Chapter 9
Coastal Erosion and Land Loss: Causes and Impacts

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> *We speak of course of that narrow strip of land over which ocean waves and moon-powered tides are masters-that margin of territory that remains wild despite the proximity of cities….*
> —W. J. Dakin—Australian Seashores

9.1 Shore "Volatility" Versus Net Erosion and Retreat

The margins of the sea are encroaching landward throughout most of the world. This is happening not simply because of sea level rise (SLR) and the inundation phenomena discussed in Chap. 7, but also because the solid material-sand, mud, gravel-composing the shore and the subaerial and subaqueous lands immediately adjacent to it is being displaced. It has long been accepted that shores—particularly sandy beaches—are cut back during high wave energy events but recover following periods of moderate to low energy during which long-period swell waves return sediments shoreward. Shepard (1950) offered the original, and classic, description of these beach "cycles" with reference to the beach at Scripps Institute of Oceanography in Southern California. More recent discussions of beach mobility can be found in most texts on coastal processes (e.g. Komar 1998; Dean and Dalrymple 2002). Such quasi-cyclic changes may be regarded as a type of *volatility* but not necessarily as indicative of chronic or irreversible coastal retreat.

The quasi-cyclic seasonal erosion and recovery of beaches are commonly superimposed on longer-term trends. When the sediments composing the shores,

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dunes and shallow sea floor are transported seaward by extreme events to depths beyond the maximum depth from which constructive or fair weather processes can return them, then erosion may be permanent, the shores will retreat landward and seas will encroach on the coastal hinterlands. Similarly, sediments cast landward by high waves and storm surge or moved along the coast by shore parallel currents will lead to retreat. In the simplest terms, when the rate of removal of coastal material exceeds the rate of input, recession will be the result and this recession will add to and exacerbate the landward translation of the land-sea interface that accompanies SLR alone. Based on a recent literature review and numerical modeling analysis, Vitousek et al. (2017) argue that because of the combination of rising sea level and anthropogenic severance of natural sediment to the coast, many beaches, particularly those on the Southern California coast, are likely to vanish by the end of the century.

9.2 Erosion of Coastal Barrier Islands and Contiguous Wetlands

According to Stutz and Pilkey (2001), coastal barrier islands and barrier spits fringe roughly 7% of the world's coasts. Such barrier systems dominate the shores of U.S. Atlantic and Gulf of Mexico coasts. Although coastal barrier islands are not usually the sites of dense habitation, except in cases of high tourist-oriented communities such as the Outer Banks of North Carolina, Florida's resort coasts and Australia's Gold Coast, they provide essential protection for communities and ecosystems situated immediately landward of the shallow lagoons or wetlands that back the islands. Erosion of the barrier systems removes or reduces the shelter provided by the islands and recent studies indicate that barrier systems are presently receding at alarming rates by way of different modes. Without the protection of the barriers, the wetlands that often exist behind the barrier islands or spits are subject to rapid, and often permanent loss. According to NOAA (2016. *U.S. Climate Resilience Toolkit*), between 1998 and 2009, the U.S. lost a total wetlands area greater than the area of the state of Rhode Island.

Cowell et al. (1995) and subsequently Lorenzo-Trueba and Ashton (2014) developed morphodynamic behavioral models to explain how barrier islands may retreat as sea levels rise. These models typically assume that some kind of equilibrium profile is maintained as the barriers migrate shoreward. Lorenzo-Trueba and Ashton (2014) describe four general modes of barrier retreat as predicted by their model. In the first, and simplest, mode, dynamic equilibrium is maintained and the shape and volume of the barrier are preserved as the barrier advances landward by overwash of dune sands onto the land surface or wetlands behind. The second possibility, "height drowning" prevails when the rate of overwash is insufficient to keep pace with landward migration and the barrier eventually becomes submerged. "Width drowning" occurs when the landward delivery of sand from the shoreface (or surf zone) is inadequate to maintain the barrier volume or when the net movement of sediment is offshore rather than shoreward. The fourth mode of retreat is characterized by episodic landward migration with periods of rapid overwash alternating with periods of relative stability. Crucial to these fairly simple models, however, is an adequate availability of sediment from the inner continental shelf. When the shelf is unable to nourish the beach and dunes, the barrier will ultimately vanish.

