</td>
<td>0.3–3</td>
<td>5–60</td>
<td>0.2–4</td>
<td>65</td>
<td>Poor due to tourism activities and groundwater discharges polluted with nutrients and toxic chemicals</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fair in inner zone due to groundwater discharges polluted with nutrients and toxic chemicals</td>
</tr>
<tr>
<td>Bahía de la Ascención</td>
<td>740</td>
<td>3–125</td>
<td>10–40</td>
<td>2–22</td>
<td>0.05–0.8</td>
<td>5–40</td>
<td>0.1–2</td>
<td>80</td>
<td>Fair near Chetumal due to groundwater and river discharges polluted with nutrients and toxic chemicals</td>
</tr>
<tr>
<td>Bahía de Chetumal</td>
<td>1098</td>
<td>3–750</td>
<td>2–20</td>
<td>5–45</td>
<td>0.05–2.6</td>
<td>20–310</td>
<td>0.1–11</td>
<td>15</td>
<td>Fair near Chetumal due to groundwater and river discharges polluted with nutrients and toxic chemicals</td>
</tr>
</tbody>
</table>

¹Soluble reactive phosphate  
²Soluble reactive silicate
by mangrove trees in the form of an “island” of mangrove trees surrounded by a freshwater spring (Trejo-Torres et al. 1993; Karim and Main 2004).

The hyperhaline swamp is an area affected by saltwater intrusion from the sea, where hypersalinity occurs because of scarce freshwater inputs during the rainy period and high evaporation rates. Some areas where the aquifer is nearly at the surface, during the rainy and nortes seasons, are flooded with brackish water, and submerged vegetation such as Chara sp. and Ruppia maritima, make them important areas for waterfowl (D. Alonzo, DUMAC, personal communication, 2010).

Unlike the other 2 subregions, this subregion does not have a sand-barrier island along the entire coast; never-
theless, Celestun and Isla Arenas coastal lagoons are found in the northern zone. In contrast, mangroves in this region are directly in contact with the sea through a fringe mangrove structure dominated by *Rhizophora mangle* without sand beaches. However, hammocks and the fringe mangroves connect through a series of channels that direct freshwater from the springs to the sea. These channels were constructed by the Maya to connect the land to the sea and were used during the Spanish Colonial Period to facilitate the extraction of precious wood (Quezada 1999).

The coastal sea is very shallow (5 m at 10 km from the coast) and is covered by extensive submerged aquatic vegetation (> 80%) that is dominated by *Thalassia testudinum* and *Syringodium filiforme*. This area has an estuarine salinity pattern, with low salinities along the coast and higher salinities toward the sea. This is because it receives freshwater inputs from springs, channels, and surface runoff. During the rainy season an extensive area of red water, may be observed that is due to tannins from the mangrove areas. The conservation status of ecological conditions in the area are good, thus characteristics such as widespread coverage of submerged aquatic vegetation could result in development of important fisheries areas in the adjacent marine zone.

### Human Impacts on the Ecosystem

The coastline and hinterland of tropical and subtropical countries have been subjected to increased use by humans, particularly for recreation and tourism. An analysis of the various uses provided information to design a prospective plan on the bases of sustainability of natural resources, socioeconomic benefits, and ecosystem services. Coastal wetlands of the Yucatan Peninsula, such as mangroves, *petenes*, coastal lagoons, swamps, sand-dune beach zone, coastal sea, seagrasses, and coral reef ecosystems, provide critical habitats for wildlife and support economic activities such as fisheries, hunting, tourism, ecotourism, mining, and commerce.

Factors that have likely harmed ecosystems on the Yucatan Peninsula coasts, reducing environmental services and endangering the goal of sustainable development include: (1) lack of information regarding the functioning of the coastal ecosystems; (2) poor communication between local, regional, and international environmental protection agencies; (3) the low level of environmental education of the local coastal inhabitants; (4) the overlapping authority of municipal, state, and federal agencies; and (5) the lack of compromise between local and foreign investments and the environment. We and other researchers (Herrera-Silveira et al. 2004; Yáñez-Arancibia et al. 2004) have proposed using the integrated coastal zone management approach to solve environmental problems within a sustainable management framework.

### Traditional Uses

A few Mayan cities have been developed along the east coast of Yucatan, including Tulum which was an important Mayan center during pre-Hispanic times. A few other settlements developed in the north, including on the islands of Cozumel and Isla Mujeres, and less important Mayan ruins are located on the west and north (Xcambo) coasts. However, the Mayans extracted salt from evaporative areas in the lagoons on the Gulf of Mexico side. Manual and traditional fishing was also practiced in the sea and coastal wetlands before the 16th century (De Landa 1985).

Post-Hispanic colonization of the peninsula coastline occurred between the 17th and 19th centuries, mostly in the west, after the establishment of 2 major urban centers, Champoton and Campeche. Río Hondo and the Chetumal Bay in the southeast were relatively densely populated during the Mayan period, with commercial and war-related activities during Hispanic times (Chenaut 1985).

None of these land settlements appeared to have created substantial environmental problems. For example, port structures are absent in Mayan ruins, and it is thought that Mayan navigation techniques were very simple. However, war during the 17th and 18th centuries on the southwestern and southeastern coasts may have affected local environments through accumulation of metallic arms and sunken ships.

### Recent Land Use

Until recently, the socioeconomic structure of the human population in Yucatan Peninsula was based on exploitation of terrestrial ecosystems, including agriculture and cattle ranching. Toward the end of the 19th century and during the first half of the 20th century, activities in the coastal zone included artisanal fisheries in lagoons and the sea, particularly in the western and eastern littoral, and salt extraction continued in the northern part. Coconuts were another exploited resource. Harbor activities
in the coastal towns (Champoton, Campeche, Celestún, Sisal, Progreso, El Cuyo, and Chetumal) consisted mainly of the export of natural products produced inland and fisheries activities. The city of Progreso was founded in 1878 following a governmental decision to move the maritime customs office 40 km to the east of Sisal and to establish a harbor closer to the main area of fiber production (*henequen*, *Agave americana*) for export to other countries. Progreso's population in 1900 was 8832, and grew to 13,785 in 1940. This rapid growth was due to substantial migration of people from inland to Progreso stimulated by official facilities for settlement in the newly created harbor (Chenaut 1985). The number of inhabitants of Sisal (former harbor) decreased from 997 in 1861 to 160 in 1940. With these exceptions, the same socioeconomic structure prevailed during the first decades of this century. With the exception of a few roads built perpendicular to the coast to facilitate transport to the harbors, the physical characteristics of the coastal zone were not significantly altered. By 1950, the only paved road was from Merida to Progreso. In summary, most of the coastal zone was naturally preserved until the 1950s.

After World War II, an economic crisis affected *henequen* production, a major socioeconomic activity in the peninsula during the end of the 19th century and first half of the 20th century. During the 1970s, state and national development programs were launched during the 1970s to promote a diversification of the economy. The Integral Program for Rural Development promoted the displacement of *henequen* farmers from inland to the coast. Most of these farmers moved to the northwestern coast because people there had more marine experience. Most people living near the eastern coast were not familiar with marine activities because they were descendants of Mayans who had migrated into what is now Quintana Roo during the Ethnic War of the 19th century.

Activities, Land Use, and Impacts in the Subregions

During the 20th century, the population of the Yucatan Peninsula, increased faster than the average rate in the rest of Mexico, mainly due to migration from other Mexican states. The rate of population growth was higher in the state of Quintana Roo than in either Campeche or Yucatan (Fig. 12.7). This population increase has generated changes in traditional activities and land use of the coastal zone; consequently, the amount of change from different sources varies along the coast. However, due to the ecological structure and functioning of the subregions described earlier, the coastal ecosystems offer similar environmental services and uses, in some cases, and different services and uses in others, which reflect the human population distribution and activities (Fig. 12.8). Thus, their response to change and their resilience should be different.
Caribbean Coast Subregion

Large-scale tourist development began at the end of the 1970s in the sand barrier of the Nichupte coastal lagoon (Cancún) in the northeast, which extends 150 km along the coast toward the south (Cancún–Tulum Corridor) and to the nearshore islands (Cozumel and Isla Mujeres). This tourist development encouraged human migration from other Mexican states. The intense tourist activity gave rise to major environmental problems: loss of mangrove forests, swamps, sand dunes, and beaches; eutrophication of coastal lagoons; degradation of water quality; and changes in the coastline due to harbor and marina construction. Massive tourism development is substantially modifying the coastal environments of this subregion; consequently, its vulnerability to natural disturbances such as hurricanes may be increased. However, the lack of long-term monitoring programs makes it impossible to determine the resistance, vulnerability, and resilience of this area.

Because coral reefs in the northern region are being subjected to continuous pressure by humans, the Mexican government declared marine protected areas in Cancún, Isla Contoy, Isla Mujeres, and Isla Cozumel so that management plans that favor sustainable use of these natural beauties could be developed. However, the lack of compromise between the national and international private tourism industries and the visitors’ lack of environmental education are the main impediments to accomplishing conservation goals. To mitigate damage to the coral reefs and reduce the pressure on their inhabitants, creation of new areas of artificial reefs could be an alternative where inexperienced visitors would cause less damage.

The central 140 km of the eastern coast on the Caribbean Sea is dedicated to nature conservation and is part of the Sian Ka‘an Biosphere Reserve (UNESCO). The most important lobster fishery in the region has been in this area for a long time, and due to an organizational structure (cooperativo) developed by fishermen, it is now one of the best examples of a sustainable activity on the Yucatan coasts.

The southernmost 120 km of the eastern coast is part of the typical tropical coastal system that we described as a transect perpendicular to the coast, including part of the coral-reef barrier that extends 800 km from southern Belize in the Honduras Gulf to Cancún. This part of the coast is currently well preserved with only small towns (each with less than 1000 inhabitants), but tourist development has been started with road construction, cruise-ship facilities, and a simple airport. Chetumal Bay, located at the border with Belize, shows symptoms of perturbation in the mouth of the Río Hondo from agricultural activities in the river watershed. The environmental condition in the northern part of the bay is better. Better management of agricultural fertilizer runoff, reforestation of the riparian forest, and a belt of wetlands along the river margins to reduce nutrient runoff are actions that could restore the river condition.

North Coast Subregion

Half of the length of the coastline in the state of Yucatan, which includes the western and easternmost zones of the coast of this state, has been declared protected areas for the conservation of habitats (Río Lagartos Biosphere Reserve, Celestún Biosphere Reserve, and state reserves of El Palmar and Dzilam) (Fig. 12.1). Environmental problems that have arisen are typical of nonintegrated anthropogenic activities. These problems include: (1) disturbance of sediments and loss of submerged aquatic vegetation due to increased boat presence in coastal lagoons, (2) loss of swamps and mangrove areas due to changes in the hydrology and land use, (3) decreased water quality and biological structure due to nonexistent wastewater treatment in urban and aquaculture areas, and (4) substantial coastal erosion caused by construction of solid structures (harbors, breakwaters, urban developments, and coastal roads) along the sand bars.

State and federal government agencies have started a sand beaches restoration program; however, because it is not based on scientific information, it has not been successful. Daily human activities can easily improve for the benefit of natural resources preservation and the local population. Construction of physical structures (e.g., vacation houses, dikes, and concrete channels) changed the flows of water and sand, which took a long time to integrate into the geomorphologic evolution of the coastal zone. This is also the case for land-use changes in the northern half of the peninsula where the human population has grown faster. Environmental problems arose parallel to the growth of Progreso. The loss of beaches was rapid on the coast west of Progreso after the construction of a 5-km-long dike–harbor. Mostly mangrove swamps and sand dunes are being destroyed 40 km along the coastal zone centered in Progreso due to the growth of villages, road construction, and semi-intensive urbanization for tourism. Development is increasing in the central north coast, including an initial intensive tourism
development, which is contributing to habitat loss and degradation as well as loss of water quality due to waste discharges from urban and industrial areas.

