Chapter 6
Coastal Systems in the *Anthropocene*

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> *All the parts incessantly work into each other's hands for the profit of man. The wind sows the seed; the sun evaporates the sea; the wind blows the vapor to the field; the ice, on the other side of the planet, condenses rain on this; the rain feeds the plant; the plant feeds the animal; and thus the endless circulations of the divine charity nourish man.*
>
> —Ralph Waldo Emerson, *Nature*—1833
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> *But man is a part of nature, and his war against nature is inevitably a war against himself.*
>
> —Rachel Carson, *Silent Spring*

6.1 People and Coasts

People are integral parts of nature and, in many respects, are becoming dominant parts. This notion is implicit in the term "Anthropocene". In no environment is the connection between people and nature more apparent than in coastal systems. Mutual causality between humans and nature plays out there on a daily basis, sometimes in very positive ways and other times in tragic ways. The enjoyment of coastal beauty and spiritual stimulation are among the positive attractions as are access to global seaways, fisheries and recreation. Death, disease and destruction wrought by severe storms and tsunamis are paramount among the downsides. But for a multiplicity of reasons, roughly half of the world's 7 billion people live within

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100 km (60 miles) of the shore. And the activities of those who live much farther inland, for example within the catchments of large rivers that run to the coast, impact the coastal environment and its residents in numerous ways. Human activities that directly impact coastal systems include urbanization, agriculture, nutrient runoff, engineering works, fisheries, oil and gas production, dredging and various forms of pollution. Natural processes that impact coastal residents include sea level rise, storms and storm surges, water-borne pathogens, tsunamis, and loss of ecosystem services. Important ecosystem services include pollination, decomposition, water purification, erosion and flood control, carbon storage, and climate regulation.

6.2 Coastal Urbanization

Worldwide there are 23 *megacities* with populations of over 10 million people. Of these, 16 are in the coastal zone (Pelling and Blackburn 2013; Blackburn and Pelling 2014). In some of these cases, urban sprawl of neighboring cities has caused mergers into huge urban "agglomerations". The ten largest of these cities are: Tokyo, Japan; Mumbai, India (Fig. 6.1); São Paulo, Brazil; Dhaka, Bangladesh; New York-Newark, USA; Calcutta, India; Shanghai, China; Karachi, Pakistan; Lagos, Nigeria; and Manila, Philippines. The combined population of these 10 cities is projected to reach 216 million by the year 2025 (von Glasow et al. 2013). However, as explained in Part 3, Chap. 12, the huge agglomeration of cities surrounding Guangzhou, China in the Pearl River Delta, now has a combined population of 66 million people making it the world's largest urban center. The population of all of the 16 coastal megacities combined in 2025 will be about 323 million. Twelve of the coastal megacities occupy river deltas that are subject to subsidence (Table 6.1; Pelling and Blackburn 2013; Overeem and Syvitski 2009). In 1975, 62 million people lived in these deltaic cities. The number had grown to 140 million by 2010 and is expected to reach 242 million by 2050 (Overeem and Syvitski 2009; Pelling and Blackburn 2013). By some estimates, the number is much larger (e.g. Dawson 2017). In his recent book, Dawson (2017) describes the dire plight of the growing number of people living in flood prone coastal urban slums. Migration has been the primary cause of the population growth of these cities to date, but poverty has dictated the concentration of people in low-lying areas.

In addition to megacities, there are many other smaller cities and towns within the world's coastal zones. Among these are a growing number of tourism oriented beachfront "strip" cities. Some of the more prominent of these include many of Florida's coastal resort towns, Australia's Gold Coast, Mediterranean coastal resorts and many Caribbean islands. In many cases the wall-to-wall high rise hotels and condos of these cities have been built so close to the shore that they do not allow for sufficient buffering against storm-induced erosion and require frequent sand re-nourishment to offset the permanent offshore loss of sand.

