

2018

Urban Areas in Coastal Zones

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Original Publication Citation

Dawson, R.J., Khan, M.S.A., Gornitz, V., Lemos, M. F., Atkinson, L., Pullen, J., and Osorio, J. C. (2018). Urban Areas in Coastal Zones. In Rosenzweig, C., W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal, and S. Ali Ibrahim (eds.), *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press. New York. 319-362

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Urban Areas in Coastal Zones

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This chapter should be cited as

Dawson, R.J., Khan, M.S.A., Gornitz, V., Lemos, M. F., Atkinson, L., Pullen, J., and Osorio, J. C. (2018). Urban Areas in Coastal Zones. In Rosenzweig, C., W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal, and S. Ali Ibrahim (eds.), *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press. New York. 319–362

Cities on the Coast: Sea-Level Rise, Storms, and Flooding

Coastal cities have been subjected to extreme weather events since the onset of urbanization. Climatic change, in particular sea level rise, coupled with rapid urban development are amplifying the challenge of managing risks to coastal cities. Moreover, urban expansion and changes and intensification in land use further pressure sensitive coastal environments through pollution and habitat loss.

The concentration of people, infrastructure, economic activity, and ecology within the coastal zone merits specific consideration of hazards exacerbated by a changing climate. Major coastal cities often locate valuable assets along the waterfront or within the 100-year flood zone, including port facilities, transport and utilities infrastructure, schools, hospitals, and other long-lived structures. These assets are potentially at risk for both short-term flooding and permanent inundation.

Major Findings

- Coastal cities are already exposed to storm surges, erosion, and saltwater intrusion. Climate change and sea level rise will likely exacerbate these hazards.
- Around 1.4 billion people could live in the coastal zone, worldwide, by 2060. The population within the 100-year floodplain at risk to a 10–21 cm sea level rise could increase from around 286 million to 411 million people between 2030 and 2060. Three quarters of the exposed populations live in south and southeast Asia.
- Expansion of coastal cities is expected to continue over the 21st century. Although costs of coastal protection could reach US\$12–71 billion by 2100, these expenses would be substantially less than taking no action.

- Climate-induced changes will affect marine ecosystems, aquifers used for urban water supplies, the built environment, transportation, and economic activities, particularly following extreme storm events. Critical infrastructure and precariously built housing in flood zones are vulnerable.
- Increasing shoreline protection can be accomplished by either building defensive structures or by adopting more natural solutions, such as preserving and restoring wetlands or building dunes. Modifying structures and lifestyles to “live with water” and maintain higher resiliency are key adaptive measures.

Key Messages

Coastal cities must become keenly aware of the rates of local and global sea level rise and future sea level rise projections, as well as emerging science that might indicate more rapid (or potentially slower) rates of sea level rise.

An adaptive approach to coastal management will maintain flexibility to accommodate changing conditions over time. This involves implementing adaptation measures with co-benefits for the built environment, ecosystems, and human systems. An adaptive strategy requires monitoring changing conditions and refining measures as more up-to-date information becomes available.

Simple, less costly measures can be implemented in the short term while assessing future projects. Land-use planning for sustainable infrastructure development in low-lying coastal areas should be an important priority. Furthermore, cities need to consider transformative adaptation, such as large-scale relocation of people and infrastructure with accompanying restoration of coastal ecosystems.

Delivering integrated and adaptive responses will require robust coordination and cooperation on coastal management issues. This must be fostered among all levels of local, regional, and national governing agencies and include engagement with other stakeholders.

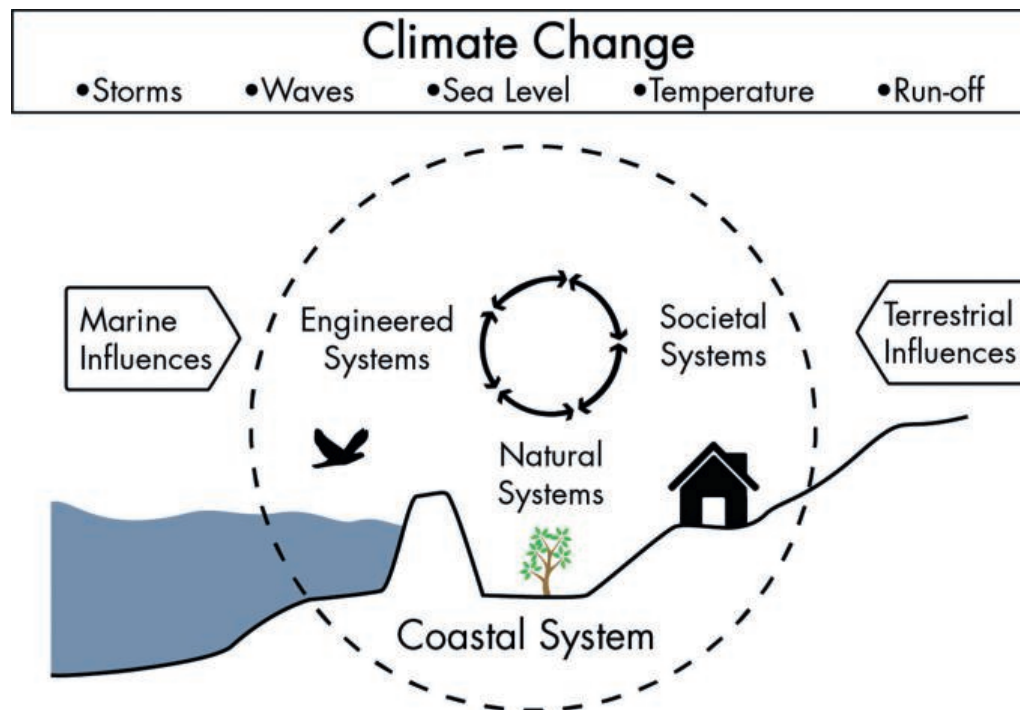


Figure 9.1 Climate change and the coastal system.

Source: Adapted from Nicholls et al., 2007

9.1 Introduction

Coastal zones around the world represent a wide diversity of features and a high variability in their ecosystems and environment, resources, and socioeconomic activities (see Figure 9.1). Moreover, these zones are extremely dynamic because of the continually changing balance of energy conveyed by tides, currents and waves, river runoff, sediment deposition, and erosion. Other shoreline changes have been induced by artificial structures intended to prevent or reduce erosion. This poses particular challenges for coastal cities, which have experienced some of the worst losses during extreme climatic events (Hall et al., 2005; Jongman et al., 2012; Hallegatte et al., 2013), while urban expansion, intensification of and changes in land use place growing pressure on sensitive coastal environments through pollution and land loss (Arthurton and Korateng, 2006). There is limited understanding of the interaction between urban and coastal systems (Pelling and Blackburn, 2014), yet it is significant from a climate perspective because of the concentration of people, infrastructure, and ecology within the coastal zone. Coastal cities therefore merit specific consideration of how they will be affected by and respond to hazards exacerbated by a changing climate.