A major threat for the future of the coastal zone is the discharge of increasingly contaminated groundwater from the city of Merida and its surroundings, where huge amounts of sewage from humans and animal farms are discharged with no treatment or only primary treatment (Aranda-Cirerol et al. 2006; Aranda-Cirerol et al. 2011). Symptoms such as increasing Chl-a concentration, loss of seagrass coverage, and more frequent harmful algal blooms indicate that consequences of eutrophication in the northern coastal zone of Yucatan have begun.

Implementing actions to reduce the aquifer pollution through better water management in urban and farming areas is important. However, the use of new eco-technologies like wetland construction for wastewater treatment, mainly in rural areas, and for pig and shrimp farms is necessary (Jackson et al. 2003; Poach et al. 2003; Day et al. 2004).

The hydrology of mangrove zones in this region has been modified by artificial inlets constructed to connect the swamp with the open sea, coastal roads that interrupt the surface runoff, deforestation for urban development, and hurricanes. In the short term, an aggressive restoration program must be implemented, but it must be based on site-specific characteristics (Zaldivar-Jiménez et al. 2010).

West Coast Subregion

Most of the human activities on the west coast are centered around 2 major urban areas, Champoton and Campeche, with nearby minor urban extensions. Most of this 200-km-long coast remains unaltered, except for a road constructed without water bypasses, which has affected mangrove areas because it has blocked surface runoff, reduced the water exchange, and caused loss of habitat, mostly in mangrove swamps in the northern zone of this region (Isla Arenas). Consequently, ecological rehabilitation programs must be implemented in the short term, with site-specific actions that are chosen according to the hydrological and sediment characteristics of each site (Zaldivar-Jiménez et al., 2010).

The central and southern zones are part of the “Reserva de los Petenes” protected area, which includes a few human activities and has good quality environmental health. Actions directed toward conservation and research must be the main activities of this area.

The major land uses of the coastal zone that we described, as well as their qualitative effects on the environment, are summarized in Table 12.3 and are grouped into 2 categories: uses and abuses. The uses include activities that do not affect or that contribute to natural renewal of the natural resources. The coastal areas where these activities are developed will not require external energy inputs for maintenance of the ecosystem structure and functions. In these areas, it may be necessary to apply anthropogenically regulated energy to improve their functions, but not at an ecosystem level (e.g., to restore a degraded piece of the ecosystem, to buffer minor impacts, or to facilitate uses of the natural resources that do not affect them irrevocably). The abuses includes activities that cause irrevocable loss of habitats and natural resources, loss of geomorphologic functions of the coastal zone, or that generate materials that degrade the environment at a rate that does not allow self-recovery.

Discussion

Four general strategies of human land use have been identified in the coastal zone of the Yucatan Peninsula during the last 30 years: conservation, semi-intensive urbanization, construction of facilities for maritime transportation and fisheries, and massive tourist development.

The use of natural areas for conservation has integrated human activities within natural systems (including tourist establishments within traditional villages while maintaining a diversified economy based on activities of local people). This type of land use improved the environmental value of the natural resources and habitats in on the north-west coast; land use in the northeastern and the central part of the east coast, through foreign tourism, also contributed to the improvement of the socioeconomic status of the local population. Minor environmental problems associated with the increasing presence of humans (water and sediment disturbances) can be easily solved.

Semi-intensive urbanization is occurring in the southernmost part of the west coast and the central part of the north coast. The major environmental problem there is loss of habitat (e.g., directly by construction of houses on the sand bars and indirectly by road construction that restricts water flows, which supply the mangrove forests). Widespread pollution by wastewater from houses and point-source pollution from food processing industries and harbor activities are increasing the environmental problems; the first symptoms are eutrophication in coastal
Massive urbanization is the third type of human use in the northern part of the east coast of the Yucatan Peninsula (Riviera Maya) and is planned for the southern part of this coast (Costa Maya) and stimulated by governmental agencies. This type of development has generated a lot of income, which caused intense migratory displacement of people from the peninsula and other parts of Mexico. However, this type of land use has also caused irreparable loss of habitats (beaches, sand dunes, mangrove forest, brackish and freshwater swamps, and seagrasses) and has degraded coastal lagoons and coral reefs. The intensity of the impact is very high due to the use and abuse of natural resources (e.g., groundwater extraction, wastewater discharge, and coral reef and mangrove forest destruction) and much more intense than the capacity of lagoons and the coastal sea, and loss of mangrove swamps. However, if the same problems persist, severe eutrophication could occur in these systems, which would reduce the possibility of developing or maintaining productive activities such as tourism and aquaculture.

Remediation of these environmental impacts is very difficult in areas in or very near urban developments because habitat restoration may only be achieved by replanning these urban areas. However, restoration must be a priority in areas surrounding urban developments because, if this strategy were followed, benefits to the environment and socioeconomic structure would be obtained with the improvement of natural resource quality and an increase in the functional, aesthetic, and recreational values of the restored areas.

Table 12.3. Major land uses of the coastal zone and their qualitative effects on the environment, grouped into 2 categories: uses and abuses.

<table>
<thead>
<tr>
<th>Land uses</th>
<th>Qualitative effects</th>
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<tbody>
<tr>
<td></td>
<td>Environmental</td>
</tr>
<tr>
<td></td>
<td>Socioeconomic</td>
</tr>
<tr>
<td><strong>Uses</strong></td>
<td></td>
</tr>
<tr>
<td>Nature conservation</td>
<td>Stability of water flows and quality</td>
</tr>
<tr>
<td></td>
<td>Sea and air storm protection</td>
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<tr>
<td></td>
<td>Improved biological productivity (e.g., fisheries)</td>
</tr>
<tr>
<td>Traditional and regulated housing</td>
<td>Integration of human requirements and natural resources turnover</td>
</tr>
<tr>
<td>Integrated tourism</td>
<td>Increasing evaluation of natural resources and territory</td>
</tr>
<tr>
<td>Food harvesting</td>
<td>Weak habitat disturbance</td>
</tr>
<tr>
<td><strong>Abuses</strong></td>
<td></td>
</tr>
<tr>
<td>Conventional road construction</td>
<td>Loss of mangrove and sand dune habitats</td>
</tr>
<tr>
<td></td>
<td>Water flow disturbances</td>
</tr>
<tr>
<td>Industrial harbor</td>
<td>Waste water and solid discharges</td>
</tr>
<tr>
<td></td>
<td>Coastal transport disturbances</td>
</tr>
<tr>
<td>Unregulated housing</td>
<td>Beach erosion</td>
</tr>
<tr>
<td></td>
<td>Loss of sand-dune habitat</td>
</tr>
<tr>
<td>Extensive tourism</td>
<td>Loss of habitats</td>
</tr>
<tr>
<td></td>
<td>Widespread pollution</td>
</tr>
<tr>
<td>Massive tourism</td>
<td>Loss of habitats</td>
</tr>
<tr>
<td></td>
<td>Point-source pollution</td>
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<tr>
<td></td>
<td>Increased storm hazards</td>
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<tr>
<td></td>
<td>Water flow disturbances</td>
</tr>
<tr>
<td>Shrimp farming</td>
<td>Habitat loss and water pollution</td>
</tr>
<tr>
<td></td>
<td>Exotic species introduction</td>
</tr>
</tbody>
</table>

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The prediction of impacts and anticipation of scenarios are possible using mathematical models that consider both ecological and hydrological variables. Using eco-hydrology as a tool for integrated management, from drainage basin to coastal areas, can help achieve long-lasting and ecologically sustainable solutions. This is the key to the management and conservation of coastal ecosystems. Progress in mathematics, particularly statistics and modeling, made it possible to give a dynamical characteristic to ecosystem research and a predictive capability. Today, a number of numerical models are available to us from various marine and coastal ecosystems, which improved our knowledge of their functioning, and more importantly, how to forecast their behavior under different scenarios.

Functioning of Yucatan Peninsula coastal ecosystems is regulated by interactions among local and regional forcing functions and pulsing events; their structural and functional characteristics are those that sustain their environmental services and promote the uses and activities within them. However, the type and intensity of the local and regional activities are causing serious threats to the coastal ecosystems of the Yucatan Peninsula, as well as loss of critical habitats. We must identify the causes of the problems, their impacts, and the consequences to develop a specific approach for their solution through mitigation and restoration. We must apply new eco-technologies and forms appropriate for the natural resources and the human population under the perspective of integrated coastal zone management and an ecosystem approach.

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Herrera-Silveira, J. A., R. Silva-Casarín, P. Salles, A. de Almeida,
Global climate change is important in considerations of integrated coastal management in the Gulf of Mexico. This is true for a number of reasons. Climate in the Gulf spans the range from tropical to the lower part of the temperate zone. Thus, as climate warms, the tropical–temperate interface, which is currently mostly offshore in the Gulf of Mexico, will increasingly move over the coastal zone of the northern and eastern parts of the Gulf. Currently, this interface is located in South Florida and around the US–Mexico border in the Texas–Tamaulipas region (Figs. 14.1 and 14.2) (Yáñez-Arancibia and Day 2004).

Within this general temperature gradient, rainfall is important (Day et al. 1989). The climate around the Gulf ranges from arid to super humid (Fig. 14.1). In parts of the southern Gulf, especially in the drainage basin of the Grijalva and Usumacinta rivers that discharge to Campeche Sound, rainfall is >3000 mm/yr. Rainfall averages between 1500 and 2000 mm/yr in the north-central Gulf from Pensacola, Florida, to the Louisiana deltaic plain, and in the southwestern Gulf in the state of Veracruz. In most of the Florida and Yucatan peninsulas and in the northwestern Gulf, rainfall is between 1000 and 1500 mm/yr. Arid areas with less than 1000 mm occur in the northwestern coast of the Yucatan Peninsula near Progreso and in the western Gulf coast between Tampico, Tamaulipas, and Corpus Christi, Texas. At this broad geographic scale, temperature and rainfall are two of the principal determinants of coastal wetland distribution (Day et al. 1989; Yáñez-Arancibia and Day 2004).

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The consensus in the scientific community is that human activity is affecting global climate (IPCC 2007), and climate change will significantly alter many of the world’s coastal and wetland ecosystems (Titus et al. 1991; Wilkinson and Buddemeier 1994; Tarasona et al. 2001; Poff et al. 2002). Thus, the general climate patterns described in the previous paragraph are predicted to change significantly in the Gulf of Mexico (Twilley et al. 2001; Poff et al. 2002; Ning et al. 2003). Global climate change will interact with, and magnify, other human stresses on Gulf Coast ecosystems and the goods and services they provide (see Day et al. 2008). Recently, Twilley et al. (2001) pointed out 3 key questions for helping the public and policymakers understand the most likely ecological consequences of climate change in the region over the next 50 to 100 years and what must be done to prepare to safeguard the economy, culture, and natural heritage of the Gulf Coast:

1. What is the likely climate future for the Gulf Coast region?
2. What might these changes mean for Gulf Coast ecosystems and the goods and services they provide?
3. How can residents of the Gulf Coast region address the challenge of a shifting climate?

Global climate change will have a number of likely impacts in the Gulf of Mexico, including increases in temperature, accelerated sea-level rise, changes in rainfall and freshwater discharge, and changes in the frequency and
intensity of tropical storms (Day and Templet 1989; Twilley et al. 2001; Poff et al. 2002; Scavia et al. 2002; Ning et al. 2003; Day et al. 2005; Yáñez-Arancibia and Day 2005; Hoyos et al. 2006; Day et al. 2008; Ortiz Pérez et al. in Chapter 15 in this volume). These changes likely will have tremendous human, economic, and ecological effects in the coming decades.

Our objective in this chapter is to describe the general functioning of coastal ecosystems in the Gulf of Mexico and the predictions of climate change, and to discuss how climate change likely will affect management of coastal ecosystems. We draw on a number of recent publications concerning the implications of climate change for coastal ecosystems in the Gulf of Mexico (Twilley et al. 2001; Poff et al. 2002; Ning et al. 2003; Day et al. 2005; Yáñez-Arancibia and Day 2005; Day et al. 2008; Ortiz Pérez et al. in Chapter 15 in this volume).