Fig. 6.1 Coastal urban skyline, Mumbai, India. Image courtesy of Pixabay PDPics free images

Table 6.1 Megacities occupying deltas 1975–2050

City	Delta	Population (millions)		
		1975	2010	2050
Karachi	Indus	4	12	31.7
Kolkata	GBM	7.9	15.1	33
Dhaka	GBM	2.2	13	35.2
Rangoon	Irrawaddy	1.8	6.3	10.8
Bangkok	Chao Phraya	3.8	8.2	11.9
Ho Chi Minh	Mekong	2.8	10	26
Hanoi	Red	1.9	4.2	10
Guangzhou	Pearl	3.1	9.6	13
Shanghai	Changjiang	11.4	20	21.3
Tianjin	Huanghe	6.2	9.8	10.1
Cairo	Nile	6	16.9	24
Buenos Aires	Parana	10.9	14.2	15.5

Data Sources Pelling and Blackburn (2013) and Syvitski (2008)

As Blackburn and Pelling (2014) point out, “collisions” between coasts and cities are already having negative impacts on both the natural environment and the people who live in the cities. These negative consequences are expected to grow significantly over the coming decades (Duraiappah et al. 2015; UNU-IHDP 2015). The coastal environmental damages caused by extensive urban developments are manifest in numerous ways. At the lowest order, the shear weight of cities and extraction of ground water contribute to accelerated subsidence and hence to local increases in the rate of relative sea level rise (e.g., Allison et al. 2016). von Glasow et al. (2013) describe several other, less obvious impacts of cities on coasts. Urban heat islands along with the obstruction of airflow by buildings alter atmospheric circulation and may block sea-breeze/land-breeze ventilation. Runoff of nutrients and pollutants—including sewerage—directly impact estuarine, marine and wetlands ecosystems and often causes toxic algal blooms. The resulting eutrophication causes "dead zones" of low dissolved oxygen in adjacent waters. Aerosols and particles released into the local atmosphere can also affect the adjacent coastal ocean. According to von Glasow et al. (2013), the atmospheric effects can reach hundreds to thousands of kilometers beyond the cities while the estuarine and marine impacts can extend tens to hundreds of kilometers seaward or down the coast. Degradation of wetlands surrounding cities reduces natural protections against storms and increases urban vulnerability.

Natural processes, and human modifications of those processes, in turn, threaten the cities and their inhabitants. Unplanned urbanization is a major contributor to the increasing risk faced by coastal city dwellers (Blackburn and Pelling 2014). The International Human Dimensions Program on Global Environmental Change (UNU-IHDP 2015; Hallegatte et al. 2013) points out that by midcentury, the flood risk to large coastal cities will have increased by nine-fold relative to the present day. The property damage and socio-economic losses for all coastal cities combined is estimated to be in the neighborhood of US $1 trillion. It must be noted, however, that such estimates are based on damages to tangible property, such as expensive real estate, and on losses of income. In most cases the "victims" of these economic losses are wealthy or affluent corporations or individuals and are typically covered by insurance. The most tragic losses are usually less quantifiable in conventional economic terms and are often borne by low-income, and uninsured, residents. In his recent book, Ashley Dawson (2017) refers to the global convergence of climate change, urbanization and poverty as "extreme cities".

The elevations of coastal cities in general are low; but the lowest income people are commonly forced by competition with the more affluent residents to occupy the lowest and most flood-prone parts of the city. In some developing countries, the most vulnerable areas are the sites of slums (Dawson 2017). The human tragedies that unfold there during floods or extreme storms cannot be described in simple economic terms. Unfortunately, decisions about the investments of limited resources in flood mitigation structures etc. are often driven more by cost-benefit analyses than by compassion. Hanson et al. (2011) conducted a detailed analysis of predicted socio-economic and environmental changes between today and 2070. They conclude that by 2070 the monetary value of assets exposed to coastal inundation will be ten times greater than today while the exposed urban populations will increase three fold. However, the exposed assets will be primarily in more affluent western nations while the greatest increases in vulnerable populations will be in poorer Asian countries. For example, the present inundation-exposed populations of the cities of Calcutta and Mumbai, India are respectively 1.9 million and 2.8 million but are projected to be 14.0 million and 11.4 million by 2070.