The low-elevation coastal zone (LECZ), the area often considered to be “coastal” and the definition used here, is described by McGranahan et al. (2007) as the area below 10 meters in elevation that is hydrologically connected to the sea. The LECZ is home to approximately 10% of the world’s total population and 13% of its urban population (McGranahan et al., 2007). Small and Nicholls (2003) estimated that in 1990 about 23% of the

world’s population and 5 million square kilometers of land area were in the LECZ. Proximity to the coast is a driver of urbanization, with coastal cities thought to provide more open access to trade, investment, resources, and tourism than those in the hinterland (Henderson and Wang, 2007). Many of the world’s largest, most populous cities are coastal: of the 26 megacities in the world in 2011, 16 were coastal and vital to shipping, fisheries, and international commerce (UN-DESA, 2012). Coastal populations have rapidly increased over the past 100 years, particularly in low- and middle-income economies (UN-Habitat, 2008).

Coastal settlements are uniquely exposed to climate hazards such as sea level rise, storm surges, shoreline erosion, and salt-water intrusion. Major coastal cities often locate valuable assets along the waterfront or within the 100-year flood zone, including port facilities, transport and utilities infrastructure, schools, hospitals, and other long-lived structures, potentially at risk to both short-term and permanent flooding. Analysis of the 136 world’s largest port cities (population exceeding 1 million in 2005) shows that the value of assets at risk exceeded US\$3.0 trillion or 5% of Gross World Product in 2005 (Hanson et al., 2011). Globally, expansion of coastal cities is expected to continue over the 21st century (Nicholls, 2004; O’Neill et al., 2014), with some analyses suggesting that more than half the global population could live in cities in the coastal zone by the middle of the 21st century (Aerts et al., 2013) and annual coastal flood losses could reach US\$71 billion by 2100 (Hinkel et al., 2014).

Urban centers built on low-lying deltas are especially vulnerable. Major deltaic cities include Khulna, Shanghai, Guangzhou, Ho Chi Minh City, Bangkok, and Rotterdam. Many are affected

by anomalously high rates of relative sea level rise often exacerbated by land subsidence caused by groundwater overdraft, sediment compaction, long-term geologic subsidence, enlarging of coastal inlets, dredging of ports and waterways, and upstream trapping of sediments in reservoirs (Syvitski et al., 2009). Highly fertile deltaic soils of places like the Chao Phraya delta, near Bangkok, Thailand (with a relative sea level rise of +13 to 150 mm/yr; Syvitski et al., 2009) or the Yangtze delta, near Shanghai, China (+3 to 28 mm/yr; Syvitski et al., 2009) can be ideal locations for growing essential food crops such as rice (Akinro et al., 2008; Malm and Esmailian, 2013). Crops are threatened not only by increased frequency of coastal flooding, but by increasing saltwater intrusion and soil salinization as saltwater encroaches further up estuaries and rivers and contaminates water (Bear, 1999; Mazi et al., 2013; Le Dang et al., 2014).

Moreover, urban coastal ecosystems perform multiple beneficial ecological services (see Chapter 8, Urban Ecosystems). Coastal wetlands, for example, help dampen wave action and protect against storm surges. They also provide important habitat for birds, fish, and other nearshore marine life, and they offer recreational opportunities. However, many urban salt marshes or mangroves have been deteriorating for decades due to land clearing, draining, water pollution, and coastal protection measures (Torio et al., 2013; Nitto et al., 2014).

Coastal cities have lived with weather extremes for centuries, but climatic change and rapid urban development are amplifying the challenge of managing coastal risks. This chapter reviews the main climatic hazards, key vulnerabilities, and adaptation options, focusing on issues most relevant to coastal cities. The few activities that reduce greenhouse gas (GHG) emission specific to coastal cities are briefly considered before exploring a number of cross-cutting issues relevant to policy-makers.

9.2 Climate Risks

Climate risks in coastal cities are shaped by geological, oceanographic, and environmental factors as well as by socioeconomic factors (see Figure 9.1). Rising sea levels will lead to more frequent coastal flooding even without other changes in storm behavior or further urban development (e.g., Tebaldi et al., 2012) (see Chapter 2, Urban Climate Science). This section reviews coastal hazards that are influenced by climate drivers and how the nature of the built, social, and environmental characteristics of a city and its environs can shape its vulnerability to these hazards.

9.2.1 Coastal Hazards and Climate Drivers

Findings from the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5) can be summarized as (Wong et al., 2014):

- Coastal systems are particularly sensitive to three key drivers related to climate change: sea level, ocean temperature and ocean acidity.

- Coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal floodings and coastal erosion due to relative sea level rise.
- Acidification and warming of coastal waters will continue with significant negative consequences for coastal ecosystems.
- The population and assets exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, and urbanization.

9.2.1.1 Sea Level Change

Global sea level rose 1.7 ± 0.2 mm/yr between 1900 and 2010 (Wong et al., 2014; IPCC, 2013). Since 1993, both satellites and tide gauges register a sea level rise of $\sim 3.4 \pm 0.4$ mm/yr (Church et al., 2013; Nerem et al., 2010; also <http://www.sealevel.colorado.edu>) High-resolution proxy and modern sea level data suggest that, relative to the last few millennia, the rate of sea level rise has accelerated since the late 19th century (Kemp et al., 2011; Engelhart and Horton, 2012; Gehrels and Woodworth, 2013), and there are indications of a more rapid acceleration in the past few decades (Masters et al., 2012; IPCC, 2013).

Local sea level changes may differ considerably from the global mean due to vertical land motions (e.g., neotectonics, glacial isostatic adjustments, subsurface fluid withdrawal [water, oil, gas], ocean dynamic processes, and gravitational changes resulting from recent ice mass loss and terrestrial water storage). Observed relative sea level changes range from an extreme drop of -17.59 mm/yr (1944–2014) at Skagway, Alaska (glacial rebound, including that from recent [19th–20th centuries] melting of nearby glaciers at Glacier Bay), and rise of 9.03 mm/yr (1947–2014) at Grand Isle, Louisiana (oil and gas extraction; sediment compaction; NOAA Tides and Currents, 2016). Anomalously high rates of sea level rise in cities like Manila; Norfolk, Virginia; and Bangkok are probably caused by excess groundwater extraction (Raucoles et al., 2013; Eggleston and Pope, 2013).

Changes in ocean water density affect different regions to varying degrees. For example, a weaker Atlantic Meridional Ocean Circulation (AMOC) due to freshening of the North Atlantic Ocean from increased ice loss from the Greenland Ice Sheet (and glaciers) could chill northwestern Europe, at the same time increasing thermal expansion of sea level along the northeast coast of North America and raising regional sea level there by an additional 0.4 to 0.55 meters by 2100 (Hu et al., 2011).