Climate, Environmental Drivers, and Aquatic Ecosystems

We focus in this chapter primarily on the consequences of climate-induced changes on several broadly critical environmental drivers related to climate that directly and indirectly regulate many coastal ecological processes including temperature, the hydrologic regime, and changes in sea level (Fig. 14.3). Some areas of the Gulf coastal region likely will become wetter, some drier, and the variability in the timing and quantity or precipitation likely will also change. These patterns will reflect both changes in local precipitation and freshwater runoff and changes in larger drainage basins. Changing tropical storm activity and accelerated sea-level rise will be critical variables affecting coastal ecosystems. Although the precise geography of these regional shifts is not completely known at present (due to limitations in climate forecasting), signifi-
Global Climate Change Impacts

Temperature regimes almost certainly will induce a wide range of ecological responses, from local extinction of individual species and changes in biodiversity to changes in the rates of ecosystem processes, such as primary production and bacterially mediated decomposition. Many species will shift their geographic ranges to the north as is happening to mangroves in the Gulf of Mexico coastal zone. Temperatures in the entire coastal zone of the Gulf of Mexico likely will become tropical in the 21st century (Fig. 14.2).

Hydrologic Regime

The hydrologic regime directly and indirectly controls the structure and function of coastal ecosystems. Precipitation in excess of evapotranspiration in drainage basins results in freshwater runoff to coastal ecosystems. Both

Figure 14.3. Conceptual model of deltaic functioning (representative of intertidal wetlands in the Gulf of Mexico). The model shows how natural pulses of freshwater, nutrients, and sediments enhance productivity and soil formation and buffer against relative sea-level rise (RSLR). Soil formation is broken down into inorganic and organic fractions, and organic matter production depends on relative land elevation, a balance between RSLR and soil formation. The symbols “+” and “−” indicate whether interactions are positive or negative. This is a key concern for understanding how climate change impacts coastal ecosystems in the Gulf of Mexico. Modified from Day et al. (1997).
Coastal Ecosystems of the Gulf of Mexico

Coastal wetlands and estuaries are among the most productive ecosystems on earth (Day et al. 1989), and some of the most productive are located in the Gulf of Mexico (Mendelssohn and Morris 2000). Deegan et al. (1986) and Bianchi et al. (1999) listed more than 50 estuarine ecosystems around the Gulf of Mexico. Three of the largest and most productive include the Mississippi Delta, the Usumacinta/Grijalva Delta and Terminos Lagoon system, and the Florida Everglades–Florida Bay system. The high productivity of these systems is related to such factors as the tropical-to-warm temperate climate, a large area near sea level, freshwater inputs, and fluctuating water levels. Freshwater input delivers nutrients (which support high production) and suspended sediments (related to accretion of wetland soils). In addition, the mixing of freshwater and seawater in estuaries creates water circulation patterns that tend to retain nutrients, which further enhance coastal ecosystem productivity. Coastal wetlands support dense populations of animals, many of them migratory and of great commercial value, and some of the largest fisheries in North America are in the Gulf.

Coastal wetland ecosystems are among the most altered and threatened natural systems, and this is certainly true of the Gulf of Mexico. Important perturbations include increased nutrient loading that leads to eutrophication, habitat destruction (especially loss of coastal wetlands), changes in hydrology, introduction of toxic materials, and changes in species composition due to overharvest and introduction of new species (Day et al. 1989; Mitsch and Gosselink 1993; Neumann et al. 2000). The Mississippi Delta alone accounts for about 40% of coastal wetlands and 80% of coastal wetland loss in the United States. This is due to both isolation of the river from the delta plain and pervasive alteration of coastal wetland hydrology (Boesch et al. 1994; Day et al. 2000; Day et al. 2007). Coastal eutrophication is a growing problem due to increasing inputs of nutrients from agriculture, industry, and human populations. One of the most notable examples of coastal eutrophication is the large hypoxic zone off the Mississippi Delta (Rabalais et al. 1998). Climate change likely will interact with the problems of wetland loss and eutrophication to make the problems worse than either human impact or climate change.

The Gulf of Mexico receives freshwater discharge from 5 countries: the United States, Canada, Mexico, Guatemala, and Cuba. Throughout the 6134 km of coastline from the southern tip of Florida in the United States to Quintana Roo, Mexico, major geographic regions include the warm-temperate Gulf of Mexico, the tropical Gulf of Mexico, and the Caribbean coast of Mexico (Yáñez-Arancibia and Day 2004). Because of variables such as an ecological gradient from temperate, subtropical, and tropical climate conditions, plus a strong seasonality between cold fronts and tropical storms, the Gulf of Mexico is a biocomplex system. Discrete complex subsystems can be defined as geographic–hydrological subregions including the western Florida rivers and groundwater discharge system, the Mississippi River basin and delta, the Texas estuaries and Laguna Madre of the United States and Mexico that is integrated by the Rio Grande/Río Bravo delta, the Usumacinta/Grijalva river basin and delta, and Río Hondo–Chetumal Bay on the Caribbean coast of Mexico (Yáñez-Arancibia and Day 2004). Along the US Gulf coast, estuaries can be divided in 3 regions: (1) the Eastern Gulf, from Florida Bay to the Suwannee River, (2) the Northern Gulf, from Apalachicola Bay to the Atchafalaya and Vermilion bays, and (3) the Western Gulf, from Calcasieu Lake to the lower Laguna Madre. Along
Global Climate Change Impacts

Coastal Ecosystems

Climate change will have a number of important impacts on coastal ecosystems in the Gulf of Mexico. These include the impacts of accelerated sea-level rise, changes in freshwater inflow, effects of increased temperature, and impacts on fish and fisheries.

Response of Coastal Wetlands to Accelerated Sea-level Rise

Coastal wetlands of the Gulf of Mexico will face accelerated sea-level rise during the 21st century. There is strong consensus that global warming will lead to accelerated eustatic sea-level rise. The IPCC (2007) predicted sea level will rise by 20–80 cm in the 21st century, with a best estimate of about 40 cm (Fig. 14.3). This is much higher than eustatic sea-level rise for the 20th century of 10–20 cm (Gornitz et al. 1982). This increase in sea level will affect the large areas of low-lying land, especially wetlands, around the Gulf of Mexico. In areas where subsidence is significant (i.e., 4–10 mm/yr), like the Mississippi and Usumacinta deltas, accelerated sea-level rise has the potential to have dramatic impacts on coastal wetlands. In these cases, eustatic sea-level rise must be added to subsidence to obtain relative sea-level rise (RSLR) to determine the rates of water level rise that coastal wetlands will experience in the 21st century. In the Mississippi Delta, for example, RSLR will increase from about 1 cm/yr to 1.3–1.7 cm/yr within this century (a 30–70% increase over the RSLR of the 20th century). Recent evidence from the Arctic, such as the melting of the Greenland icecap, and decreasing albedo due to loss of sea ice and land snow cover, has suggested to some climate scientists that sea-level rise will be significantly higher by 2100, perhaps a meter or more (Rahmstorf 2007).

Sea-level rise over the last several decades has reportedly led to salinity intrusion and wetland loss in a number
of coastal areas around the world and in the United States and Mexico, including Long Island (Clark 1986), the mid-Atlantic region (Kana et al. 1986; Hackney and Cleary 1987), Chesapeake Bay (Stevenson et al. 1985), the Mississippi Delta (Salinas et al. 1986; Conner and Day 1989; Day et al. 2000), the southern Gulf of Mexico (Ortiz-Perez and Mendez Linares 1999), and the Po and Rhone deltas (Ibáñez et al. 1996; Ibáñez et al. 1997; Pont et al. 2002). Because sea-level rise over the last century is 2 to 9 times lower than the projected sea-level rise expected over the next 100 years (Neumann et al. 2000), an increasing loss of coastal wetlands is a great concern. The projected rise in sea level from global climate change will certainly place these productive and important ecosystems under additional stress, with the potential for extensive dieback of intertidal plants and declines in fish nursery grounds (Pauly and Ingles 1999). Several areas of extensive coastal wetlands around the Gulf will be threatened by rising sea levels. These include the southern Everglades, the Mississippi Delta, the Alvarado system, the Usumacinta/Grijalva–Laguna de Términos system, and the Petenes of the Yucatan Peninsula.

During periods of sea-level rise, coastal wetlands can only persist when they accrete vertically at a rate at least equal to water level rise (Cahoon et al. 1995a). Coastal marshes are indeed able to accrete at a rate equal to the historical rate of sea-level rise (1–2 mm/yr) (Gornitz et al. 1982) and persist for hundreds to thousands of years (Redfield 1972; McCaffey and Thompson 1980; Orson et al. 1987). However, given the predictions of accelerated sea-level rise over the next 100 years, soil accretion in most coastal wetlands will have to occur at a rate 2 to 9 times that of the last century for the wetlands to survive. Some coastal wetlands can survive such high rates of sea-level rise. In the Mississippi Delta, for example, accretion rates higher than 10 mm/yr have been measured (Day et al. 2000; Day et al. Chapter 5 in this volume).

Two important physiological causes of loss of wetlands are flooding stress due to increased flooding duration and salinity stress (Mendelssohn and Morris 2000). Global climate change likely will exacerbate both of these stresses. Accelerated sea-level rise will significantly increase flooding duration. Unless wetlands can accrete vertically at the same rate as water level rise, coastal vegetation will become progressively more stressed and ultimately die. Even at current rates of RSLR of about 1 cm/yr, most wetlands of the Mississippi Delta do not have sufficient rates of vertical accretion to survive (DeLaune et al. 1983; Hatton et al. 1983; Conner and Day 1991). Rising sea level combined with lower freshwater input will lead to increased saltwater intrusion and salinity stress. This especially threatens the extensive tidal freshwater wetlands of the delta. This combination of high RSLR, increased temperature, and lower freshwater input results in the north-central Gulf having the highest vulnerability to climate change in the United States (Thieler and Hammar-Klose 2001), as well as the southern Gulf (Ortiz-Perez and Mendez Linares 1999).

Coastal wetland plants live in the intertidal environment characterized by alternate flooding and draining, waterlogged soils, depletion of oxygen, and the production of natural toxins such as sulfides that inhibit plant growth (Mendelssohn and Morris 2000). To cope with these harsh conditions, coastal plants have a number of adaptations, including the production of “aerial” roots and aerenchymal tissue that allow them to capture oxygen needed by the roots. But these adaptations lead to survival only as long as the average water level remains relatively constant. Accordingly, coastal wetlands exist within a fixed elevation range, where the frequency and duration of inundation by seawater are relatively constant (McKee and Patrick 1988). Because plants become progressively more stressed and ultimately die if they are inundated for too long (Mendelssohn and McKee 1988), an increase in water levels due to sea-level rise can severely stress the integrity of coastal wetland ecosystems. This is particularly true in the Gulf of Mexico where climate change may result in reduced freshwater runoff and thus increased salinity which, when combined with rising sea levels, will result in multiple stresses on plants (Yáñez-Arancibia et al. 1998).

The rate at which vertical accretion occurs is a function of the combination of the inputs of both inorganic and organic material to the soil (Fig. 14.3). Organic material is mostly derived from the growth of plant roots, whereas inorganic material is mostly supplied in the form of sediments that come from either the sea or freshwater sources. Riverine sediments are generally more important because their input is more frequent and they contain nutrients that enhance organic soil formation. River water also supplies freshwater that buffers saltwater intrusion and iron that precipitates toxic sulfides (DeLaune and Pezeshki 2003; DeLaune et al. 2003). Many rivers flowing into estuaries now carry only a fraction of the inorganic sediment that they did historically. For example, sediment discharge to the Mississippi Delta has decreased by at least 50% since 1860, largely due to the building of Missouri River dams, which capture and store the suspended
sediment in the river water and contribute to the significant loss of coastal wetlands (Kesel 1989; Meade 1995). Sediment input likely will decrease from the Usumacinta/Grijalva river system because of the construction of large dams. Some projections of climate change are that local freshwater discharge to Gulf of Mexico estuaries will decrease (Day et al. 2005). This may result in coastal wetlands that are less able to survive accelerated sea-level rise due to a combination of inadequate accretion and increasing salinity.