As outlined by the IHDP (2015), the three main strategies for addressing future flood threats to coastal cities are: "retreat", "resist" or "attack". For small communities, retreat is usually the least costly and simplest option; it simply involves relocating to higher ground. But it is frequently unpopular because it means abandoning prior investments or traditional neighborhoods. For megacities, retreat is difficult to accept—but it was seriously considered after the 2011 flood of Bangkok. (For more information on the Bangkok floods of 2011 see InterNations online at URL: https://www.internations.org/bangkok-expats/guide/moving-to-bangkok-15519 and the Taylor (2011) article in *The Atlantic*.) To resist requires the construction of defensive structures such as levees, floodgates, pumps etc. Such structures directly alter surrounding environmental conditions such as estuarine circulation. Finally, the "attack" option is the most expensive because it involves the reclamation of lands surrounding the city. Hino et al. (2017) recently examined 27 cases where managed retreat from natural hazards was successful in relocating 1. 2 million people. However, these cases were relatively small scale and did not involve whole cities. In fact, those authors note that applications of the "retreat" model face serious challenges given the projected scale of climate-induced displacements and the many difficulties of resettlement. In its summary for decision makers, the UNU-IHDP (Duraiappah et al. 2015) recommends the following strategies for future adaptation: (1) seek greater understanding of what is happening; (2) consider managed retreat or relocation; (3) consider combined approaches that include engineering structures, natural enhancements such as the planting of mangroves, and improved early warning systems based on better forecasts of flood events. Dawson (2017) points out that, although retreat is typically regarded as the "last taboo", it may be the only realistic option over the long term.

6.3 Agriculture and Its Impacts

Globally, the area of the earth's surface covered by croplands is roughly equivalent to the size of the South American Continent and that occupied by animal agriculture is similar to the area of Africa (IGBP 2013; Nature Conservancy; Fig. 6.2). By the year 2050, the food requirements of the world will roughly double. Clearly, however, the fraction of the earth's surface devoted to food production cannot also double without catastrophic environmental consequences: agriculture is a major contributor to climate change and animal agriculture is a major source of methane and consumer of water (Rust 1981; Crutzen et al. 1986). Most of the agriculture is not concentrated in the coastal zone but is farther inland. However, many of these inland farmlands are located within the catchments of major rivers, which flow to coasts. In addition to carrying water and sediments to the sea they also carry nutrients from farm fertilizers along with pesticides sprayed on crops. Pesticides can kill aquatic organisms and reduce biodiversity in coastal and estuarine waters and in wetlands.

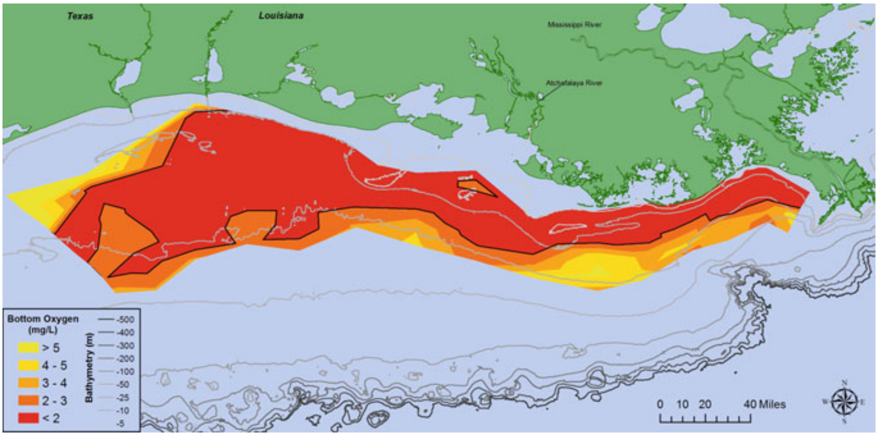

Fig. 6.2 Distribution of bottom-water dissolved oxygen, July 24–July 30, 2017. Black line denotes 2 mg l^{-1}. *Data source* N. N. Rabalais, Louisiana State University & Louisiana Universities Marine Consortium; R. E. Turner, Louisiana State University. Funding: National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science