In the simple "roll-over" model, it is assumed that the barrier is composed of a deeply-rooted body of sand. This is the case in some instances but in many other cases the "barrier" is little more than a thin veneer of sand migrating over an eroding surface of salt marsh or relict marsh peat as in the Cedar Island case described in Chap. 5 (Fig. 5.9). In a recent analysis of the retreat of Virginia's barrier islands, Deaton et al. (2017) describe the how the processes of barrier island retreat are reducing the area of wetlands behind the islands and are also causing the tidal prism of the back-barrier estuaries to diminish. The cases they describe are experiencing both wash over and shore erosion and are thus narrowing. They attribute the loss of salt marsh to burial by sands from the migrating barrier islands. Figure 9.1a shows an example of washover fans burying the marsh behind and Fig. 9.1b shows the dead marsh peat being exhumed on the "beach" as the sands migrate landward. As discussed in Chap. 5, Zinnert et al. (2017) point out that the marsh grass, *Spartina patens* is tolerant of burial and can survive periods of burial beneath transgressing sands. However, the marsh cannot thrive in the high-energy surf zone environment once the protective barrier has migrated landward.

The worst losses of coastal lands in the United States are taking place on the Gulf of Mexico coast, particularly in coastal Louisiana where the rate of land loss is popularly described as equivalent to "a football field every hour". "*The barrier islands of Louisiana are eroding at an extreme rate. In places up to 100 feet of shoreline are disappearing every year. Though it has long been assumed that this*

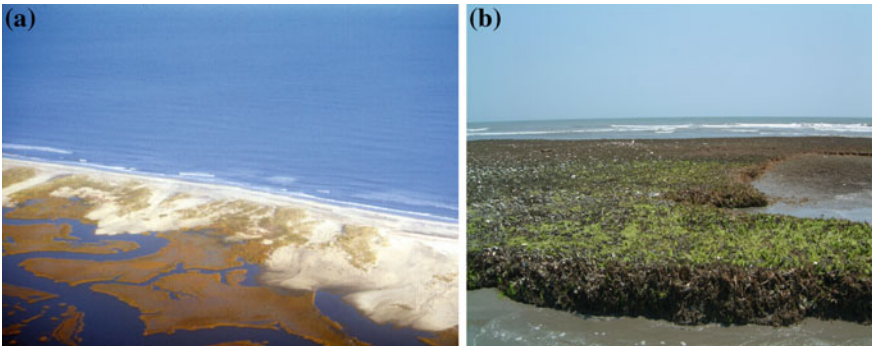


Fig. 9.1 The outcomes of barrier island "roll over" on Cedar Island, Virginia's Eastern Shore. A. Washover fans of the narrow and thin barrier burying the marsh and tidal channels to the west. B. Relict marsh peats compose the foreshore left behind by the migrating barrier. (Photos: L. D. Wright)

erosion was due to the area's rapid rate of relative sea level rise, recent studies by the U.S. Geological Survey show that other coastal processes, such as the longshore redistribution of sediments, are responsible for this erosion."—Dr. Jeffrey H. List, U.S. Geological Survey (USGS Fact Sheet *Louisiana Barrier Islands: A Vanishing Resource)*. We will examine the unique situation of Louisiana in more detail in Part 3. Rosati and Stone (2009) describe the recent evolution of the barrier islands along the northern Gulf of Mexico (NGOM) coast, which includes the Florida Panhandle, Alabama, Mississippi and Louisiana. In contrast to most of the U.S. Atlantic coast barriers, the NGOM barriers are backed by extensive bays, sounds or open water areas such as Santa Rosa Bay, Mobile Bay, Mississippi Sound and Barataria Bay. Storm surges can significantly raise water levels within these bays and cause erosion to shores behind the barriers. The width and height of the dunes comprising most barrier systems are not uniform along the coast and Houser et al. (2007) show, with reference to Santa Rosa Island in west Florida, that barrier island responses to the high waves and storm surges associated with severe storms are critically dependent on dune height and width. In the case of Louisiana, subsidence is progressively enlarging the open water areas (Morton et al. 2002) while the width and height of transgressive barriers like the Chandeleur Islands are diminishing.