One management strategy to offset sea-level rise and promote continued coastal wetland productivity is to actively utilize the resources of Gulf Coast rivers rather than letting most freshwater, sediments, and nutrients flow directly to the sea. An example of this is the Mississippi Delta where levees have led to most river water discharging directly to the Gulf. This has led to widespread wetland loss (Day et al. 2000; Day et al. 2007). In an effort to solve this problem, river diversions are being used where structures allow river water to flow back into coastal wetlands (Lane et al. 1999; DeLaune and Pezeshki 2003; DeLaune et al. 2003; Lane et al. 2004; Day et al. 2007).

In some cases, wetlands can migrate inland as sea level rises. However, human development in many areas prevents this. In addition, elevation in the uplands bordering coastal wetlands often increases rapidly, and upland migration can support only a small fraction of the wetlands that are lost.

Effects of Changes in Freshwater Input on Coastal Ecosystems

General circulation models (GCM) are not consistent in their predictions of the effects of climate change on precipitation and temperature, which are important determinants of freshwater inflow to estuaries. For example, runoff estimates for the Mississippi River basin differ greatly between the Canadian CGCM1 model and the Hadley HADCM2 model (Wolock and McCabe 1999). Both models predict an increase in future extreme rainfall and runoff events, but they differ in both the magnitude and direction of changes in average annual runoff. For example, the average annual runoff of the Mississippi River basin is predicted by the Canadian model to decrease by 30% by the year 2099 but is predicted to increase by 40% by the Hadley model. Estimated changes in freshwater inflow into major US estuaries projected by the Hadley model by the year 2099 range from 100% to −40%. Similar calculations based on the Canadian model indicate significantly reduced inflows for all coastal regions except the US Pacific coast (Wolock and McCabe 1999). For the northern Gulf coast, the Hadley model predicts a 3–19% reduction in freshwater inflows for US Gulf coast estuaries by 2034, with the exception of Matagorda Bay. By 2100, the model predicts that freshwater inflow in Florida Gulf coast estuaries and Mobile Bay will increase 7–37%, but flows in estuaries from Lake Pontchartrain to Matagorda Bay will decrease 10–40%. Thus, many coastal and estuarine ecosystems likely will experience changes in freshwater inflow. However, the manner in which these changes will occur is not known. There has already been a small, but significant, increase in the flow of the Mississippi River during the past half-century (Justic et al. 2003).

Similar changes in freshwater inflow can be expected for the southern Gulf of Mexico. Although the predictions of local changes in precipitation and runoff are uncertain, the precautionary principle suggests that management plans for the Gulf Coast should consider such changes. For example, rainfall has increased in the mountains of Oaxaca and Chiapas, leading to a significant increase in freshwater discharge of rivers in the southwestern portion of the Gulf of Mexico, and this must be included in dealing with coastal management in these areas as indicated in Figure 14.3.

For much of the US coast, most GCMs predict that winter and spring rainfall will increase, although models differ as to whether precipitation will increase or decrease in summer and fall (Wigley 1999). For the Gulf of Mexico, however, local freshwater input likely will decrease. The Gulf is characterized by 2 general types of freshwater input. The Florida and Yucatan peninsulas are carbonate karst platforms characterized by groundwater discharge to the Gulf and a lack of surface rivers. The northern, western, and southern areas of the Gulf, by contrast, have surface-water input from rivers. Important river systems including the Mississippi (mean flow about 18,000 m3/s), Usumacinta/Grijalva Delta (4500 m3/s), Mobile River (2000 m3/s), Panuco River (450 m3/s), Coatzalcoaclos River (450 m3/s), Alvarado–Papaloapan Delta (600 m3/s), and Rio Grande/Río Bravo (historically 160 m3/s, but at present sometimes nearly zero) (Yáñez-Arancibia and Day 2004). Only the Mississippi, Usumacinta/Grijalva, and Rio Grande/Río Bravo drain continent-sized basins. Most of the water in the Mississippi comes from the upper basin, mainly the Ohio River, and thus is largely unaffected by weather and climate in the Gulf region. The rivers in the southern Gulf (Usumacinta/Grijalva Delta,
Increased freshwater input can be both beneficial and detrimental to coastal systems. Both will likely occur in the Gulf region. The benefits of freshwater input stimulating vertical soil accretion have already been highlighted. An additional benefit could be an increase in fisheries production in coastal systems (Nixon 1988). This results because the nutrients in freshwater that flow into estuaries stimulate primary production, which in turn increases the energy available for organisms that fish eat. In the coastal marshes of the southern Everglades and in the Mississippi Delta, there are current management plans to increase freshwater flow to coastal areas mainly for habitat restoration (Sklar et al. 2005; Day et al. 2007). In the Mississippi Delta, these diversions add sediments that increase accretion, lower salinity to combat saltwater intrusion, and benefit fisheries and wildlife. However, diversions could lead to algal blooms because of the added nutrients and they could add pollutants, which may severely affect organisms in these areas. Thus, diversions will have to be studied and managed carefully to avoid problems. In contrast, if freshwater input decreases, it likely will lead to less accretion, lowered productivity, and saltwater intrusion. A recent study documented that reduced freshwater input to the East China Sea from the Yangtze River by the Three Gorges Dam reduced diatom populations (Gong et al. 2006).

One negative impact associated with an increase in freshwater runoff to coastal ecosystems is an excessive increase in nutrients. Agricultural runoff and sewage wastewater from human activity in tributary watersheds already is degrading many coastal ecosystems in the Gulf of Mexico and elsewhere. Nuisance algal blooms and low oxygen in bottom waters kill fish and shellfish, as has been well documented in Chesapeake Bay (Kemp et al. 1992; Harding and Perry 1997) and off the coast of Louisiana in the Gulf hypoxic zone (the so-called “dead zone”) (Rabalais et al. 1996). Management suggestions have been made to reduce high nutrient loading to streams and coastal waters. For the Mississippi River basin, for example, these recommendations included changes in farming practices, buffer strips along streams, use of wetlands to improve water quality, and reduction of nitrate in river water by diversions into riparian ecosystems and the Mississippi Delta (Mitsch et al. 2001). The increased runoff may also lead to problems with toxic pollutants (e.g., heavy metals and organic chemicals) if there are high levels of these chemicals in the runoff.

**Effects of Increased Temperature on Coastal Vegetation**

The Intergovernmental Panel on Climate Change (IPCC 2007) predicted that global temperatures will rise 1–5 °C during the 21st century. Temperature directly controls many vital life processes, and a change in the thermal regime (extreme temperatures, their duration, and seasonal rates of temperature change) can directly regulate rates of growth and reproduction. Strong geographic gradients in temperature exist from the tropics to the...
Twilley et al. (1999) used the FORMAN model (Chen and Twilley 1998) of mangrove tree growth to test the response of forest communities to freeze frequency. They found that when freezes occurred more often than once every 8 years, mangrove forest structure was reduced by one-half (basal area) compared to the forest structure during periods with no freezes, and black mangroves dominated community composition. Along the Louisiana coast, freezes historically occurred about every 4 years. By the spring of 2008, however, a killing freeze had not occurred for 19 years, and small black mangroves were found over a large area. Near Port Fourchon, Louisiana, aerial photography shows an area of 30 ha of salt marsh in 1993 that had been converted to black mangrove by 2000, a mangrove expansion rate greater than 4 ha/yr. If this trend continues, mangroves will spread over much of the northern Gulf coast. During the drought in 2000, black mangroves were observed to withstand higher temperatures, salinity, and water stress better than salt-marsh plants (McKee et al. 2004). Thus, succession from tidal marshes to mangroves may lessen the impact of drier, higher-salinity conditions.

Because mangroves have many of the same ecological functions as salt marshes (high productivity, habitat for wildlife and fish, sites of nutrient uptake, etc.), a switch in Gulf coastal wetlands from salt marshes to mangroves might not change ecosystem function much. However, if the climate becomes more variable with freeze-free periods interspersed with occasional hard freezes, it could be more difficult for either marshes or mangroves to survive, resulting in a loss of wetland habitat. Furthermore, not enough is known about the relative susceptibility to hurricane damage of salt marsh versus mangrove forests to predict effects of hurricanes on the stability of coastal ecosystems as mangroves spread.

Increased temperature may interact with other stressors to damage coastal marshes. For example, during the spring-to-fall period of 2000 in the Mississippi Delta, large areas of salt marsh were stressed and dying. This appeared to be the result of a combination of effects related to a strong La Niña event that resulted in unusually low freshwater discharge from the Mississippi River, below-normal tide levels in coastal Louisiana, and prolonged local drought. McKee et al. (2004) suggested that reduced tidal flushing coupled with decreases in local rainfall associated with climate change may dramatically affect tidal marshes. A warmer, more variable climate characterized by more common droughts, and more frequent La Niña events, may severely stress coastal salt marshes in such a manner.
Effects of Climate Change on Coastal Fish and Fisheries

A number of investigations have demonstrated relationships between fisheries yields and the high nutrient loads, freshwater inputs, shallow depths, large areas of tidal mixing, coastal vegetated area, area of lagoon–estuarine systems, and resulting high primary productivities that are typical of estuaries and estuarine plume ecosystems (see Deegan et al. 1986; Nixon 1988; Pauly and Christensen 1995; Sanchez-Gil and Yáñez-Arancibia 1997). Thus, despite the small aggregate spatial extent of estuaries (<1% of the global marine area), approximately 50% of US fishery yields have historically been derived from estuarine or estuarine-dependent species (Gunter 1967; McHugh 1967; Houde and Rutherford 1993; Vidal-Hernandez and Pauly 2004). In the Gulf, the fraction is considerably higher (Houde and Rutherford 1993); estuarine-dependent species dominate in large and valuable commercial and recreational catches. For example, Gulf menhaden (Brevoortia patronus) support the second largest US fishery by weight, and penaeid shrimps support the fifth largest by value, with shrimp landings alone valued at $400 million to $500 million per year.

A large fraction of the harvested secondary production in the Gulf’s “fertile crescent” around the Mississippi River, in the eastern Gulf around Florida Bay and the Everglades, and in the southern Gulf around the Usumacinta Delta and Laguna de Términos is derived from estuarine ecosystems, including areas on the shallow shelf that are influenced by estuarine plumes (Darriell 1990; Christensen and Pauly 1993; Sanchez-Gil and Yáñez-Arancibia 1997; Chesney and Baltz 2001). High river discharge rates, large freshwater surpluses, and high water residence times are characteristic of these estuaries (Deegan et al. 1986). This suggests that much of the production and subsequent trophic transfer may occur outside of the physical boundaries of the estuaries, i.e., in association with plumes of freshwater over shallow continental shelves. These contrasting mechanisms of trophic delivery to the fishery forage base, and ultimately to larger consumers (i.e., estuary versus shelf) introduce uncertainty in how we view the functionality of estuaries, the shelf ecosystems they influence, and the influence of climate change.

Estuarine Dependency

Fish production in estuaries and in coastal ecosystems is governed by the laws of trophic supply; demand and changes in nutrient supply for primary producers can filter up through the food web to fishes, thereby increasing fish production if overall production is increased at lower trophic levels (Pauly and Yáñez-Arancibia 1994; Pauly and Christensen 1995; Pauly et al. 1998). Moreover, estuaries serve as nursery areas for fishes that spawn offshore, enter the estuary as larvae or juveniles and, after a period of juvenile residency, move back offshore as preadults to complete their life cycles (Yáñez-Arancibia et al. 1994). While in the estuaries, larvae and juveniles are abundant and often experience phenomenal growth rates (> 30% per day in weight) and biomass production that result from very high consumption rates (Deegan et al. 1986; Cowan and Houde 1990; Deegan 1990; Houde and Zastrow 1993; Pauly and Yáñez-Arancibia 1994). However, factors that have been hypothesized to result in increased abundances of young fishes in estuaries such as (1) retention of fish in certain areas within an estuary as a result of physical processes, (2) physical concentration of fish in a system as a result of a net positive flux of individuals from other areas, and (3) concentration via differential survival of individuals in areas of high productivity and/or low predation such that G:Z (the ratio of instantaneous growth to instantaneous mortality) is maximized, apparently are not well documented in estuarine nursery habitats along the northern Gulf (Lyczkowski-Shultz et al. 1990). This is especially true given that many of the physical processes (e.g., 2-layered circulation resulting from strong tidal forcing) suggested as important factors in more comprehensively studied, temperate estuaries are not as evident and cannot be assumed to be important in maintaining the high levels of fisheries production in estuaries that are characteristic of the fertile crescent. As such, the estuarine-dependency paradigm may not apply as well in the fishery systems in the Gulf, at least in wide, estuarine plume extensions onto the continental shelf. We contend that high fisheries production may be more attributable to estuarine-like conditions that cover large portions of the inner continental shelf during high river discharge periods because relatively few fish species are wholly adapted to life cycles within lagoon–estuarine systems.