Nutrient over enrichment in coastal waters from non-point sources causes damaging stresses on aquatic, estuarine and marine ecosystems by fueling nuisance blooms of algae, bacteria and phytoplankton (Dale et al. 2010; Rabalais et al. 2007). Once the plant biomass sequesters the available nutrients, the plants die and fall to the seabed where they decay and, in that process, consume dissolved oxygen. This creates extensive near bottom zones of oxygen deficiency, or *hypoxia*, popularly referred to as "dead zones" because fish and other marine life cannot survive there. Diaz and Rosenberg (2008) report that there are at least 400 dead zones in coastal and estuarine waters around the world. The World Resources Institute provides an interactive map of eutrophication and hypoxia for more than 700 coastal areas worldwide (see World Resources Institute URL: https://www.wri.org/resources/data-sets/eutrophication-hypoxia-map-data-set). Perhaps the best known of these hypoxic zones is in the northern Gulf of Mexico where the Mississippi River discharges large amounts of agriculture-derived nutrients along with abundant fresh water, which stratifies the coastal ocean. Stratification suppresses vertical water column mixing and the downward flux of oxygenated water from the surface thereby exacerbating the hypoxic conditions. Figure 6.2 shows the extent of the hypoxic zone (in red) on the Louisiana continental shelf in the summer of 2014. Additional dissolved oxygen maps showing the frequency of hypoxia may be obtained online from the NOAA National Centers for Environmental Information (see URL: https://www.ncddc.noaa.gov/interactive-maps/coastal-habitats/). The Mississippi River catchment that is the source of nutrients covers 40% of the contiguous United States and extends northward into Canada. It embraces much of America's "breadbasket" including regions of corn agriculture for ethanol in Iowa. Gilbert and Burford (2017) recently presented results showing that harmful algal blooms (HABS) are increasing worldwide, in part because of increased nutrient loading to coastal waters and in part because HABS are rapidly adapting to global changes in ocean and coastal environments including altered levels of CO_2.

The conflicts between agriculture and coastal environments are highly complex and involve much more than nutrient runoff. As is the case for other coastal interactions, the cause-effect impacts are bidirectional. For example, croplands in low-lying coastal plains are subject to damage from salt-water inundation during storms or intrusion in ground water with rising sea level. Sugar cane farming in south Florida has had severe negative impacts on the highly sensitive Everglades because of nutrient runoff and also caused extreme blooms of toxic algae along Florida's Atlantic and Gulf Coasts in 2016. Sugar cane farming in Queensland Australia has also had damaging impacts on the Great Barrier Reef and solutions for this problem under active consideration include implementation of "polluter pays" laws (Queensland University of Technology 2015). In Europe, while it is well accepted that agriculture is essential, it is also understood that farming should proceed in ways that are environmentally sound and ethical. To that end, the European Union has established a *Common Agricultural Policy* (*CAP*), which requires farmers to meet certain environmental standards in order to be eligible for subsidies (e.g. Vernier 2012). In addition, in France, farmers are required to pay fees for consumption of irrigation water and for the runoff of pesticides (Vernier 2012).