9.3 Retreating Marshes and Wetlands

Coastal wetlands provide critical ecosystem services, including carbon sequestration, protection from storms, flood control, habitat for a variety of species, fisheries, water quality improvement, recreational and aesthetic opportunities, and cultural values etc. (Costanza et al. 1997; Engle 2011). However, wetlands have been disappearing at an unprecedented rate over the past several decades. Coleman et al. (2008) analyzed geologic and geomorphic data on 42 world deltas and found a total of 15,845 km^2 (6118 mi^2) of wetlands were irreversibly lost at an average rate of 95 km^2/year (37 mi^2) in 14 of these deltas from the middle of the 1980s to the early 2000s. With a similar trend in the other deltas, a total wetland loss would be on the order of 364,000 km^2 in the 42 deltas. Dixon et al. (2016) found the world's marine/coastal wetlands declined at an average rate of 38% from 1970 to 2008, with the highest decline rate of 50% in Europe, followed by 41% of decline in Asia, 28% in North America, 19% in Africa, and 17% in Oceania. This dramatic loss of coastal wetlands is due to natural causes and anthropogenic conversion of wetlands for agricultural and industrial uses (Coleman et al. 2008). In the United States, the vast majority of wetland loss occurred in the northern Gulf of Mexico coasts of Louisiana and Texas (Dahl 2006; Dahl and Stedman 2013). About 99% of the losses of estuarine emergent wetlands between 2004 and 2009 were caused by coastal storms, land subsidence, SLR, salt-water intrusion, wave erosion etc. The conversion of coastal wetlands to other land uses are rare as they are protected by various State and Federal coastal regulatory measures and are not allowed to be converted to other land uses (Dahl and Stedman 2013). A retreating marsh is shown in Fig. 9.2.

Stability of the coastal wetland platform under SLR reflects the balance between inputs due to allochthonous (externally derived) matter deposition and in situ vegetation production, versus losses through subsidence, erosion, and organic matter decomposition (Neubauer 2008). Feedback among inundation, sediment trapping, and vegetation productivity help maintain coastal wetlands facing SLR (Morris et al. 2002). However, when the relative rate exceeds a threshold, coastal wetlands can collapse (Wu et al. in press; Loucks 2006; Kirwan et al. 2010; Ratliff et al. 2015).

A suite of models have been developed for predicting the response of coastal wetlands to relative SLR (e.g., Morris and Bowden 1986; Park et al. 1989; Costanza et al. 1990; Martin et al. 2000, 2002; Reyes et al. 2000; Morris et al. 2002, 2016; D'Alpaos et al. 2007; Kirwan and Murray 2007; Mudd et al. 2009; Ross et al. 2009; Stralberg et al. 2011; Fagherazzi et al. 2012; Rogers et al. 2012; Hagen et al. 2013; Schile et al. 2014; Ratliff et al. 2015; Wu et al. 2015; Enwright et al. 2016; Clough et al. 2016; Wu et al. in press). These models vary in structure, complexity, and ease of application. Simpler models empirically capture the key characteristics of wetland dynamics, require less data, and are easily applied, but interactions and feedbacks between geo-morphological and ecological processes are missing or overly simplified (e.g. Park et al. 1989; Wu et al. 2015; Kirwan and Guntenspergen 2009). For example, the Sea Level Affecting Marshes Model (SLAMM) model uses digital elevation data and other information to simulate potential impacts of long-term SLR on wetlands and shorelines. More sophisticated models mechanistically account for the important interactions and feedback mechanisms among