Moreover, in the subtropical and tropical regions of the Gulf, and especially in areas where high river discharge leads to estuarine-like conditions on the continental shelf,
the distinction between estuaries and the shallow shelf is less than in areas where discharge is lower (Pauly and Yáñez-Arancibia 1994; Yáñez-Arancibia et al. 1994). If strict estuarine-dependency of continental shelf populations is largely valid for estuarine regions as a whole (Longhurst and Pauly 1987), it may not be as valid in the Gulf in areas characterized by soft-bottom communities on the inner shelves associated with extensive deltaic systems, high river discharge, and extensive estuarine plumes on the shallow shelf (Deegan et al. 1986; Pauly 1986; Pauly and Yáñez-Arancibia 1994; Yáñez-Arancibia et al. 1994; Sanchez-Gil and Yáñez-Arancibia 1997; Baltz et al. 1998; Pauly et al. 1998; Chesney et al. 2000; Sanchez-Gil et al. 2008).

Disentangling the relative contributions to fisheries production of estuarine vs. estuarine-like inner shelf ecosystems may be the key to long-term resource management, especially in light of rapidly changing conditions such as climate change. In this context, the predicted long-term effects of climate change on Gulf of Mexico fisheries are uncertain and depend upon the time horizon that defines subsequent habitat change. As stated earlier, numerous models and review papers from the southeastern Atlantic and Gulf relate survival of young fish, recruitment within estuaries, and fisheries yields to river runoff, salinity and water temperature regimes during critical time periods, percent availability of suitable estuarine nursery habitat, precipitation, favorable wind fields, hypoxia, and sea-level fluctuations. In the short term, warmer water and higher growth rates plus expansion of salt marshes inland with sea-level rise may favor productivity of estuarine-dependent marine species. However, this enhanced productivity may be temporary because of long-term negative effects of sea-level rise and wetland loss on fishery habitats (Kennedy 1990; Zimmerman et al. 1991; Chesney et al. 2000).

Many of the predicted climate changes will also influence circulation patterns and transport of salt water within coastal environments. Hydrodynamics in the Gulf of Mexico shallow estuaries generally are dominated by meteorological (winds) rather than astronomical conditions (Lee et al. 1990). Any change in winds will alter existing circulation, especially given the relatively small tidal amplitudes and shallow depths in Gulf of Mexico estuaries and their adjacent shallow coastal shelves. For example, the refilling of estuaries in the northern Gulf after the relaxation of strong northerly winds during a cold frontal passage is probably responsible for the transport of coastal materials and biota (e.g., salt water, sediment, eggs, and larvae) into the estuaries (Rogers et al. 1993 and papers cited therein). Consequently, changes in the intensity and frequency of frontal passages could severely alter estuarine circulation and recruitment of estuarine-dependent fish species. In addition, changes in rainfall and runoff will alter coastal and estuarine salinity gradients, thus altering circulation and long-term salinity patterns (Wiseman et al. 1986). Such changes may be sufficient to destabilize shallow coastal habitats, thereby affecting plant and animal species in these habitats.

A clearer understanding of the links between the nursery function of coastal wetlands, hydrology, and climate variation is emerging (Baltz et al. 1993; Chesney et al. 2000; Cowan et al. 2008). Interannual variation in the timing and extent of high-water conditions in salt marshes may contribute to annual variation in fishery recruitment. Because many fishes regularly move onto flooded marsh to feed, marsh access is apparently important to their growth and survival. Studies in Louisiana, where tides are small, indicated that interannual variability in wind patterns influences the frequency of flooding of salt-marsh habitats, and subsequently shrimp landings (Childers et al. 1990). In other coastal wetlands with larger, semi-diurnal tides, marshes flood more predictably, and some fishes may spend as much as one-third of their time in flooded habitats. For species that use high intertidal habitats as nurseries, variability in habitat availability driven by climate change may strongly influence recruitment, particularly in the systems of the northern Gulf where the tidal range is small.

In the semiarid region of Texas, the lack of freshwater and the highly saline shorelines limit the development of emergent marshes in Laguna Madre. Should climate change extend this low rainfall regime northward on the Texas coast, the area of existing intertidal marshes will diminish because of shoreline retreat and enlarged salt bars landward (similar historical conditions have been observed in Laguna Madre). Such marsh habitat is unlikely to be replaced by mangroves or seagrasses, at least in the near term. This loss of essential nursery habitat needed to maintain estuarine-dependent fishery productivity may cause fishery yields to decline below historical levels. This prediction is supported by significant declines in shrimp and blue crab (Callinectes sapidus) commercial yields in South Texas bays and Laguna Madre during drought and warm winter conditions of the 1990s (Texas Parks and Wildlife Department 2000). In contrast, Haas et al. (2001) predicted increased shrimp abundance in northern Gulf estuaries with increased estuarine salin-
ity, thus highlighting the uncertainty associated with estimating the effects on fisheries of interacting variation in precipitation and river discharge, salinity, temperature, and hypoxia in climate-change scenarios.

Changes in Tropical Storm Intensity and Frequency

Until recently, only general empirical evidence existed that global climate change would increase the frequency and intensity of tropical storms (Knutson et al. 1998; Wigley 1999; IPCC 2007). Raper (1993) reported that there was some empirical evidence that the frequency of Atlantic hurricanes might increase with increasing sea-surface temperatures. In addition, warmer sea-surface temperatures suggested that hurricanes might reach higher latitudes more often. Storms may also be accompanied by greater rainfall intensity (Wigley 1999).

Recent reports, however, have drawn stronger conclusions concerning storms and climate change. Emanuel (2005) reported that sea-surface temperatures in the tropics had increased by about 1 °C over the past half century, and during this same time, hurricane intensity or power had increased by about 80%. This increase in intensity was due to both more powerful storms and increased duration of these storms. Emanuel linked these changes, at least partially, to global climate change. Webster et al. (2005) reported an increase in the number of category 4 and 5 storms over the past several decades. Some have argued that these increases in storm intensity, strength, and duration are not linked to climate change but are due to decadal cycles in tropical storm activity. Hoyos et al. (2006) analyzed factors contributing to hurricane intensity and concluded that the increasing numbers of category 4 and 5 hurricanes for the period 1970–2004 was directly linked to the increase in sea-surface temperatures. Regardless of whether the recent intensification of hurricanes is due to climate change or is part of a decades-long cycle, the Gulf region likely will experience more and stronger hurricanes in the coming decades.

In general, long-term changes in the frequency, intensity, timing, and distribution of strong storms will most likely alter the species composition and biodiversity of coastal marshes of the Gulf of Mexico, as well as important ecosystem rates such as nutrient cycling and primary and secondary productivity (Michener et al. 1997). For coastal systems of the Gulf, the effects likely will be both positive and negative. For example, hurricanes greatly increase the rate of soil accretion in marshes, thereby helping to offset accelerated sea-level rise (Cahoon et al. 1995b). Runoff generated by hurricanes introduces freshwater and nutrients that can enhance coastal wetland productivity (Conner et al. 1989). In the arid areas of South Texas, freshwater input can also stimulate productivity by reducing salinity stress (Conner et al. 1989).

On the negative side, hurricanes can reduce the structural complexity of forested wetlands such as mangroves and tidal freshwater-forested wetlands (Doyle et al. 1995; Rybczyk et al. 1995; Stone and Finkl 1995). The locations with the highest probability of hurricane landfall are South Florida and the Mississippi Delta, and probabilities for the entire Gulf are high. The coastal ecosystems of the southern Gulf are dominated by mangroves, and, if warming continues, the Mississippi Delta and much of the northern Gulf will become increasingly dominated by mangroves. This trend, combined with increased hurricane frequency, would reduce the structure of these forests and destroy some of them. Freshwater-forested wetlands of the Mississippi Delta are slowly degrading and disappearing because the increased flooding from rising water levels has largely eliminated the establishment and growth of young trees (Chambers et al. 2005; Keim et al. 2006). Hurricanes can also cause tree loss; for example, during the passage of Hurricane Andrew in 1992, an extensive swath of mangrove trees were downed and defoliated across the lower Florida Peninsula (Doyle et al. 1995), and nearly 10% of trees in freshwater-forested wetlands in Louisiana were blown down in this single storm (Rybczyk et al. 1995). The kind of damage resulting from the interaction between rising water and hurricanes would be amplified by an increase in hurricanes and would hasten the loss of these forests in the Mississippi Delta and elsewhere. High runoff from hurricanes can also lead to excessive nutrient loading and eutrophication problems. For example, record runoff from Hurricane Floyd into the Pamlico Sound estuary, North Carolina, led to water quality problems (Paerl et al. 2000).

Human Activity and Coastal Management Implications

Increasing temperature, acceleration of sea-level rise, changes in freshwater runoff, and increasing hurricane intensity are the climate forcings that will affect coastal ecosystems in the Gulf of Mexico. These forcings interact with each other and with human activities to exacerbate
the impact of climate change (Day et al. 2008). For example, sea-level rise and reduced freshwater inflow lead to both increased salinity and flooding duration, resulting in multiple stresses on wetland plants. This is especially important for large expanses of coastal wetlands such as those that exist in the Mississippi and Grijalva deltas and in the Everglades. In the southern Gulf of Mexico, Yáñez-Arancibia et al. (2009) pointed out that sustainability for social and economic development must be based on the functioning of natural ecosystems, and climatic change effects must be incorporated into environmental planning because coastal erosion, salt intrusion, sea-level rise, and rainfall variability will affect development initiatives. Yáñez-Arancibia et al. (2009) suggested that economic development in the coastal zone should be based on ecological integrity. These resources represent a “natural capital” that supports the economic health of society. The goods and services provided by natural capital represent the “interest” generated by human investment in natural ecosystems. The perspective of sustainable development in the southern Gulf should be linked to the ecological integrity of coastal ecosystems with healthy and resilient conditions. This is the reason that healthy ecosystems support a healthy economy. Economic development pressure in the Mexican region of the Gulf may be approaching a non-sustainable condition (Yáñez-Arancibia et al. 2009). Climate change will alter the potential for sustainable management.

Anthropogenic changes interact with climate forcings, leading to combined effects that are often more severe than either impact acting alone. In the Mississippi Delta, isolation of the delta from the river with levees and pervasive hydrologic alteration has caused a high rate of coastal wetland loss (Boesch et al. 1994; Day et al. 2000; Boesch et al. 2006; Day et al. 2007; Day et al. 2008). These changes have also made the delta more vulnerable to accelerated sea-level rise and reduced freshwater input due to climate change. In the Everglades, hydrological alterations and diversion of freshwater flows for agriculture, human consumption, and flood control have reduced freshwater input into the lower Everglades, resulting in salt-water intrusion, wetland loss, eutrophication, and habitat changes (Sklar et al. 2005; Day et al. 2008; Madden in Chapter 2 in this volume). In addition, runoff from the agricultural area south of Lake Okeechobee has caused nutrient enrichment in the upper Everglades, which has resulted in replacement of native vegetation with cattails (Typha spp.). In the arid and semiarid watersheds of the coasts of South Texas and northern Tamaulipas, freshwater withdrawals have resulted in lowered freshwater input. This is especially the case for the Rio Grande/Río Bravo where discharge has been greatly reduced, at times completely (Yáñez-Arancibia and Day 2004). These types of changes will make the effects of climate change worse, and management is needed to counter these changes. Similar conclusions have been reached for the Rhone, Ebro, and Nile deltas. River discharge has been reduced by more than 90% for the Ebro and Nile deltas (Stanley and Warner 1993; Ibáñez et al. 1996; Pont et al. 2002), and in all 3 deltas, reduction of river input to the deltas and hydrological alterations have led to water quality problems and wetland loss. Pont et al. (2002) concluded that human impacts in the Rhone Delta will worsen the impacts of climate change.