The need to increase food production significantly over the next several decades cannot be denied and climate change is already negatively impacting food production (FAO 2016). To overcome these impacts and to reduce coastal damage, new, innovative and efficient agricultural practices that minimize environmental damage must be evolved. These innovations may well come at the expense of profits for large "agri-businesses" and will likely involve more emphasis on grains, vegetables and less on animal agriculture. Aquaculture will probably also play greater roles in feeding a growing population. On an optimistic note, it should be noted that an example of "*intelligent co-operation with nature*" is found in centuries old Balinese *Subak* practices of terraced rice agriculture. This system, which involves tightly interwoven cultural and environmental systems and dates back to the 9th Century, has recently been adopted by the UNESCO World Heritage Committee (2015). According to the World Heritage Committee (2015): "*The Subak system of democratic and egalitarian farming practices has enabled the Balinese to become the most prolific rice growers in the (Indonesian) archipelago despite the challenge of supporting a dense population.*"

6.4 Coastal Fisheries

Since prehistoric times, access to coastal fisheries has been a key advantage of living near the coast and seafood is still the dominant source of protein in many parts of the world. According to the UN Food and Agricultural Organization (FAO

2009, 2016), 3 billion people worldwide depend on seafood for essential parts of their nutrition and 500 million people in developing countries derive their livelihood from fisheries and aquaculture. Fish capture and aquaculture have increased steadily over the past 50 years although most of the increases since 1985 have taken place in China (FAO 2009, 2016). While the direct negative impacts of fisheries are less dramatic than some of the effects of agriculture, over fishing in particular is reducing species diversity and, of course, adversely impacts fisheries. The FAO (2016) reports that climate change threatens the sustainability of capture fisheries and aquaculture development in several ways. Ocean acidification and warming seas are slowing the ability of shellfish to produce shell through calcification, hypoxia in coastal waters limits the extent of fish habitats, more intense storms damage or destroy coastal shellfish farms and reductions in freshwater discharge by rivers have a direct effect on coastal salinity and thereby on the health of oysters.

The invasion of various tropical and alien species into higher latitude coastal waters often results in harmful competition with indigenous species. A prominent example is the ongoing migration of lionfish, which consume juveniles of other species, up the U.S. east coast. Warming seas can alter the reproductive cycles of fish, as well as growth rate and the timing of spawning (Perry et al. 2005). According to the recent synthesis prepared by the FAO (2016), models that take account of changing environmental conditions, and primary production of phytoplankton predict large-scale redistributions of marine fish catch characterized by increases in high-latitude regions and declines in the tropics. This will increase the vulnerability of small-scale tropical fisheries in poorer, less developed regions. To overcome some of these threats and remain resilient, the FAO (2016) recommends increasing the diversity of fisheries species and techniques and integrating more understanding of anticipated climate and coastal change into fisheries strategies and policies.

6.5 Coastal Oil and Gas Exploration and Production

Offshore and coastal plain oil and gas production directly impacts coastal systems around the world in numerous ways. Some of the regions affected include the Northern Gulf of Mexico, Mexican east coast, Arctic North Slope of North America; much of the Brazilian Coast; the West Coast of Africa; the North East Atlantic and North Sea Coasts of Europe, Australia's northwest coast; the Indonesian coast; and China's Bohai, Yellow Sea, East China Sea and South China Sea coasts. In addition to the obvious and highly publicized effects of oil spills, there are numerous other ways that the industry alters the coastal environment. For the case of the North Sea coast, the OSPAR Commission (2009) points out that: "*Environmental impacts may arise at all stages of oil and gas activities, including initial exploration, production and final decommissioning. There is a broad range of environmental concerns including those relating to oil discharges from routine operations, the use and discharge of chemicals, accidental spills, drill cuttings,* *atmospheric emissions, low level naturally occurring radioactive material, noise, and to some extent the placement of installations and pipelines on the sea bed*" (OSPAR 2009, p. 8). Direct and sometimes dramatic alterations of the coastal systems are caused by the industry's infrastructure including dredged access canals, pipelines, port facilities and, of course, the wells and platforms themselves.