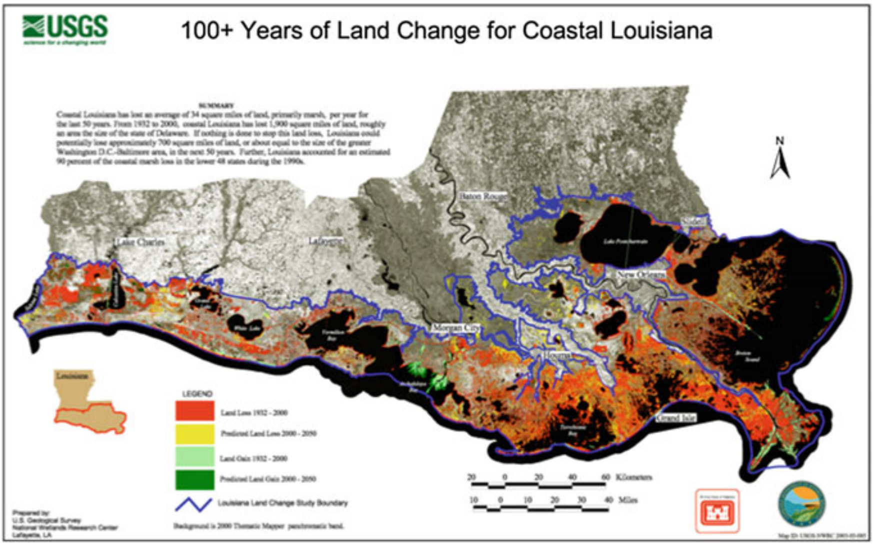
Fig. 9.2 Salt marsh retreat on the Louisiana Coast due to wave erosion and sea-level rise Photo by Wei Wu

vegetation, sediment, hydrology, and sea level factors, but generally require more input data, and are difficult to implement, especially at broader spatial scales (e.g., Costanza et al. 1990; Martin et al. 2000; Reyes et al. 2000; Morris et al. 2002). The various models highlight the importance of accounting for feedback among inundation, sediment trapping, and vegetation productivity in predicting wetland change. They also emphasize the need to integrate the environmental drivers other than sea-level rise in predictions, such as increased concentration of CO_2 and rising temperature, as they interact with sea-level rise to affect coastal wetland dynamics.

9.4 Disappearing River Deltas

Deltas owe their existence to the fact that rivers have been able to supply sediment to the coast at rates that have exceeded the rate of removal by oceanographic processes or the rates of relative submergence by subsidence and rises in relative sea level. Unfortunately, today, sediment supply has been sharply reduced by multiple anthropogenic factors as described in Chap. 4 while rates of subsidence have been increased, also by humans. Already, subaerial deltaic lands are rapidly disappearing and the disappearance is sure to accelerate as the rate of SLR accelerates over the coming decades. According to Overeem and Syvitski (2009), in the year 2009 roughly 26,000 km^2 (10,039 mi^2) of the world's deltaic land surfaces were below sea level and about 96,000 km^2 (37,066 mi^2) were highly vulnerable at elevations less than 2 m (6.6 ft.). As pointed out in Chaps. 4 and 6, deltas currently support twelve megacities and 500 million people so relocation is not a realistic option in many or most cases.

When Hurricane Katrina made landfall on the Louisiana coast in 2005, it caused a storm surge of up to 8.5 m (28 ft) that devastated New Orleans, particularly in the Ninth Ward, and killed over 1800 people (NHC). A comparable storm surge was generated by Hurricane Camille in 1969 but the impact on New Orleans was minimal. The difference between the 1969 and 2005 impacts was attributable largely to loss of protective wetlands separating the city from the Gulf of Mexico over the intervening 36 years. The Barras 2006 reported that just prior to Katrina, the Mississippi Delta, was losing land at the rate of 65–90 $km^{2/}$yr (25–35 mi^2) (Fig. 9.3). Numerous human activities, including the dredging of canals as well as the isolation of the delta plain from renewed sediment supply contributed to the land loss. Then, in 2005, Hurricanes Katrina and Rita together converted an additional 15% of Louisiana's wetlands to open water (Barras 2006; Xing 2015) thereby exposing even more wetlands to wave action and erosion. Hurricane Katrina alone caused over 250 km^2 (97 mi^2) of coastal lands to disappear in two days (Barras 2006). Today, extensive engineering works (see Chap. 6) protect New Orleans even though it is sinking. But the surrounding lands and wetlands are more vulnerable than ever. According to Barnes and Virgets (2017), over 5180 km^2