Changing ocean dynamics including Gulf Stream slowing are being linked to anomalous sea level rise off the East Coast of the United States (Yin and Goddard, 2013; Ezer, 2013), emphasizing that local and global sea level changes will have a significant impact on coastal cities. In the future, the highly populated coastal northeastern United States (including major cities such as Boston, New York, Baltimore, and Washington, D.C.) is expected to become a “hotspot” of enhanced regional sea level rise largely owing to these ocean circulation changes (Yin et al., 2010; Carson et al., 2016).

9.2.1.2 Coastal Storms: Storm Surge, Waves, and Winds

Current and future flooding and storm damage frequency depend on various factors including changes in sea level, surge, and storm intensity, duration, and wave height. These also significantly affect coastal erosion. The frequency of tropical cyclones, their intensity, and the number of countries impacted has remained stable since the 1970s (Peduzzi et al., 2012), although the intensity of the strongest North Atlantic cyclones has increased (Elsner et al., 2008). Whether the total number of tropical cyclones will increase as a result of climate change is uncertain, but the number of more intense cyclones may grow (Bender et al., 2010; Knutson et al., 2010). Within the past three decades, maximum intensities of tropical cyclones have shifted away from the equator (Kossin et al., 2014). A continuation of this trend would increase flood hazards for nontropical coastal communities, which hitherto were less exposed to such damaging storms.

Evidence of changes in mean and extreme winds is weak, although analysis suggests that wave heights have been increasing in the Northeast Atlantic between 1958 and 2002 and in the Southern Ocean between 1985 and 2008 (Wong et al., 2014). Increases in coastal populations and economic development along with rising tropical cyclone intensities and sea level will magnify cyclone risks and damages (Mendelsohn et al., 2012; Hallegatte et al., 2013; Estrada et al., 2015).

Extratropical cyclones show no consistent large-scale changes in behavior during the past half-century, and, projected changes in extra-tropical storm activity remain uncertain. Rising sea level has led to increased coastal flooding, as for example in New York and elsewhere along the U.S. East Coast (Grinsted et al., 2012; Talke et al., 2014). Heavy precipitation from extratropical cyclones adds to the impacts of coastal flooding because of the large synoptic scale of the storms and their duration over several tidal cycles, often leading to overflow of stormwater drainage systems.

Case Study 9.1 Norfolk, Virginia: A City Dealing with Increased Flooding

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Keywords	Sea level rise, flooding, adaptation
Population (Metropolitan Region)	246,393 (U.S. Census Bureau, 2015)
Area (Metropolitan Region)	140.2 km ² (U.S. Census Bureau, 2010)
Income per capita	US\$56,180 (World Bank, 2017)
Climate zone	Cfa – Temperate, without dry season, hot summer (Peel et al., 2007)

Norfolk, Virginia was settled more than 400 years ago by European immigrants. The deep protected harbor and many creeks provided a perfect location to establish trade routes and access to the interior. The city has a population of approximately 250,000 in a larger region (Hampton Roads) of about 1.5 million people in many cities including the largest city in the state: Virginia Beach. Norfolk is home to the largest navy base in the world and many other defense-related activities. Nearly one-half the region's economy is defense related. Those same harbors and creeks abut very low land with highest elevations of less than 10 meters. Over time, with filling of waterfront areas and small creeks combined with sea level rise, the city is experiencing increased flooding (Ezer and Atkinson, 2014; Sweet and Parks, 2014). This has become especially noticeable since the 1970s, as Case Study 9.1 Figure 1 (third panel) shows.

The high local sea level rise rate in Norfolk (~4.5 mm/y over the past 80 years and ~6 mm/y over past 10 years) is two to three times faster than the global rate and is accelerating (Boon, 2012; Ezer and Corlett, 2012; Ezer, 2013). This is the result of three main factors: (1) global sea level rise due to thermal expansion and land ice

melt, (2) local land subsidence due to post-glacial rebound and local underground water extraction (Boon et al., 2010), and (3) potential climate change-related slowdown of the Gulf Stream (Ezer et al., 2013). Norfolk is situated in the mid-Atlantic region that has been declared a “hotspot for accelerated sea level” (Sallenger et al., 2012) and a “hotspot for accelerated flooding” (Ezer and Atkinson, 2014). The alleged slow-down of the Gulf Stream may be caused by inter-decadal variability (e.g., Watson et al., 2016; Yin and Goddard, 2013). But is still considered likely if future ice melting of Greenland continues or intensifies.

Norfolk faces two types of coastal flooding threats. One is often called minor or nuisance flooding (Sweet and Park, 2014). This occurs during high tides without any local storm (some offshore wind or a weakening Gulf Stream can cause this to happen), when many streets near the water start to flood (see Case Study 9.1 Figure 2). The hours that this occurs have already increased in the past due to sea level rise (see Case Study 9.1 Figure 1, third panel). This is expected to dramatically increase in the future (see Case Study 9.1 Figure 3), such that certain streets will be under water and not usable for extensive parts of the year.

The second is significant (major) flooding that is related to the effect of tropical and extra-tropical storms, winter storms, and Nor'easters. While the impact of climate change on the frequency and intensity of tropical storms and hurricanes is complex, the frequency of and damage from major storm surges has already increased in recent years because of sea level rise (see Case Study 9.1 Figure 1, first panel). Storms that in the past caused only minor or moderate flooding are now causing major floods and more damage to property because of the additional sea level rise on top of storm surge.

ADAPTATION TO RISING SEAS AND STORM SURGES

In 2011, it became clear that Norfolk was experiencing more flooding from both nuisance flooding and from passing hurricanes and winter storms. The Mayor of Norfolk at the time recognized this and directed the city to formally plan for increased flooding.

Norfolk is using a three-pronged approach (Norfolk, 2013):