Perhaps nowhere is the conflict between hydrocarbon production and nature more palpable than in the Northern Gulf of Mexico where 40% of the US wetlands coincide with activities that supply roughly one third of the nation's oil and gas (Mendelssohn et al. 2012). The Gulf of Mexico continental margin is a mature offshore oil and gas production area generating more than 1.7 million of barrels of oil per day, through more than 3500 oil platforms. Currently the northern Gulf has 45,000+ km (28,000+ mile) of underwater pipes exposed to structural damage from extreme oceanic and atmospheric events. In 2010, British Petroleum's *Deepwater Horizon* production platform in the northern Gulf of Mexico exploded, killing 11 people. This event was followed by an uncontrolled blowout that persisted for 87 days during which 4.9 million barrels of crude oil were discharged directly into the sea. The wetlands of the Mississippi delta and the Louisiana coast, which account for a third of the US fish production, were affected as toxic oil slicks spread over large areas of coastal marshland (Mendelssohn et al. 2012). Fortunately, the oil did not penetrate very far into the interior of the marshes. However, the adverse effects on the benthic habitats of the continental shelf are becoming more apparent with time. As is typical of processes in the *Anthropocene*, causal connections between humans and nature in the Mississippi Delta are bidirectional: the oil industry's $100 billion dollar investment in infrastructure is now under serious threat from land sinking and relative sea level rise (Traywick 2017).

The National Petroleum Reserve-Alaska, which includes the large Prudhoe Bay oil field discovered in the 1960s, lies immediately south of the coasts of the Beaufort and Chukchi Seas on Alaska's North Slope, an expansive coastal plain covered by permafrost. To the east of this reserve near the Canadian border is the Arctic National Wildlife Reserve. A summary report released in 2003 by the National Research Council (2003) assessed the cumulative effects of oil production from the 1960s to 2001 on the coastal environment. As of the date of that report, no significant oil spill had occurred. However, cumulative damage had resulted from the extensive infrastructure including roads, raised pipelines and helipads, which have largely remained since their original construction. Tundra damage from off-road vehicle traffic was also reported. More recently, NOAA's National Marine Fisheries Service (NOAA-NMFS 2016) carried out an extensive environmental impact study for alternative future scenarios of future oil and gas exploration utilizing seismic surveys and exploratory drilling. Among numerous minor to moderate impacts, the study concludes that acoustic impacts on beluga and bowhead whales would be significant and that, although unlikely, a large oil spill caused by an exploratory drilling accident could result in widespread environmental damage. Temporary disruption to wildlife is also caused by exploratory drilling installations such as Mars Island, which was built completely from spray ice for exploratory drilling by Amoco Exploration in January and February of 1986 in western

Fig. 6.3 Mars Ice Island, Beaufort Sea Alaska. Image shows a 60-day exploratory well built 8 km (5 mi) offshore of Cape Halkut near the National Petroleum Reserve in Alaska (NPRA), an area of land on the Alaska North Slope owned by the United States federal government and managed by the Department of the Interior, Bureau of Land Management (BLM). (Photo courtesy of Bureau of Ocean Energy Management)

Harrison Bay in Alaska. The island was built on the land-fast first-year ice in a water depth of 7.6 m (25 ft) to provide grounded platforms in shallow water. Mars Island was approximately 8 m (26 ft) thick and 213 m (700 ft) in diameter and used to support a drill rig as shown in Fig. 6.3.

6.6 Tourism Impacts

Sandy beaches and beach resorts are among the world's most popular tourist destinations. The throngs of tourists that frequent these sites each year are commonly accommodated in the hotels, condominiums and resorts that comprise beach-front "strip cities". Some of the impacts that these complexes have on coastal environments were described in Sect. 6.2. But, as described in detail by Davenport and Davenport (2006), there are myriad other impacts and some of these are long lasting. Coastal tourism began in the 19th century and has accelerated since then. Today, 63% of Europeans choose coastal sites for their vacations. The threats are from mass tourism and transport. According to Davenport and Davenport (2006) "Tourism is now the largest single economic sector in the World. Impacts of leisure transport and tourism on the coastal environment are considerable, have increased (and are currently scheduled to continue increasing) in non-linear fashion, and are extremely difficult to manage or limit". One of the most problematic factors involves mass tourism and extensive use automobiles for transport. Pollution and runoff from parking lots cause damage. Boats, cruise liners and various types of personal water-craft (e.g., jet skis) damage reefs and grass beds and wakes cause beach erosion (e.g., Parnell and Koefoed-Hansen 2001; Soomere and Rannat 2003; Bilkovic et al. 2017). Trampling of intertidal habitat and coral reef damage inadvertently inflicted by scuba divers are also harmful. Fortunately, although highly sensitive environments such as marshes and mangrove swamps are visited by small numbers of low impact eco-tourists, those environments do not suffer from mass tourism.