Coastal Louisiana has lost an average of 34 square miles of land, primarily marsh, per year for the last 50 years. From 1932 to 2000, coastal Louisiana has lost 1,900 square miles of land, roughly an area the size of the state of Delaware. If nothing is done to stop this land loss, Louisiana could potentially lose approximately 700 square miles of land, or about equal to the size of the greater Washington D.C.-Baltimore area, in the next 50 years. Further, Louisiana accounted for an estimated 90 percent of the coastal marsh loss in the lower 48 states during the 1990s.

Fig. 9.3 Coastal land loss in Louisiana in the century prior to Hurricane Katrina (from the U.S. Geological Survey 2004)

(2000 mi^2) of coastal land have been lost over the past century and that much again could be lost within the next 50 years. The Gulf of Mexico is progressively invading the Mississippi Delta.

9.5 Thermal Erosion of Arctic Coasts

The dramatic reduction of sea ice in the Arctic Ocean, described in Chap. 2 (see Fig. 2.8and Chap. 16) is being accompanied by equally dramatic erosion of the Beaufort Sea and Chukchi Sea coasts. This coastal realm is backed by the Arctic North Slope coastal plain of Alaska and Canada. The flat, relatively low-elevation, coastal plain, north of Alaska's Brooks Range, is a tundra surface comprised of a thin active (alternate freezing and thawing) layer of mosses and lichens overlying a much thicker substrate of permafrost, or permanently frozen soil. The interstitial ice normally holds the soil together but thawing causes the soil to lose its "cement" which makes it easily erodible. As the Arctic Ocean has increasing opened up (become ice free) during the summer, higher waves and warmer water have washed the shores. The exposed permafrost at the shore has gradually melted, releasing the sediments previously secured by the ice to the more energetic waves, which carry this sediment away causing coastal recession. The thermal erosion at the shore typically allows the permafrost to collapse in large blocks (Fig. 9.4) to be further eroded by waves and waters that are above freezing temperatures.

Fig. 9.4 Thermal erosion of the permafrost shoreline on Alaska's Beaufort Sea Coast. (Photo From USGS; Photo Credit: U.S. Department of the Interior|U.S. Geological Survey URL: https://walrus.wr.usgs.gov/climate-change/hiLat.html. Contact: Laura Zink Torresan

The U.S. Geological Survey has recorded the erosion rates of the Arctic coast over several decades. Jones et al. (2009) reported that, between the years 2002 and 2007, a 64 km (40 mi.) section of the Beaufort Sea coast retreated at an average rate of 14 m (45 ft) per year. Of course, erosion rates vary appreciably along the coast. In a more recent USGS Open File Report, Gibbs and Richmond (2015) conclude that for the entire 1600 km coastal reach from the Canadian border to Icy Cape on the Chukchi Sea coast, the average rate of retreat is 1.4 m/year (4.6 ft/year) and the local maximum rate is 18.5 m/year. (60 ft/year). As pointed out in Chap. 2, the Arctic Ocean could be completely ice free in summer by mid century. The coasts would be subject to attacks from larger waves and warmer water bathing the frozen permafrost shores. According to Gibbs and Richmond (2015) in the years ahead "—Arctic coasts will be more vulnerable to storm surge and wave energy, potentially resulting in accelerated shoreline erosion and terrestrial habitat loss in the future." This represents a classic case of positive (self reinforcing) morphodynamic feedback: accelerated ice melting and coastal retreat will increase exposure to wave attack by increasing the open water fetch distance over which wave-generating winds can blow. And as pointed out previously, the decreased albedo resulting from the increased area of ice-free open water will be followed by continued warming of the earth-and coastal recession, which in turn will further increase the open water area. Coastal retreat in the Arctic is likely to accelerate in the years ahead. The socioeconomic and ecological impacts Arctic coastal land loss are discussed in more detail in Chap. 16.