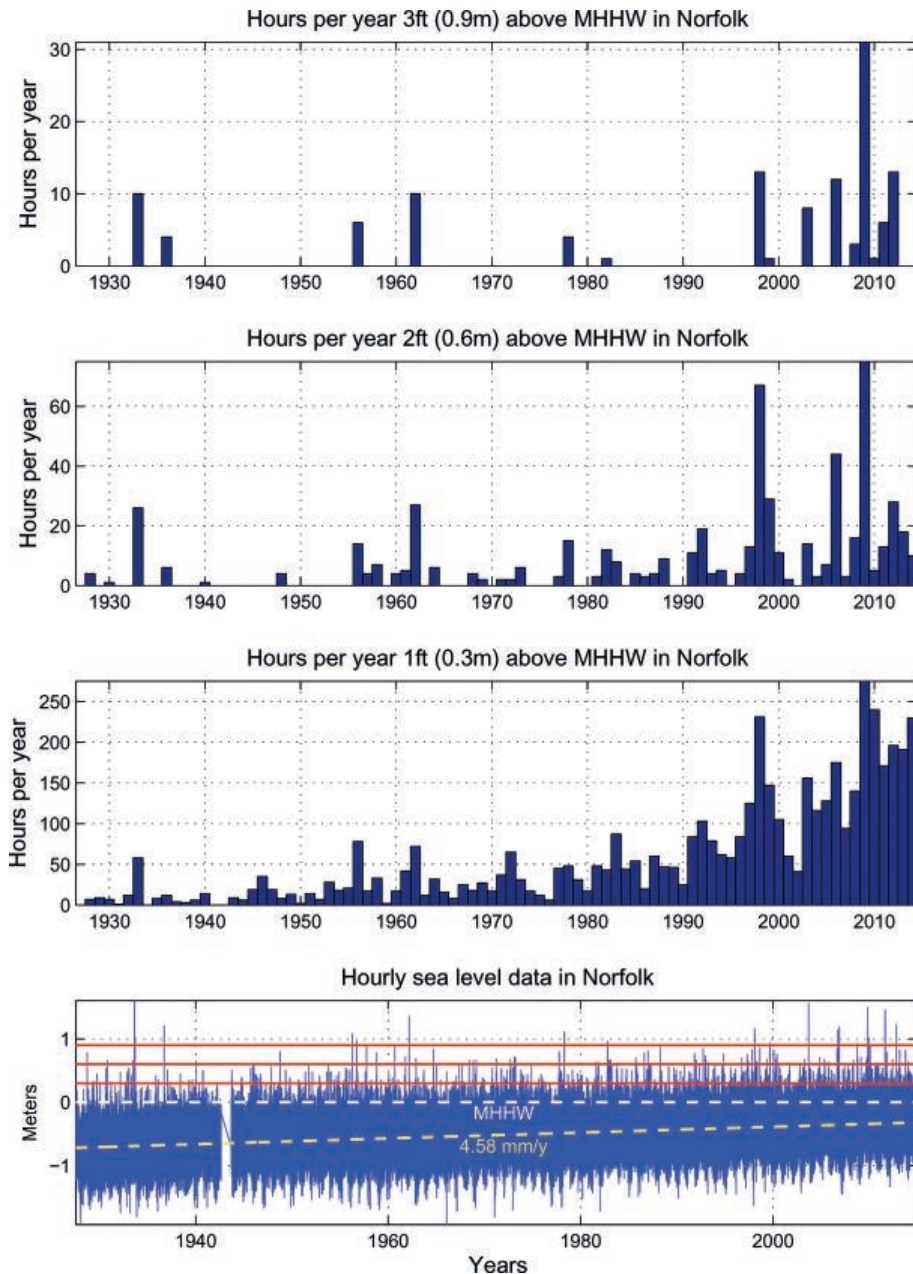
Prepare – Nature can be unpredictable. Norfolk’s residents and its government must address that unpredictability with thoughtful preparation. Community preparation resources include community response teams, detailed transportation and evacuation strategies, sound planning practices and use of a National Incident Management System to vet preparedness concepts and principles.

Mitigate (i.e., reduce risks) – Like other coastal cities, Norfolk is vulnerable to the increased severity of storms and flooding caused by relative sea level rise. Immediate and long-term

solutions range from simple landscaping techniques that allow adequate storm water drainage to complex engineering projects designed to reroute and deflect water.

Communicate – Communication is a critical link in implementing Norfolk’s flooding strategy. To prepare for future events as well as to cope during an event, direct and timely communication between the government and citizens is fundamental. Norfolk actively seeks input from residents. The City uses a wide range of communication tools to achieve these goals.

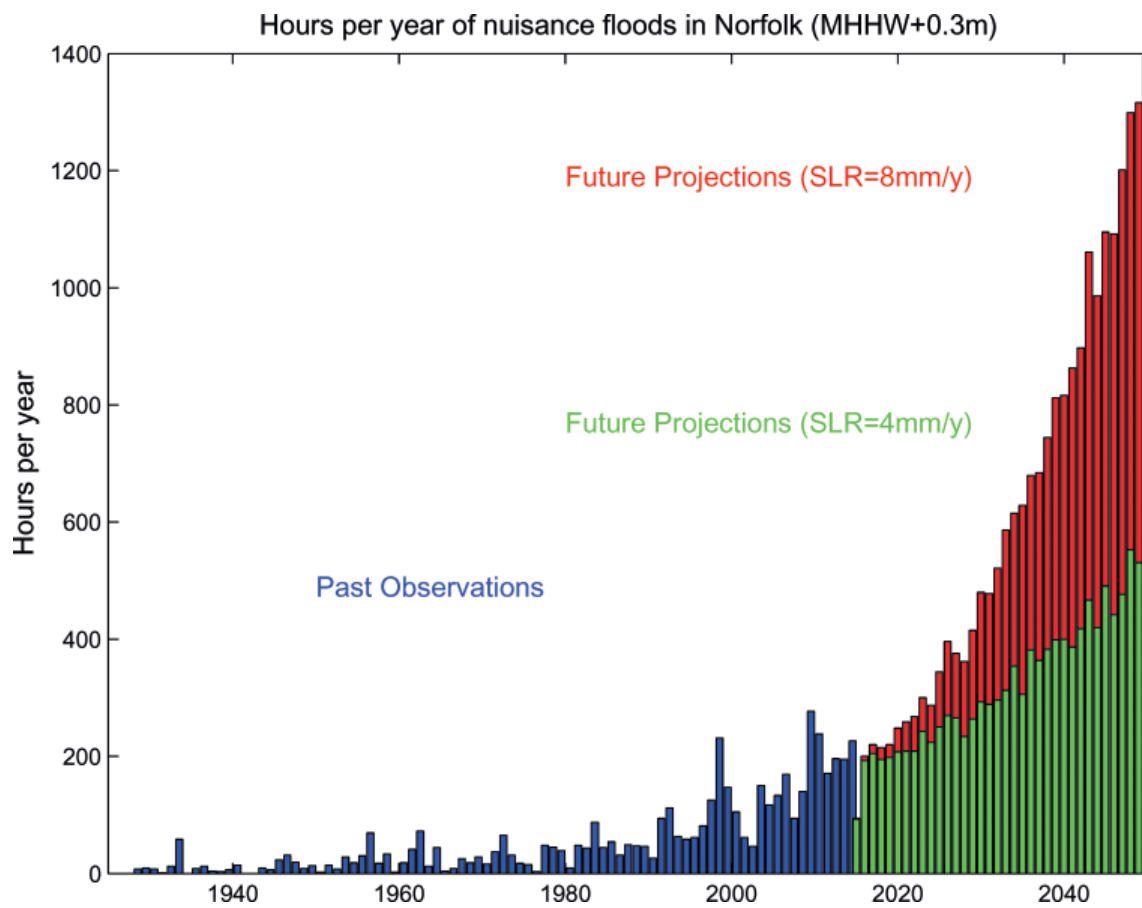
In 2014, Norfolk was designated one of 100 Resilient Cities by the Rockefeller Foundation (Norfolk, 2014).