Management for climate change will require working with natural systems to enhance their ability to survive climate forcings. Fundamentally, sustainable management should be based on system functioning (Day et al. 1997; Day et al. 2000). A basic management approach is that of ecological engineering, which is defined as “the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both” (Mitsch and Jørgensen 2003). This approach combines basic and applied science for the restoration, design, and construction of ecosystems. Ecological engineering relies primarily on the energies of nature, with human energy used in design and control of key processes.

Maintaining healthy coastal ecosystems is important because they will be more resistant to climate change. This will involve careful management of freshwater, sediment, and nutrient resources and working with natural systems to adjust to climate change. As noted earlier, diversions of freshwater can enhance the ability of coastal wetlands to survive sea-level rise and increases in salinity. However, care must be taken to minimize the potential for eutrophication. Where possible, wetlands should be allowed to migrate inland as sea-level rises. Increasing temperature is already affecting coastal ecosystems. The increase in mangrove forests in the northern Gulf is an indication of this warming trend. Perhaps mangroves could be planted in transitional areas to ensure that their establishment occurs in an orderly manner. Hurricanes have been a regular, if episodic, occurrence in the Gulf of Mexico for thousands of years, and they bring positive benefits to coastal ecosystems. They are more likely to be deleterious when coastal ecosystems are degraded and when humans put themselves in harm’s way. If hurricanes become more frequent and stronger, the structure of coastal ecosys-
tems (i.e., barrier islands, mangroves, coastal freshwater-forested wetlands) possibly will be diminished. The best defense against hurricanes seems to be healthy ecosystems.

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A number of coastal settings are present in Mexico, both in the Pacific Ocean, to the west, and in the Gulf of Mexico and the Caribbean Sea to the east, comprising a total length of 10,554 km of frontal coast open to the sea. With the coastal lagoons and islands, this totals about 24,945 km of coastline (Ortiz Pérez and De La Lanza 2006). These shorelines, to a greater or lesser extent, are subject to the rise in mean sea level, which will cause mostly irreversible modifications in coastal genesis and morphology, the expression of natural ecosystem landscapes, and substantial socioeconomic effects in local populations.

Mexico’s Gulf of Mexico coastline extends approximately 2775 km with an additional 4900 km of shoreline along inland water bodies that are protected by low sandy barriers. The coastal plain varies from 15 to 30 km wide and is cut by more than 25 important rivers and 23 lagoons of variable size. The terrestrial geomorphic processes, mainly fluvial, lacustrine, and swamp, as well as the littoral morphodynamics, have resulted in a complex interactive system of different transitional types among barrier islands, fluvial mouths, deltas, and estuaries, that are closely linked to flood plains, lagoons, salt marshes associated with mangroves, marshes, and mangrove forests (Ortiz Pérez et al. 1996).

This complex, transitional land–sea structure determines the occurrence of important geomorphological changes of variable degrees in Mexico’s littoral Gulf coasts, at different spatial and timescales (Psuty 1965, 1967; Ortiz Pérez 1988; Ortiz Pérez and Espinosa 1991; Ortiz Pérez 1992), derived from the influence of global climatic change on sea level. In turn, many of these changes are accelerated by human activities, which intentionally or unintentionally accentuate this indirect greenhouse-gas effect on the coastal system (Titus 1987) and lead to a rise in the mean sea level.

The environmental changes and modifications in coasts are evident in specific regions, such as low sandy-beach coasts, including the associated coastal and deltaic plains (Ortiz Pérez and Gutiérrez 1985; Ortiz Pérez and Benítez 1996). The marine erosion of beaches at estuarine mouths, bars, and barrier islands is a result of these changes, which become evident by the retreat of the coastline toward the interior of the continental portion. The consequences of this phenomenon are erosion, flooding, and salinization of nearby soil, surface waters, and groundwater; in turn, these influence the structural characteristics and spatial distribution of the associated ecosystems (Pannier 1992). Separately, the purpose of land use is altered, which directly affects the regional economy, which on occasion leads to the abandonment of land and the exodus to nearby, currently nonvulnerable areas.

Island territories are also affected by variations in sea level and risk serious and total modifications of their coastal ecosystems to a greater extent compared to continental systems. As an example, in the insular Caribbean, specifically in Cuba, the largest of the Greater Antilles and its 4 peripheral archipelagos, vulnerability is becoming an increasing concern given that threatened lowlands and wetlands comprise 6000 km² (5.4% of the country’s total area) with 440 beaches and 380,000 ha of mangrove for-
estos and 244 human settlements (63 urban and 181 rural) with 1,400,000 inhabitants (13% of the national total). In this coastal panorama, sea level has risen 2.9 mm/yr (GEF–PNUD 1999) over the past 3 decades and is projected to rise between 8 and 44 cm by the year 2050 (Pérez Hernández 2003). Coastal retreat has been reported for several beaches across the country, with maximal effects above 3 m/yr in the Rosario, Pepilla, and Mayabeque beaches to the south of the La Habana province (Pérez Hernández 2003) and others in the country. Undoubtedly, the geographic changes associated with these scenarios will be of incalculable dimensions.

The predictions for rise of mean sea level for intra-American seas are varied, ranging from 1–2 mm/yr over the last 100 years, and this rise can be explained by climate-related factors (e.g., Raper et al. 1996). And in other records, a rise of 10 cm is predicted for 2025 (Hanson and Maul 1994) and from 10–20 cm in the 20th century (e.g., Raper 2000), but all of them coincide in the rise of the sea level, which determines future major environmental and socioeconomic crises in coastal areas on a global scale. In this sense, the IPCC (2001) has warned of a rise 2 to 5 times as high as the estimate by Raper (2000) for the present 21st century. In previous years, the IPCC (1998), based on less reliable records, projected rises between 50 and 90 cm, but more recently this estimate decreased to between 13 and 68 cm (IPCC 2001).

In contrast, the coastal dynamics not only depend on oceanic phenomena and geographical factors but additionally on the interactions with natural terrestrial processes and human socioeconomic actions, for instance, the changes caused by human activities in the Mexican Pacific coastline by modifying the meandering pattern of the Río Grande de Santiago in the state of Nayarit (Ortiz Pérez and Romo 1994). This situation was accelerated due to sediment retention by 2 dams built in the area and led to a decline in the sedimentation process at the delta and hence reversed the erosion process from fluvial to marine.

According to the authors, this situation suggested the retreat of the coastline, resulting in a rapid change in the deltaic morphology and fostering the replacement of terrestrial habitats along the extent of affected flood plains. In contrast, Méndez Linares (2003) found that migration or succession of different mangrove communities to the front of the Barra de Navidad lagoon in the state of Jalisco was due to the accretion process of the Río Seco deltaic fan, which today continues adding sediments to the eastern end of the lagoon. These “sedimentary-trap” conditions created by the formation of a complex spit–tombolo on the coast during the Quaternary restrain the direct interaction of these fluvial–lagoon processes with the littoral abrasive–cumulative processes.

In this sense, changes in the coastline may have global, regional, and local effects (Duke et al. 1998), while the dynamic status in the functioning of ecosystems varies on short timescales; for example, daily or intra-daily scales such as the contrast of daily (day–night) variation, tidal cycle, storm rainfall, swells, and wind, factors which are mostly meteorological and that produce intense changes in coastal dynamics over a short period of time and occur with variable magnitude (Acevedo 1997). These atmospheric dynamics become more intense and complicated in the Gulf of Mexico and northern Caribbean Sea due to the influence of hurricanes (June–October), the energy of which determines broad variations and even irreversible changes in coastal areas. In the case of cold fronts, up to 15–20 nortes occur per year between October and March, with associated wind velocities reaching 100 km/h and higher (Ortiz Pérez et al. 1996) and leading to waves between 1.4 and 2.3 m high (Lankford 1977).

The functioning of mid-term states is governed by atmospheric circulation with seasonal temperature and rainfall variations, resulting in annual cycles, comprising coastal and continental currents, wave cycles, and even phenomena with periods of more than a year. The following landscape development stages may be differentiated: young (formation) stage, plant succession, recent sedimentary sequences, various mangrove ages, and recent readjustments derived from changes in salinity and humidity under a total process of evolutionary change. Changes can be either steady or sudden as a result of the combination and balance of the different factors and coastal physiography, which confers various levels of spatial and temporal magnitude to the coastline sensitivity to structural and functional modification and leads to disruption of the self-regulated internal integrity of the coastal system.

One cause determining disruption of balance in the coastal zone is the recent tectonic movement regime of the earth’s crust, which may give rise to 3 basic situations (Fig. 15.1): (A) areas where a rise in sea level and intense tectonic uplift results in the formation of emersion, abrasive, and steep coasts; (B) stable tectonic areas where the rise in sea level will determine coastal transgressions; and (C) areas under intense subsidence where the sea transgression undoubtedly will reach extreme levels. The last case involves the highest conflicts for coastal system development, both in terms of natural ecosystems and for
ment measures aimed at preserving these fragile ecosystems. Given the historical and current trends in the development of human settlements and their socioeconomic infrastructure along coastal zones, those in the Gulf of Mexico and the Mexican Caribbean area, with more than 4 million inhabitants, are no exception. It is essential to establish regional and local land-use management strategies immediately to ameliorate the effects of extreme hydro-meteorological phenomena, unfortunately strengthened by sea-level rise, and to achieve proper planning in zones where the earth’s crust is subsiding, yet to be revealed through the use of applied geodesy.

The Reality of Coastal Retreats

The expanded influence of the sea is already evident in wetlands, deltaic plains, mangroves, and lagoons that are connected to the sea and even in those isolated by barriers because they communicate by capillarity or saline intrusion. Given that the majority of coasts along the Gulf of Mexico and Caribbean Sea are low sandy coasts with extensive adjacent wetlands located less than 1 m above mean sea level, such marginally distributed fringes would be directly affected by the rise in sea level (Table 15.1), as well as the immediate surrounding zone (Table 15.2), where elements at potential risk from the variations in mean sea level are considered.

Geographical and Historical Cartographical Evidence and Risk Scenarios

The areas potentially affected by the rise in mean sea level, in terms of both vegetation and land use, are shown as percentages for the different regions of the Gulf of Mexico and Caribbean Sea coastlines. In the supralittoral zone, more than 75% of mangroves are located between the central-southern Gulf and Caribbean coastlines, comprising an approximate area of 4234 km² (Fig. 15.2a); the region with the highest proportion of halophyte species is the central southern coastline, with nearly 50% of cover (1170 km²) compared to the rest of the coastlines (Fig. 15.2b).

Water bodies and lagoons with the largest area along the coastlines are located on the northeastern and southeastern Gulf of Mexico coast and comprise more than 3000 km² (Fig. 15.2c). In the infralittoral zone, swamps are widely spread in the south-central Gulf (34%) and Caribbean areas (36%) with respect to the total extent of the coastline (Fig. 15.2d); grasslands comprise nearly 50% at

Figure 15.1. Interactions between the rise in mean sea level and crustal stability of the earth in coastal zones: (A) tectonic rise of the crust of the earth; (B) tectonic stability; and (C) intense subsidence. The current situation is shown to the left; expected scenarios derived from a rise in mean sea level are shown to the right.