9.6 "Tipping Points" for Coastal Submersion

So long as the rates of SLR have remained relatively slow, or at least below certain critical levels, it has been possible for coastal lands to keep pace and remain emergent, or at least remain within the intertidal zone, by means of a combination of sediment accumulation and organic production. However, it has long been understood that there must be limits to the rate of drowning beyond which accretion cannot cope and permanent submersion will prevail. Several recent studies (e.g., Kirwan et al. 2010; Morris et al. 2002, 2016; Ratliff et al. 2015; Schile et al. 2014; Turner et al. 2017; Watson et al. 2017a, b; Wu et al. in press) have focused on determining what these critical inundation rate "tipping points" might be under different circumstances. The studies have involved various combinations of methodologies including statistical analyses of historical trends, numerical modeling and stratigraphic analyses of sedimentary cores. Morris et al. (2016) determined that intertidal wetlands on the U.S. East Coast and Gulf Coast can accrete at rates up to 3 mm/year (.12 in./year) via organic production and up to 2 mm/year (.08 in./year) as a result of deposition of inorganic sediment for a total maximum accretion rate of 5 mm/year (.20 in./year). Watson et al. (2017a, b) arrived at a similar conclusion with respect to the maximum accretion rate of New England salt marshes and reported that, in that particular region, the rates of relative SLR may have already reached the tipping point for wetlands loss. Relative SLR at rates in excess of ~5 mm/year (>.2 in./year) would thus likely result in wetlands loss and submersion of the intertidal realm.

Turner et al. (2017 *in press*) recently reanalyzed stratigraphic data and radiocarbon ages for deposits associated with 36 of the world's deltas spanning the Holocene SLR period of the past 22,000 years. Their results indicate that for 90% of the delta deposits examined, the onset of significant delta formation took place roughly 8000 years ago at a time when the rate of SLR had slowed to somewhere between 10 mm/year (.39 in./year) and 5 mm/year (.2 in./year), typically <6 mm/year (.24 in./year). They argue that if this rate of SLR is the tipping point for the onset of delta growth as the rate of rise decelerates, it may also be the tipping point for delta destruction as the rate of rise accelerates.

As shown by Morris et al. (2016), the accretion rates vary depending on plant productivity, root:shoot ratio, suspended sediment concentration, sediment-capture efficiency and episodic events. This leads to high spatial variability in wetland accretion rates and SLR thresholds on sustainability of coastal wetlands. At a river dominated estuary on the Mississippi Coast—lower Pascagoula Bay, the measured accretion rates is up to 8.6 mm/year (.34 in./year) with a standard deviation of 3.7 mm/year (.15 in./year) using fallout radionuclides (137Cs and 210Pb) (Wu et al. 2015). Some other studies showed higher sea-level rise threshold than 5 mm/year (.2 in./year) based on different settings of sediment concentration in water columns and tidal range. Kirwan et al. (2010) predicted the threshold of SLR rate as 10 mm/year (.39 in./year) in a typical estuary in the southeastern US and western Europe with suspended sediment concentrations greater than 20 mg/L (20,000 ppb) and tidal ranges great than 1 m (3.28 ft). Wu et al. (in press) predicted a SLR threshold of 8.4 mm/year (.33 in./year) for the Grand Bay National Estuarine Research Reserve which receives limited freshwater input, has an average of total suspended sediment concentration as 18 mg/L (18,000 ppb) and microtidal range of 0.6 m (1.96 ft) (Wu et al. in press). Wu et al. (in press) proposed a new threshold of accelerated sea-level rise to study the tipping point for coastal wetlands under the scenario of accelerating SLR. They also raised the point that other landscape metrics that quantify spatial patterns of coastal wetland distribution in addition to total area, for example, indices to represent fragmentation, should be considered when SLR tipping point is derived.