Case Study 9.1 Figure 1 Hours per year that street flooding occurs in parts of downtown Norfolk, Virginia for (from top to bottom) major floods, moderate floods, and minor floods. The hourly water level data are also shown. MHHW = mean higher high water.



Case Study 9.1 Figure 2 Example of minor street flooding that is occurring more often in Norfolk, Virginia because of sea level rise.



Case Study 9.1 Figure 3 Projection of hours per year of minor flooding in Norfolk, Virginia, for two different sea level rise rates: low (green) and high (red), relative to past flooding (blue). MHHW = mean higher high water.

CREATION OF INTERGOVERNMENTAL PILOT PROJECT

As the flooding threat was increasingly recognized, a plan was developed to bring together the many federal agencies (primarily the Department of Defense) with the local cities to work together toward an adaptation strategy (Steinhilber et al., 2015):

Initiated in June 2014, the Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project (Intergovernmental Pilot Project or IPP) convened at Old Dominion University (ODU) is an effort to use the knowledge skills and expertise of all regional stakeholders. The goal

is to create a framework or template for intergovernmental strategic planning that can be used outside the region and to implement that integrated strategy in Hampton Roads, Virginia. This is creating an effective and efficient method for planning holistically for sea level rise and recurrent flooding. Old Dominion University acts as the convener of the IPP and supports it with expert faculty, research facilities, and access to partnerships within academia (e.g., the Virginia Institute of Marine Science (VIMS) and William and Mary's Virginia Coastal Policy Center).

This pilot project is planned to be the initial phase of a regional, state, and federally organized approach to coastal resilience.

Meanwhile, a statistically significant trend in the frequency of high surge events has been observed, generally associated with landfalling Atlantic tropical cyclones (Grinsted et al., 2012). Extreme surge events tend to occur in warmer years. Projected 21st-century warming patterns furthermore suggest that the frequency of storm surges similar in magnitude to those associated with Hurricane Katrina could increase by a factor of 2 to 7 for each 1°C rise in temperature (Grinsted et al., 2013). A higher surge generates more potential energy and therefore poses a greater risk to life and property. The surge-related threat will be exacerbated by rising sea level. A recent study that combines the effects of tropical cyclone intensity with a flood index based on duration and excessive high water during hurricane season along the eastern U.S. finds major increases in flood risk (Little et al., 2015). In the conservative RCP2.6 emissions scenario, the flood index increases by 4–25 times by 2080–2099 relative to 1986–2005, soaring upward by a factor of 35–350 in the high RCP8.5 scenario. This study, however, omits non-oceanographic components of sea level change, such as ice mass loss and gravitational or glacial isostatic effects, which may increase local sea levels even further.

The frequency of “nuisance flooding” (less-extreme tidally related coastal flood events) has been increasing in areas of rising sea level, including much of the United States (Sweet and Mara, 2015; Sweet et al., 2014). After removing the sea level rise component caused by anthropogenic-induced temperature increase, Strauss et al. (2016) conclude that two-thirds of U.S. “nuisance flood” days since 1950 can be attributed to climate change. Human-induced sea level rise has increased the number of flood days by more than 80% between 1955–1984 and 1985–2014.

Coastal populations face increasing risks to the combined effects of sea level rise and coastal flooding. The number of people within the 100-year flood plain exposed to flooding for a 10–21 cm rise in global sea level could increase from around 286 million to 411 million between 2030 and 2060 (Neumann et al., 2015). Of these, 75% live in south and southeast Asia, with a substantial growth expected in Africa (e.g., in the Nile and Niger Deltas). Economic losses and adaptation costs will also rise. One study estimates that average flood losses for the 136 largest coastal cities may increase from US\$6 billion in 2005 to \$52 billion by 2050, due to socioeconomic changes alone (Hallegatte et al., 2013). Adding a 20–40 cm sea level rise plus subsidence

would increase these costs to \$60–63 billion by 2050, even with adaptations to present flood probabilities. Another study finds that 0.2–4.6% of the world’s population could face annual floods under a sea level rise of 25–123 cm by 2100 (Hinkel et al., 2014). Costs of coastal protection (e.g., dikes) could range between US\$12 to 71 billion by 2100, but would be much lower than costs of no protection.

9.2.1.3 Other Drivers of Urban Coastal Risks

Freshwater Inflows

Heavy rainfall accompanying coastal storms can cause severe inland flooding and also compound flood risks associated with high surge levels (Wahl et al., 2015). Precipitation has generally increased over Northern Hemisphere mid-latitude land areas, particularly since the 1950s (IPCC, 2013). In many parts of the world, the frequency, intensity, and/or total precipitation have increased over the past century (Jenkins et al., 2008; Jones et al., 2013; Colle et al., 2015;). A high storm surge in conjunction with heavy precipitation can lead to excess runoff and/or increased river discharge. The number of compound flood events has increased significantly during the past century for many major U.S. cities, exacerbated by long-term sea level rise (Wahl et al., 2015). More frequent, heavy rainfall will also increase flood risk for cities along tidal rivers (e.g., London, Rotterdam, New Orleans, Bangkok, Shanghai, Haiphong), which face flooding from both high surges and overflowing rivers. Moreover, low-lying cities increasingly rely on energy to pump water from their drainage systems that are below high water levels. Conversely, anthropogenic activities such as the construction of upstream reservoirs can reduce the freshwater flows and lead to fluctuations in acidity and salinity and associated impacts (Haque, 2006; Das et al., 2012; Gao et al., 2012).

Salinization/Salt Water Intrusion

An important consequence of sea level rise is saltwater intrusion upstream and into coastal aquifers, potentially jeopardizing urban drinking water supplies and contaminating agricultural soils (see Case Study 9.2). This is a slow process, which can be accelerated by human-induced activities such as excessive extraction from aquifers (Ferguson and Gleeson, 2012).

Case Study 9.2 Vulnerabilities and Adaptive Practices in Khulna, Bangladesh

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Keywords	Vulnerability, planned and autonomous adaptation, salinity, drainage, coastal
Population (Metropolitan Region)	1,013,000 (UN, 2016)
Area (Metropolitan Region)	72.6 km ² (BBS, 2013)
Income per capita	US\$1,330 (World Bank, 2017)
Climate zone	Aw – Tropical savannah (Peel et al., 2007)

Khulna, the third-largest metropolitan city in Bangladesh, is situated in the southwestern Gangetic tidal floodplains. The city is one of the five largest river ports in the country and a gateway to the Sundarbans – the world’s largest mangrove forest and a Ramsar site. This central urban corridor of the southwest coastal region of Bangladesh is important for its proximity to the second-largest national seaport at Mongla (Murtaza, 2001). Apart from agriculture, shrimp export processing activities are major contributors to the national economy

(Aqua-Sheltech Consortium, 2002). Globally, Khulna is one of the 15 most climate-change vulnerable cities (IIED, 2009) and the eighth most vulnerable city in terms of projected flood loss and gross domestic product (GDP) losses (Hallegatte et al., 2013).