6.7 Ports, Engineering and Infrastructure

Roughly two thirds of the Netherlands surface area is low lying and would be inundated on each high tide if it were not for the extensive system of artificial dikes that have protected the country for nearly a millennium. An outcome of this is that the Netherlands has been world leader in coastal engineering for many decades. Today, the Netherlands has 350 km of coastline, 27% of the country is below sea level and 55% of it is flood prone (Santinelli 2016). Protection is provided by an elaborate system of dunes, dikes, floodgates and frequent land reclamation by onshore pumping of shelf sediments. The Netherlands model is commonly invoked by coastal managers all over the world as an example to be explored as a potential solution to coastal flooding and erosion. Such considerations are under serious review for protecting lower Manhattan. Elsewhere on the U.S. coast and around the world, the variety of coastal protection structures include seawalls, jetties and armored airport runway extensions.

The levee system on the lower Mississippi River and delta has long provided protection from flooding to Louisiana's lowlands and to the city of New Orleans but has also deprived the delta of much needed sediment re-nourishment. The history of this system and the roles, some of which were tragic, that it played during the Mississippi River flood of 1927 are described in eloquent detail by Barry (1997). Levee failure during the storm surge produced by Hurricane Katrina in 2005 was a major cause of the deadly flooding of the Ninth Ward and other parts of New Orleans. The impact of the levee system on the Mississippi Delta was understood as far back as the 19th century. E.L. Corthell wrote the following in 1897: "*The conditions are very different now from those existing prior to the construction of levees. There are at present no annual accretions of sedimentary matters from the periodical overflows of the river. These accretions formerly were a little more than equal to the annual subsidence of the lands…No doubt the great benefit to the present and two or three following generations accruing from a complete system of absolutely protective levees, excluding the waters entirely from the great areas of the lower delta country, far outweighs the disadvantages to future generations from* *the subsidence of the Gulf delta lands below the level of the sea and their gradual abandonment due to this cause.*"

Ports and harbors around the world involve significant human alterations of bays, estuaries and the lower courses of rivers by combinations of levee and breakwater construction, hardened shores, cargo loading facilities, rail and heavy truck access, warehouses and oil storage tanks, pipeline terminals, cruise liner terminals and channel deepening by dredging. Wakes from boat and ship traffic and spills of oil and gas are common disruptions. Improper port design can allow harbor resonance, which can cause excessively high oscillations and overtopping during storms. The recurring need for maintenance dredging in many ports has significant impacts on benthic habitats and can also lead to erosion of the adjacent coasts and beaches. Healy et al. (2002) report an example of a New Zealand port that was redesigned with guidance from numerical models to accommodate anticipated demands for ship traffic while minimizing ecological impacts and allowing dredged material to be used to nourish adjacent beaches. Figure 6.4 shows an example of a modern, multi-purpose port complex, Port Everglades, in southeastern Florida. Facilities such as Port Everglades are in increased jeopardy of damage or closure from storms caused by structural damage or entrance shoaling. On a much larger scale, it is the world's major port cities that are most acutely threatened by future inundation (Hanson et al. 2011). These threats will be considered in more detail in cases described in Part 3.

Fig. 6.4 Port Everglades, Broward County Florida (near Ft. Lauderdale). Photo courtesy of, Broward County, FL Environmental Planning and Community Resilience Division

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