Notably, the present rate of global SLR of 3.1 mm/year (.12 in./year) (Fig. 3.3) is below the thresholds described in the above studies if regional subsidence is neglected. However, as discussed in Chap. 3, the IPCC (2013) analyses indicate that the rate is likely to be between 8 and 16 mm/year (.31 and .63 in./year) by the mid to latter part of the 21st century, neglecting any potential collapse of major Antarctic ice sheets. And, of course, in the case of deltas, subsidence is added to the effects of SLR. It would thus seem wise to prepare for the possibility that, world wide, vast areas of wetlands and deltaic lands may be replaced by open water before the end of this century.

9.7 Socioeconomic Consequences of Coastal Land Loss

For some low-lying small island nations, such as the Marshall Islands and Maldives, entire populations are at risk of becoming “climate change refugees” because relocation to high ground within their country is not possible. Notably, northern European coasts fronting the North Sea, particularly the Netherlands, have for centuries relied on complex coastal engineering programs to protect lands that are increasingly below sea level-in some cases by more than 2 m (6.6 ft; Dronkers and Stojanovic 2016). These programs are essential to the Netherlands survival but are extremely costly. In the United States, Hauer et al. (2016) predicted that by 2100 SLR of .9 and 1.8 m (2.95–5.9 ft) would place land areas projected to house 4.2 million and 13.1 million people respectively at risk of inundation. This amounts to a three-fold increase in the vulnerable population under the scenario of 1.8 m (5.9 ft) SLR by 2100 relative to today. In addition to monetary costs, population growth and economic development are severely constrained. Fortunately, however, the affected Northern European countries are relatively affluent and their prospects of resilience are reasonably good. This is not the case for the populations of many coastal megacities such as Mumbai, Dhaka, Calcutta and Lagos where the loss of habitable land enhances misery and disease and forces some homeless people to live in the bottoms of boats and canoes (e.g. in Lagos, Nigeria; McDonnell 2017). Perhaps most dramatically of all coastal land loss worldwide, the Marshall Islands are experiencing serious inundation on a regular basis and are likely to become uninhabitable in the foreseeable future causing the displacement of an entire nation (Goodell 2017).

The most serious losses of coastal lands in the U.S. are taking place in Louisiana (see Sect. 9.3 and Chap. 13) and are bringing the Gulf of Mexico closer and closer to cities like New Orleans, Houma and Lake Charles. From a recent economic impact study supported by the Environmental Defense Fund, Barnes and Virgets (2017) conclude that $3.6 billion in business, residential and infrastructure assets are presently at risk in Louisiana and the loss of these assets could cause an additional loss of $7.6 billion per year in nationwide economic activity. With the continued disappearance of protective wetlands, increased exposure of homes, industries and infrastructure could allow a single hurricane to destroy as much as $138 billion in assets (Barnes and Virgets 2017). On the positive side, however, Barnes and Virgets (2017) note that if plans for coastal restoration can be implemented, up to 10,500 jobs could be created. There are numerous other consequences of wetlands loss that cannot be readily expressed in monetary terms. The traditional culture and ways of life of Cajun and Creole residents of coastal Louisiana are among these. Two threatened "cultural islands", Tangier Island, VA and Smith Island, MD, also exist in the Virginia and Maryland portions of the Chesapeake Bay and are experiencing severe erosion and frequent inundation. High rates of SLR in the Chesapeake Bay are evidenced by erosion of marsh and salt water intrusion that is slowing killing woodland trees and shrubs that are not adapted to the high marsh. In these locations, many homeowners who do not want to leave are hoping for their States to build seawalls and breakwaters.

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