VULNERABILITIES

The geographic setting of Khulna makes it sensitive to climate change. The city area is generally flat, with an average ground elevation of 2.5 meters from mean sea level and elevations ranging between 0.45 and 5.4 meters (ADB, 2011). This low elevation causes tidal flooding and drainage congestion during high tides in the adjacent Rupsha and Bhairab Rivers (see Case Study 9.2 Figure 1). Increasing frequency of severe cyclones and storm surges, rising tidal water levels, saline water incursion, changing rainfall patterns, and rising temperature are the principal climate change-induced stresses that have major implications for the citizens’ lives and livelihoods (Khan et al., 2013).

The rate of temperature rise in Khulna is higher than that observed or projected elsewhere in the country. The number of extremely cold nights is decreasing and the heat index is increasing. Sunshine duration shows a decreasing trend, and humidity shows an increasing trend. Rainfall is increasing in terms of both magnitude and number of rainy days. However, the annual maximum rainfall and the number of days with high-intensity rainfall have remained almost the same. The monsoon is apparently strengthening toward the end of the rainy season. The annual maximum tidal high water level is increasing, and



Case Study 9.2 Figure 1 Low-lying areas in Khulna, Bangladesh, vulnerable to tidal flooding.

the annual minimum low water level is decreasing at a rate of 7–18 millimeters and 4–8 millimeters per year, respectively. Variation in water salinity, tidal water levels, and river discharges during different time periods indicates that human interventions through upstream water diversion and coastal polder construction have also contributed significantly to the hydro-morphological changes in the region (Mondal et al., 2013).

ADAPTIVE RESPONSES

Various adaptive responses, both planned and autonomous, are observed in Khulna. The planned responses at the city level include infrastructure development for drainage, water supply augmentation, and flood management whereas the autonomous responses by communities and households involve improving water and food security and creating alternative livelihood opportunities (Khan et al., 2013). To reduce dependency on saline groundwater, Khulna Water Supply and Sewerage Authority (KWASA) has planned to construct a treatment plant and increase the size of the impounding reservoir

(ADB, 2011). Such initiatives would still exclude marginalized communities from the city supply coverage. Further interventions are needed to improve institutional capacities (finance, manpower, skill, treatment, cost recovery, etc.) and community capacities (rainwater harvesting, wastage reduction awareness, etc.) to cope with the vulnerabilities. A drainage master plan, yet to be implemented by Khulna City Corporation (KCC), aims to reduce waterlogging in the Khulna Aqua-Sheltech Consortium (2002).

The vulnerable communities usually devise a range of autonomous adaptive practices to reduce their vulnerabilities. Various forms of rainwater harvesting are seen that provide drinking water for domestic uses. This option, however, is feasible for only a few months. Construction and maintenance of most of the systems require special skill and support. Communities often install hand-dug tube wells for drinking water supplies, whereas pond water is used for other domestic uses. New forms of collective actions to cope with adverse conditions are also seen in Khulna. In waterlogged areas, communities construct temporary foot-bridges made of brick and bamboo. Temporary drains are also excavated to relieve drainage congestion.

Groundwater Flooding

In some locations, including Miami and much of south Florida (see Case Study 9.3), sea level rise can increase the risk of groundwater flooding. A rise in sea level will simultaneously raise water tables, saturate the soil, expand wetlands, and increase flooding during heavy rainfalls (Rotzoll and Fletcher, 2013). However, abstraction from aquifers lowers water tables, which can reduce the likelihood of flooding. Thus, groundwater withdrawals can potentially mitigate the effects of a rising water table that is driven by sea level, although this may instead increase the likelihood of saltwater intrusion.

Shoreline Erosion

High waves and/or water levels during intense storms lead to beach erosion and shoreline retreat. This occurs along the California coast during a strong El Niño event, such as during the winter of 2015–2016 (e.g., see NOAA, 2015; Southall, 2016). Sea level rise will generally increase erosion rates (Bird, 2008; IPCC, 2014). Around developed areas, this can lead to disruption of sediment movements and coastal “squeeze,” i.e., loss of land and environmental degradation.

Acidification

Increased CO₂ has been linked to increased ocean acidification, which is considered to be one of the largest threats to marine organisms and ecosystems (Billé et al., 2013). Coastal zone waters are much more sensitive to these changes than open ocean, and acidity may increase from a pH of 8.16 in 1850 to 7.83 by the end of the 21st century (Lerman et al., 2011), albeit with considerable spatial variability. For example, Cai et al. (2011) project a decline in the Northern Gulf of Mexico of pH 0.74 over the same timeframe. A lower ocean pH decreases calcification and inhibits coral growth. Corals are furthermore under stress due to ocean warming, which results in bleaching and increased mortality (Wong et al., 2014). Ocean acidification

will also adversely affect most other marine organisms including fish, crustaceans, molluscs, and the calcified single-celled marine organisms (e.g., foraminifera and coccoliths) that play an important role in regulating the ocean’s inorganic carbon cycle. This would thereby detrimentally impact various economic sectors (e.g., fisheries, aquaculture, tourism) and consequently the coastal cities that depend upon these activities (Cooley and Doney, 2009; Narita et al., 2011; Burke et al., 2011).

Sea Surface Temperature

Increased sea surface temperature can increase the likelihood of a number of climate-sensitive diseases such as cholera and parasitic diseases (Chou et al., 2010; Cash et al., 2013; Baker-Austin, 2013). Limited evidence has associated harmful algal blooms with sea surface temperature variability (Glibert et al., 2014).

9.2.2 Vulnerabilities

Disasters are not caused solely by climatic events but by their interactions with urban systems (IPCC, 2012; Birkmann et al., 2010). The scale of a disaster, and risk more generally, is in part a function of the nature and magnitude of the hazard, but also the vulnerability of the urban system, including infrastructure, transportation networks, residences, and communications, which is locally specific to each city. Understanding these vulnerabilities is crucial for effective adaptation and disaster reduction (see Adger, 2006; Sherbinin et al., 2013).

9.2.2.1 Vulnerability in Natural Systems

Ecosystems

Coastal ecosystems have a richer flora and fauna than many other natural environments and consequently provide a number of useful ecosystem services (Jones et al., 2011). These include

supporting wildlife habitats, food-web support for fish and shellfish, flood buffers, shoreline erosion control, recreation, and waste assimilation (Hopkinson et al., 2008).

Ecosystems in the coastal zone are susceptible to climate hazards through a number of mechanisms. Sea level rise and other climate-sensitive drivers are expected to increase the rate of erosion and salinity intrusion in many parts of the world, but anthropogenic activity is also an important driver of degradation for coastal ecosystems and biodiversity reduction (Moser et al., 2012). These present major threats to coastal ecosystems and are already resulting in widespread global losses (Nicholls et al., 2008b; Nicholls et al., 2012).