Mangrove ecosystems have been used as indicators of change in the coastline (Pannier 1992). Semeniuk (1994) reported that the response of mangroves to future changes in mean sea level remains uncertain, whereas in deltaic areas it will vary significantly. Consequently, the greenhouse effect and global warming may have impacts at different scales, and depending on the range of physical and chemical conditions, mangrove systems may respond differently along the coast. For example, a small rise in sea level in a coast undergoing active sedimentation may affect the sedimentation patterns and, consequently, the associated mangrove systems. In another case, a similar rise in sea level may directly affect the mangrove vegetation, flooding its habitat, and this same condition in a third locality may cause a migration of mangrove vegetation over a muddy tidal plain, advancing to the sea. Finally, in an arid locality, a slight rise in sea level may cause the death of mangrove trees as a result of stress and their low reproductive rate.

The geodiversity context of coasts in the Gulf of Mexico and the Caribbean Sea is so broad, diverse, and multifactorial that in view of the global and/or regional changes in mean sea level, spatial analyses and specific modeling will be required to determine its significance as well as to specify prevention, mitigation, and management measures aimed at preserving these fragile ecosystems.
Comparative cartographic interpretations for 1943–1958 and 1972–1984 (Ortiz Pérez and Benítez 1996) showed that coastline retreat is a common event along the whole deltaic front in the states of Tabasco and Campeche, with a mean rate of 8 m/yr and up to 15 m/yr in extreme years at the San Pedro–San Pablo river mouth, and 8.5 m/yr with extreme values of up to 21 m/yr on the Atasta coast. Recent calculations (Ortiz Pérez et al. 2005) comparing the coastline in 1972, 1984, and 1995 along the Tabasco coast revealed alarming coastal retreat in various sectors, such as (from west to east) El Alacrán (127 m); Tupilquillo (28 m); Barra Tupilco (17 to 98 m); Playa Azul (47 m); La Unión, first section (37 m); Playa El Limón (262 m); Playa Dos Bocas (91 m); Playa Bruja (35 m); Barra Chiltepec (104 m); the south central portion, with 2580 km² (Fig. 15.2e). In contrast, agricultural zones are distributed extensively across the central and south-central coastlines, with over 400 km² (Fig. 15.2f), and dune fields account for 42% and 36% along the Campeche and Yucatan-Gulf coastlines, respectively (Fig. 15.2g). The largest urban areas that may be potentially affected by variations in mean sea level are distributed from the central Gulf to the Mexican Caribbean coastline.

Morphological modifications or changes in the coastline are the clearest evidence of its retreat to the interior of the continent (Ortiz Pérez 1992) (Fig. 15.3), demonstrated through comparative analysis of aerial images taken on different dates above the San Pedro and San Pablo rivers deltaic front at the border between Tabasco and Campeche. The destruction of land, erosion, and flooding shown in Figures 15.4–15.7 are also evidence of these coastal changes.

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to the east, at Playa Azul, also in Tabasco, coastal retreat calculated by comparison of cartographic sequences and current ortho-photographs yielded values of 47 m between 1984 and 1995, or a rate of 4.3 m/yr. Moreover, estimates by inhabitants in this area (Renato Segura, local resident, personal communication, 2004) revealed a substantial retreat of 25 m in 5 years. Interviews with the inhabitants of this village revealed a substantial retreat of 25 m in 5 years (Concepción de la Cruz Martínez, local resident, personal communication, 2004), with a rate of 5 m/yr. This estimate is similar to the data obtained during the last monitoring year, 3 m/yr.

Currently, some of the most critical sectors are located in the Sánchez Magallanes village in the state of Tabasco where the coast retreat has led to the destruction of a portion of the settlement (Fig. 15.4). Interviews with the inhabitants of this village revealed a substantial retreat of 25 m in 5 years (Concepción de la Cruz Martínez, local resident, personal communication, 2004), with a rate of 5 m/yr. This estimate is similar to the data obtained during the last monitoring year, 3 m/yr.

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Arancibia and Day (2005) presented calculations on the Caribbean coast of Mexico (Quintana Roo state) where Hurricane Wilma impacted the Cancún coast with waves and an 8 m storm surge with a dramatic erosive effect. Additionally, modifications of this sort in sandy coastal zones are accelerated by human activities such as sub-

reflect a retreat rate of 1.5 m/yr because they consider that the retreat from 1932 to date has surpassed 100 m.

The beaches of the Yucatan Peninsula, located farther to the east, also do not escape the erosive effects of the sea, with values of up to 30 m of retreat at Playa del Carmen and Holbox Island (Excelsior 2000). Recently, Yáñez-

Figure 15.3. Detail of the retreat of the deltaic front of the San Pedro River (Tabasco–Campeche) from comparative cartography and recent ortho-photographs (Ortiz Pérez et al. 2005).

Figure 15.4. Coastal retreat at the town of Sánchez Magallanes, Tabasco, Mexico, in September 2004. Notice the houses threatened by the sea and the defenses (“Yucateco” palisade fronts and sand sacs) built by inhabitants to attenuate the effects of waves.

Figure 15.5. Mangrove communities serve as indicators of coastline instability due to characteristics of their zonation (Pannier 1992). They are highly susceptible to sudden changes that cause their disappearance.
marine sediment extraction from the nearby insular platform, inadequate construction of tourist and residential infrastructure upon the fragile beach elements and dune strips, and the design of the so-called “hard solutions” such as concrete pier dams built perpendicularly to the coast. On Varadero beach in the north of Cuba, these activities jointly led to a loss of 50,000 m³ of sand per year since 1978 (Juanes Martí 1996; Juanes Martí et al. 1998). This amount was then restored along more than 12 km of beach during 2 beach nourishment projects: first, by dredging and simple addition of 763,000 m³ of sand (Juanes Martí et al. 1998), and second, by trailer suction hopper dredging in 1998, comprising 1,078,835 m³, with a cost of more than US$5,000,000 (Hernández Santana and Reyes González 2002). This practice is common in Caribbean insular beaches and is even seriously affecting coral reef ecosystems indirectly (P. Alcolado, Agencia de Medio Ambiente de Cuba, personal communication, 2001).

In addition to beach nourishment by the addition of sand, one way to prevent erosion that is currently being applied in many locations, including the Cancún beach, is construction of submarine defenses parallel to the beach, using Sandtainers or geotextiles to reduce wave energy. This method has yielded favorable results in the construction of artificial beaches in Cuba’s central-northern region.

Tectonic Subsidence and its Role in the Modification of Coastal Ecosystems

Subsidence is a regional or local phenomenon that is an additive effect of the rise in sea level at a global scale. Land sinking or subsidence directly depends on subsoil structure and recent tectonics in the corresponding geological basin (Bird 1993; Ortiz Pérez and Benítez 1996). All interactions take place on or around sediment accumulation, in deltaic or marginal geological basins, where deposit of hundreds or even thousands of meters has occurred throughout geological time. Subsidence starts from the uneven distribution and arrangement in which sediments are deposited in the basin, given that the weight and compaction of the sediment column causes the steady sinking of the earth’s surface (Fig. 15.8).

Differential subsidence occurs because the thickness and weight of sediments differs throughout the basin. Sediments that are closer to the continent become wedged and thinner toward the basin borders where their descent is slower because they weigh less. At the distal, central, and deeper portions of the basin, the sedimentary column
gets thicker and sinks faster, resulting in an uneven subsidence. Other common elements of the subsoil geologic structure, such as normal active faults, contribute to faster subsidence. These faults will be active as long as the weight of the sedimentary cover remains and is renewed by inputs that will enlarge the column and accentuate the descent of the continental fringe.

In contrast, along with the effects of the atmosphere–sea interactions and their repercussion on the rise in mean sea level, determination of recent tectonic movements of geological structures upon which coastal ecosystems rest is vital, mainly for the youngest plains, to detect the current descending sectors, which are already changing and/or degrading the terrestrial cover (Hernández Santana and Magaz García 1993). Under such conditions, littoral abrasion with the coastline retreat and penetration of saline water into groundwater increased, resulting in the salinization of freshwater bodies and agricultural land, development of lagoonal–swamp processes, modification and replacement of plant cover, as well as alteration of microclimatic parameters, temperature and water balances, and hence land use and terrestrial cover degradation. This terrestrial "oceanization," conditioned by tectonic subsidence, may surpass the most irrational human alteration of coastal zones.

For this reason, geographic modeling of the interactions between the forces of global or regional changes in insular and continental coastal territories must refer to the stability levels in the earth’s crust and the current tectonic trends, as a geographic core of development, and current and future changes in terrestrial cover. In these cases, land-use management, conservationist management strategies, and inversion and construction policies are all obliged to contemplate the magnitude and spatial influence of the geodynamic regime of the earth’s crust.

In the coastal region of the Cauto River basin, the largest Cuban hydrographical basin that empties into the Caribbean Sea, the comparative geodesic calculations of the

Figure 15.8. Consequences and effects of variations in mean sea level in relation to socioeconomic, physical, and biological factors.
first-order leveling coastlines between the periods 1948–1968 and 1970–1981 yielded subsidence of −2 to −3 mm/yr (Hernández Santana et al. 1989). This subsidence, when added to the effects of dam construction since 1964 has reduced sedimentary transport and allowed penetration of saline water tens of kilometers inland, leading to the salinization of groundwater and soil, which in turn has contributed to the alarming degradation of its natural and human–natural ecosystems. Other evidence of these effects, caused by the rise in mean sea level, is found in the comparative cartography between the 1950s and the present: mangrove ecosystems advanced 100 to 300 m (about 5 m/yr) into the basin; Cabo Cruz village was reconstructed upon the highest abrasive terrace, to the east of the original settlement; portions of the colonial road of the region disappeared under muddy areas or because it approached the present coast; and the total marine transgression of keys and cumulative forms in the Manzanillo littoral zone at the Gulf of Guacanayabo.

Effects from the Interference with other Biological and Socioeconomic Factors

From the subsidence phenomenon (Fig. 15.8), a series of effects with global environmental repercussions emerge. In addition to loss of land by beach erosion and concomitant coastline retreat on the mainland, penetration of the saline tidal wedge inland caused salinity of estuarine waters to increase and modified estuarine conditions. In turn, this stimulated the sediment-deposition process by promoting the formation of “mud plugs” due to the flocculation of electrostatically charged clays and/or aggregates of fine particles when they come in contact with saline water (follow the feedback circuit in Fig. 15.8). The obstacles formed by sediment deposition constitute barriers that restrain the free flow of freshwater runoff, which contributes to deficient drainage that translates into a potential increase of floods. These are examples of physical factors.

Inland sedimentation, more frequent floods, and slopes with little incline also contribute to a higher hydrographic instability of water courses; the modifications in the fluvial trajectory lead to frequent floods because of poor drainage conditions. These processes give rise to new deposit centers, phenomena that form almost imperceptibly and that contribute to uneven subsidence and reduction of the coastal lagoon surface, as determined by Ortiz Pérez and Benítez (1996) in the case of the El Vapor, Las Piñas, and the Marentes lagoon system at the mouth of the Palizada River, surrounding the Laguna de Términos, with sediment accumulation >15%. In this way, a new positive feedback subsystem is completed within a larger system (Fig. 15.8).

The repercussions on biological factors in an open system are evident. For example, the input represented by saline intrusion from the external environment, in this case seawater, and the lack of control of this input within the system, result in salinization of adjacent soils and the likely contamination of shallow water bodies. Both alterations affect the condition of the habitat in general, because there is a change toward physiological aridity, as part of the desertification process, which is evident in the withering and death of vegetation. Changes also occur in the vegetation structure and composition through the replacement of hydrophyte communities by colonization with halophyte grasses and sparsely distributed, young, shrubby mangroves, a detriment to the capacity of the soil to support vegetation (Zavala 1988).

The overall trend is modification of the habitat added to the stress imposed by simultaneous inland migration of hydroseries and ecotones due to displacement of coastal and lagoon littoral fringes toward the continent. Subsequently, the original zonation of freshwater wetlands is reduced and/or broadened due to the barrier of positive relief (heights from 1 to 10 m) that limits expansion toward the interior.

Not all consequences of this impact can be easily visualized. For example, a series of limiting factors for biological diversity, adaptation, and establishment of a new biocenosis, processes that, in terms of overall productivity, translate into a decrease and/or replacement of the natural productivity of ecosystems, and consequently, into decreases in and/or other effects on basic natural resources (water, soil, and vegetation).

The trend has been for the system to form a set of linked events around the secondary succession process, characterized by being out of phase, that is, out of balance as long as the migration and an external control of succession persist. In this way, these phenomena as a whole lead to natural resource abatement issues (Fig. 15.8). At this point, the model enters the economic sphere, in the reference framework of societal effects and actions.

The pressure exerted by population growth and the economy have transformed the natural function of lowlands adjacent to the coast because natural resources are degraded when perturbed by an inappropriate land use.
One example is deforestation, in which tropical forests, swamps, and mangroves are replaced by grasslands for extensive cattle raising and/or through burns, normally controlled, in the dry season to promote growth of grasslands.

These issues become aggravated when added to the effects of global climate change, specifically atmospheric heating caused by increased concentration of greenhouse gases such as carbon dioxide (CO₂), methane, chlorofluorocarbons, and other gases that are capable of absorbing infrared radiation and retaining heat in the atmosphere (PNUMA 1989). The heat trapped in the atmosphere has been calculated to increase global temperature by 3–4 °C and will also cause the temperature of the oceans to increase. This rise in air and water temperatures may cause ice blocks to break off ice sheets and reach intermediate latitudes where further melting occurs, a phenomenon that will surely foster the acceleration of sea-level rise.

**Vulnerability of the Mexican Coastline in the Gulf of Mexico**

Geomorphological monitoring allows us to determine different coast types, products of geological history, and the distinctive lithological nature of the formations they include; for example, the rocky coasts made of hard or consolidated materials can be distinguished from coasts constituted of soft materials where low sandy coasts are modeled. In this way, coasts can be differentiated in terms of the arrangement of their geomorphological components (erosion, transport, and accumulation forms), which become evident through the coastline instability and can be summarized in 3 likely types: transgressive coast, regressive coast, and stable equilibrium.

Regressive behavior is defined as coastline advancement toward the sea. It occurs through sedimentation (accretion) at the deltaic front by transportation of coastal sediments and continental emersion from tectonic movements, and/or by the accumulation of volcanic materials.

Transgressive behavior is observed when the coastline retreats inland by subsidence or continental or insular sinking, due to recent descending tectonic movements, by both sediment compaction and the development of normal growth faults in marginal geological basins and/or rise in sea level. In addition, coastline retreat toward the continent can be caused by an reduction of the fluvial or deltaic sediment supply (by dams, fluvial deviation channels, dikes, and other constructions) and interferences by human infrastructure projects (pier dams, piers, and breakwaters).

Stable coasts are unaffected by eustatic movements, are in apparent equilibrium, in which movements cannot be detected with current knowledge or measurements, and hence, are neutral. This category is conventionally assigned to the undifferentiated coastline that requires further investigation to determine its condition and arrangement in relation to eustatic movements.

For the identification of the first 2 types, a comparative table of attributes was constructed, most of which are visible components that are expressed at the surface, except for the sedimentary environment and the ecological implications, which do not necessarily lead to processes evident at a territorial level (Table 15.3). These analytical elements were used to identify the zonation of fragile coastal areas or those most vulnerable to the advancement of the sea to the continent and were used to estimate impacts with environmental implications. According to this characterization and on the basis of the modification to the coast classification system proposed by Ortiz Pérez and Espinosa (1991), six coast types can be identified along the Mexican coastline of the Gulf of Mexico (Fig. 15.9): abrasive coasts, abrasive–cumulative coasts, cumulative coasts, deltaic cumulative coasts, coasts of flood plains and intertidal cumulative plains, and biogenic coasts.

**Abrasive Coasts (Rocky Coasts)**

The environment of abrasive coasts is dominated by the constant action of waves, with the formation of sea terrace levels and cliff-shaped coasts. A singular case in the Gulf coast is the Cazones abrasive zone, in the state of Veracruz, which stands out in the subsiding geological context of the Tampico–Misantla basin. This abrasive zone responds to the differentiated tectonic ascents existing in some blocks with a low rank in this oil basin, evidenced in structural profiles with exploratory purposes (López 1979).

**Abrasive–Cumulative Coasts (Mixed Coasts)**

The abrasive–cumulative coast environment has waves buffered by the refraction of the incidence angle; that is, coastal sites alternate between those that project into high-energy seas and those in areas of low-energy seas or buffered waves and local sediment transport by littoral-
drift beach currents. A typical case in the Gulf is the coastal sector associated with the Los Tuxtlas volcanic edifices in the state of Veracruz.

**Cumulative Coasts (Low Sandy Beaches)**

The cumulative coast environment has constant, constructive, low-energy waves, with supply and abundant beach deposits. Sedimentation is interrupted only in times of storms by erosive waves and berm formation. This coast type has a variable beach profile, both in the Gulf of Mexico and in the northern Caribbean Sea (beaches located north of Cuba, Hispaniola, and Puerto Rico), depending on the regime of waves and sea currents during the summer and winter.

**Deltaic Cumulative Coasts**

Three deltaic cumulative coast environments can be identified: (1) fluvial sedimentation processes that prevail...
in environments with scarce wave energy, (2) wave modeling at the deltaic front and sediment redistribution in bars at both sides of estuary mouths, and (3) macrotidal environments characterized by estuary mouths with high physical energy, circulation, and mixing (for example, the Colorado River delta).

Coasts of Flood Plains and Intertidal Cumulative Plains
On these coasts, tidal oscillation (ascending and descending) is usually accompanied by extensive sedimentation processes, alternating flooding cycles of variable magnitude and marginal plains exposed during low tide, and highly variable characteristics at the surface (sequences of high evaporation and salinization and successive flooding). Normally, this coastline type occurs in flood plains protected from the open sea, in interior or protected waters (for example, the Petenes and Sian Ka’an plains).

Biogenic Coasts (Mangrove and Coral Barrier)
The distinctive characteristics of biogenic coasts are absence of a beach and mangroves exposed to the direct action of waves but with a low physical energy. The coralline coast and/or coast with shell fragments (coquina), emerges at ebb tide and forms abrasion platforms at the wave front, morphology modeled by karstic dissolution processes with influence of underground runoff from the continental fringe (for example, the Cancún–Tulum coast).

Response to Modifications in Mean Sea Level
The reactions and consequences, in terms of alterations of ecosystems and their environmental services, as well as the level of economic losses that coastal systems will suffer as a result of the rise in sea level, are not fully predict-
Sea-Level Rise and Vulnerability

This leads to inertia. The geodynamic monitoring program outlined above would greatly contribute to solving this preventive–corrective need in matters of coastal land-use management, in the most vulnerable sectors. The socioeconomic impact on the environment is evident, as well as the repercussions of the rise in mean sea level on global and regional scales. The consequences of this phenomenon are steadily more visible and of a greater magnitude; for this reason, prevention, mitigation, and control actions must be implemented. To prevent potential impacts, the identification and measurement of changes that occur in the coastline is proposed, as well as monitoring the modification of the fluvial network and the expansion of temporal and permanent flood-prone areas and, once the most vulnerable and at risk areas are identified, establishing the corresponding preventive and mitigating measures (Table 15.4). The best solution for any timescale is the combination of the 3 groups of measures within the framework of an integral management plan for the coastal zone (Cendrero et al. 2004). This proposal for the Gulf of Mexico and Caribbean Sea is shown in general terms in Figure 15.10.

Conclusions

The projections related to the rise in mean sea level are not questioned, given that the steady rise over the past decades and its noticeable effects in the lowlands of the world coastal system represent the most perceivable and

Table 15.4. Some alternative responses to face the rise in mean sea level.

<table>
<thead>
<tr>
<th>Coastal vulnerability</th>
<th>Response</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low vulnerability</strong></td>
<td>Defense</td>
<td>Construction of infrastructure works (dikes, barriers, filling platforms, etc.) to protect villages, ports, oil refineries, and industries in general</td>
</tr>
<tr>
<td>Very low coastal plains, with prevalence of relief of cumulative genesis (deltaic, fluvial, and marine).</td>
<td></td>
<td>Foster the cumulative fluvial regime through the elimination of upstream engineering traps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Conservation of ecosystems acting as natural buffering barriers facing the waves and sea energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fixation of dunes and coastal vegetation</td>
</tr>
<tr>
<td><strong>Intermediate vulnerability</strong></td>
<td>Adaptation</td>
<td>Adoption of territorial land-use management plans and restrictions in critical zones, preferring extensive over intensive uses for agriculture, cattle raising, and fisheries</td>
</tr>
<tr>
<td>Low plains, with episodic marine influence, subjected to climatic seasons and extreme hydrometeorological events</td>
<td></td>
<td>Fixation of dunes and coastal vegetation</td>
</tr>
<tr>
<td><strong>High vulnerability</strong></td>
<td>Retreat</td>
<td>Inventory of potential critical areas for the elaboration of abandonment plans</td>
</tr>
<tr>
<td>Very low plains with permanent marine influence and with no possibilities of application of defense and adaptation measures</td>
<td></td>
<td>Human retreat from the territory and relocation of human settlements, economic infrastructure, and primary activities in nonvulnerable areas</td>
</tr>
</tbody>
</table>
irrefutable evidence and events. This chapter has focused on the implications and consequences of sea-level rise as a phenomenon that coexists with the subsidence of the earth's crust as a result of regional and local tectonics as well as due to compaction and descent of the Gulf of Mexico coastal depocenters.

This trend is also reflected in the changes of coastal ecosystems, the dominance of their polygenetic cumulative morphology, the coastal hydrodynamics values and the retreat of Mexico's Gulf coastline, and the geological–geomorphic evolution of the continental passive fringe itself, guided by the differential descent of the marginal geological basins (Burgos, from Tampico–Mizanta; Vera-cruz; Salina del Itsmo; Comalcalco and Macuxpana) and the tectonic–structural faults in the Yucatan Peninsula. In this context of steady marginal accretion and differential sinking, structures stand out for their trend toward stability and/or uplift, displaying abrasive marine terraces and cliff-like sectors, either continuous or intermittent, as in the case, from north to south and east, of the Cazones region, in the coastal volcanic mountains of the eastern end of Macizo de Teziutlán, in the volcanic premountain and mountain relief of Los Tuxtlas, and in the plains and terraces of theYucatan Peninsula.

Unfortunately, the lack of direct quantitative and systematic oceanographic, hydrological, and geodynamic indicators hinders the determination, with finer precision, of the modalities and properties of the land–sea interactive phenomenon and its spatial consequences. The results obtained and commented on so far provide a
trend-oriented framework, also very valuable in relation to preventive, corrective, and control measures.

The advantage of the approach used here is the identification of the areas most vulnerable to the rise in mean sea level and its current and projected effects. The knowledge and analysis presented here about coastal vulnerability are derived from the comparative interpretation of cartographic sequences and aerial–photographic materials, as well as from monitoring along the whole coastline over 15 years. In turn, the physiographical arrangement of coastal components was the analytical key that enabled detection of changes, modifications, and effects (erosion, flooding, and salinization), the latter through identification of changes in vegetation cover and land use. Comparing 1972, 1984, and 1995 revealed maximum coastal retreat values between 354 and 589 m for the state of Tabasco leeward of the Usumacinta River mouth, between 98 and 127 m in the Barra de Tupilco–El Alacrán portion, and between 87 and 262 m at the Paraíso and Limón beaches, respectively. This phenomenon has affected ecosystems, human settlements, and the coastal highway network. Furthermore, the oil pipelines have been unearthed and exposed to the most aggressive natural and human agents, generating likely scenarios for other types of chemical contamination threats in ecosystems located in Veracruz and Tabasco.

The evaluations presented here have identified and provided evidence of the negative effects in the field. We have indicated the most immediate ways to reach a multifactorial quantification of the rise in mean sea level. We have provided a means to classify, through new environmental degradation indicators, the degree of coastal vulnerability. We have also identified ways to orient strategic management policies with government and social actions to prevent and mitigate the inevitable consequences of the glacio-eustatic crisis already underway in the global coastal system.

References