Losses in ecosystem services can lead to other significant knock-on impacts. Removal or disturbance of coastal vegetation, for example, makes the coastal zone more vulnerable to erosion and sea level rise (IPCC, 2014b). Wetlands (salt marshes, mangrove forests, seagrass meadows, etc.), as well as dunes and beaches, provide important habitats and also mechanisms for dissipating wave energy during storms. Under natural conditions these systems are able to accommodate rising sea levels by retreating landward, but human settlements and infrastructure often confine coastal ecosystems leading to squeeze and ultimately total loss (IPCC, 2012). Ocean warming and acidification can affect animals and algae, particularly coral reefs through bleaching and reduction in calcium carbonate production.

Aquifers

Aquifers are susceptible to saltwater intrusion, furthered by sea level rise and flooding by waves and storm surges (Nicholls and Cazenave, 2010). They are also affected by reduced recharge from increases in temperature and evaporation and from changes in precipitation patterns. The risk to aquifers is often increased by unsustainable groundwater extraction rates and anthropogenic pollution (Ferguson and Gleeson, 2012). The risk related to water supply reduction is very high all over the world (Moser et al., 2012). Urban areas on small islands are often particularly dependent on aquifers, so in such places the risk is particularly acute.

Land

Land losses are expected to increase in the next decades due to submergence, coastal erosion, and reduced sediments from rivers flowing into deltas (often resulting from human activities to control rivers and reduce coastal erosion elsewhere). It is not only territory loss and its direct consequences to the economy, but the increased cost in protection measures is also expected to be significant (Hanson, 2011; Giosan, 2014). In addition to environmental drivers, conflict and economic, technological, and political factors can all influence population movements and lead to long-term shifts in the location and viability of coastal cities (McLeman, 2011).

These trends are most evident in the Asian and African mega-deltas that are seeing uneven spatial economic development

as populations move into the largest cities (Seto, 2011). Nearly half a billion people live on or near the world's deltas, many in major Asian cities such as Shanghai, Dhaka, and Bangkok. Deltas are the landform most vulnerable to sea level rise owing to low elevation, low topographic gradient, and erodible sediments (Schiermeier, 2014; Schmidt, 2015). Construction of dams, levees, and other floodplain engineering structures have starved deltas of sediments, adding to the natural land subsidence and risk of inundation (Syvitski et al., 2009). Deltaic environments, such as lagoons, wetlands, and dunes, harbor hotspots of biodiversity including thousands of species of plants and land and aquatic wildlife that would be threatened by inundation.

9.2.2.2 Vulnerability of Socioeconomic and Engineered Systems

Growing populations and urban development add to the increased vulnerability posed by natural coastal hazards. Much of this new growth will occur in flood-prone, low-lying coastal locations. Many of Asia's largest port cities are already and will be increasingly at risk (Fuchs, 2010) (see Table 9.1). By 2070, roughly half of the world's population exposed to coastal flooding will be concentrated in just ten megacities, all but one of which are in Asia (Hanson et al., 2011) (see also Table 9.1). The concentration of commerce, industry, tourism, and trade makes coastal cities vulnerable in distinctive ways.

Built Environment

Buildings and their cities are directly impacted by land degradation and losses. Resilience in these cities is related to the quality and distribution of infrastructure, transportation, and urban facilities, as well as the availability and quality of natural resources.

Urban planning, often shaped by national policy and governance, is central to avoiding exposure (Hanson et al., 2011; Walsh et al., 2013). Buildings are often ill-adapted to accommodate and resist coastal risks such as flooding and storms. Informal settlements, often located in the most risk-prone urban areas and vulnerable to landslide-susceptible slopes, flooding, river erosion, and the like continue to grow, particularly in developing nations. Reduced adaptive capacity of the occupants is compounded by building conditions such as deficiency in materials, structural safety, accessibility, overcrowded homes, and the lack of adequate urban infrastructure (Satterthwaite et al., 2007; Handmer et al., 2012).

Economic Infrastructure

Urban infrastructure systems (e.g., transport, water, energy, communications, wastewater and solid waste management) are often readily disrupted by extreme events (Handmer et al., 2012). Interruptions to the energy supply can lead to a cascading impact on other infrastructures that require power to operate. Damages to transportation systems can propagate more widely by stopping flows of people, goods, and services, with economic

Table 9.1 ARC3.2 coastal cities: Current population, observed rate of relative sea level rise, and projected relative sea level rise for the 2050s and 2080s.

Note: ARC3.2 Cities include Case Study Docking Station cities, UCCRN Regional Hub cities, UCCRN project cities, and cities of ARC3.2 Chapter Authors.

City ^a	Population	Observed RSLR, mm/yr ^b	Projected RSLR, 2050s ^c	Projected RSLR, 2080s ^d
Abu Dhabi	1,765,000		+15 to 60 cm	+23 to 124 cm
Accra	4,010,050		+17 to 58 cm	+23 to 119 cm
Antofagasta	296,900	-0.79	+13 to 55 cm	+20 to 116 cm
Antwerp	1,744,860		+18 to 70 cm	+25 to 140 cm
Athens	3,475,000		+15 to 55 cm	+22 to 116 cm
Bangkok ^{e f g h}	15,645,000	1.07	+15 to 57 cm	+21 to 122 cm
Boston ^h	4,794,447	2.81	+16 to 70 cm	+23 to 141 cm
Brisbane	2,065,000	0.58	+15 to 58 cm	+23 to 124 cm
Buenos Aires	15,355,000	1.52	+14 to 54 cm	+19 to 115 cm
Can Tho	1,200,000		+14 to 58 cm	+21 to 122 cm
Cape Town	3,740,000	1.94 ⁱ	+16 to 57 cm	+22 to 118 cm
Chula Vista	3,095,310		+14 to 56 cm	+21 to 118 cm
Colombo	5,000,000		+14 to 59 cm	+22 to 122 cm
Copenhagen	1,290,000	0.55	+16 to 70 cm	+25 to 140 cm
Cubatão	1,664,140		+14 to 56 cm	+22 to 118 cm
Dakar	3,137,200		+15 to 56 cm	+22 to 118 cm
Dar es Salaam	4,364,540		+15 to 60 cm	+22 to 122 cm
Dhaka ^f	14,171,600		+14 to 57 cm	+21 to 122 cm
Dublin	1,205,000	2.14	+15 to 65 cm	+24 to 131 cm
Durban	3,440,000		+14 to 58 cm	+20 to 118 cm
Fort Lauderdale	5,564,640		+15 to 62 cm	+21 to 123 cm
Genoa	615,000	1.18	+15 to 56 cm	+22 to 118 cm
Gold Coast	620,000	1.63	+15 to 58 cm	+23 to 124 cm
Gothenburg	590,000	-1.67; 0.34	+17 to 70 cm	+24 to 140 cm
Hayama	32,835		+13 to 65 cm	+20 to 129 cm
Helsinki	1,090,620	-2.31	+18 to 75 cm	+26 to 148 cm
Hong Kong ^g	7,187,000	3.25	+15 to 60 cm	+22 to 123 cm
Istanbul	13,755,000		+15 to 55 cm	+22 to 116 cm
Jakarta ^{f h}	9,610,000		+14 to 58 cm	+21 to 122 cm
Khulna ^f	759,620		+14 to 57 cm	+21 to 122 cm
Kingston	585,000		+14 to 57 cm	+20 to 119 cm
Kunshan	1,970,000		+13 to 59 cm	+21 to 122 cm
La Ceiba	204,140		+15 to 59 cm	+21 to 122 cm
Lagos ^f	21,000,000		+16 to 58 cm	+23 to 120 cm
Lima	9,752,000		+14 to 55 cm	+21 to 117 cm
London	14,031,830		+17 to 70 cm	+24 to 139 cm
Los Angeles	12,828,840	0.96	+14 to 56 cm	+21 to 118 cm
Makassar	1,484,000		+15 to 58 cm	+22 to 122 cm

Table 9.1 (continued)

City ^a	Population	Observed RSLR, mm/yr ^b	Projected RSLR, 2050s ^c	Projected RSLR, 2080s ^d
Manila	11,856,000		+14 to 60 cm	+21 to 124 cm
Maputo	2,615,000		+15 to 58 cm	+22 to 120 cm
Masdar	921,000		+15 to 60 cm	+23 to 124 cm
Matara	761,370		+14 to 59 cm	+22 to 122 cm
Ebro Delta (Mediterranean Spain)			+15 to 57 cm	+22 to 119 cm
Melbourne	4,246,350		+12 to 56 cm	+18 to 116 cm
Miami ^{f g h}	5,564,640	2.39	+15 to 62 cm	+21 to 123 cm
Middelfart	37,980		+16 to 70 cm	+25 to 140 cm
Mumbai ^{e f g h}	20,748,400	0.81	+15 to 58 cm	+23 to 122 cm
Naples	4,996,100	2.33	+15 to 56 cm	+22 to 116 cm
New Songdo City	2,879,780		+13 to 60 cm	+20 to 124 cm
New York ^{f g h}	18,897,100	2.84	+16 to 71 cm	+23 to 139 cm
Norfolk	1,671,700	4.61	+15 to 67 cm	+23 to 129 cm
Portmore	685,000		+14 to 57 cm	+20 to 119 cm
Rio de Janeiro	11,835,710		+15 to 56 cm	+21 to 118 cm
Rotterdam ^g	1,175,480		+18 to 70 cm	+25 to 140 cm
San Diego	3,215,000	2.15	+14 to 56 cm	+21 to 118 cm
San Francisco	6,455,000	1.94	+14 to 56 cm	+21 to 118 cm
Santo Domingo	3,265,050		+14 to 56 cm	+20 to 117 cm
Seattle	3,439,810	2.03	+14 to 56 cm	+21 to 118 cm
Semarang	1,670,000		+14 to 58 cm	+21 to 122 cm
Shanghai ^{f g}	24,750,000		+13 to 59 cm	+21 to 122 cm
Shenzhen ^h	12,775,000	3.25	+15 to 60 cm	+22 to 123 cm
Singapore	5,469,700	3.2	+15 to 58 cm	+21 to 122 cm
Surat ^h	6,081,320		+15 to 58 cm	+23 to 122 cm
Sydney	4,391,670	0.60; 0.96	+16 to 64 cm	+24 to 128 cm
Tacloban	221,170		+14 to 61 cm	+21 to 125 cm
Tangerang Seltan	1,443,400		+14 to 57 cm	+21 to 122 cm
Tokyo ^{f g}	37,833,000	1.88	+13 to 65 cm	+20 to 129 cm
Townsville	170,000	1.85	+17 to 70 cm	+25 to 141 cm
Trondheim	863,130	-2.12, -1.11	+15 to 56 cm	+22 to 117 cm
Venice	340,000	2.47	+14 to 56 cm	+21 to 118 cm
Victoria	1,765,000	1.37	+15 to 60 cm	+23 to 124 cm

^a Cities and population data from ARC3.2 Case Study Docking Station (CSDS), unless otherwise indicated.

^b Historic relative (local) sea level rise trends, in mm/yr (uncorrected for local land movement). Data sources: U.S. and some international stations: NOAA Tide and Currents (Last accessed August 7, 2017). Other: <http://www.psmsl.org/products/trends/txt> (last updated May 15, 2017).

^c Sea level rise projections for the 2050s. Numbers represent the 10th and 90th percentiles of the model-based frequency distribution, in cm. Methodology based on Horton et al., 2015. (Glacial isostatic adjustment (GIA) and glacial "fingerprint" components are not included, which may increase/decrease the projected sea level rise for the selected city).

^d The same for the 2080s.

^e Population data from: Demographia World Urban Areas. 13th Annual Edition: 2017(04); United States Census Bureau.

^f Among the top twenty cities ranked in terms of population exposed to a sea level rise of 0.5 m and 1 in 100-year flood event by the 2070s (after Hanson et al., 2011).

^g Among the top twenty cities ranked in terms of assets exposed to a sea level rise of 0.5 m and 1 in 100-year flood event by the 2070s.

^h Among the top twenty cities ranked by average losses (in US\$ million) for a sea level rise of 20 cm by 2050, with adaptation (after Hallegatte et al., 2013).

ⁱ Simon's Bay, near Cape Town, South Africa.

Note: Additional information on sea level rise impacts on many of these cities can be found in Surging Seas: Risk Zone Maps: Interactive maps of the area flooded by high water levels (tides, surges, sea level rise) in increments of 1 meter (or 1 foot) for the selected city. Mapping Choices: Interactive maps of the area inundated by sea level rise for temperature increases of 2°C and 4°C, in 2050 and 2100, for the selected city. Source: <http://sealevel.climatecentral.org>. See also Strauss et al., 2015. Carbon choices determine U.S. cities committed to futures below sea level. Proceedings of the National Academy of Sciences 112(44):13508–13513. The Climate Central website also provides a Risk Finder for U.S. cities that lists basic socioeconomic data, vulnerable infrastructure, and other relevant information.

consequences (Wilbanks and Fernandez, 2014). This can result in the total closure of tunnels and jeopardize population safety because disaster contingency plans are usually dependent on safe evacuation routes (Dawson et al., 2011a). Disruptions in even a small area can become more significant if they involve an important transport interchange, such as a sea- or airport. Many of these are situated on low-lying reclaimed land. Drainage and sewer systems are sensitive to sea level rise and flooding, which can lead to discharge pollution in nonseparated systems. Depending on the degree of sea level rise or storm surge, drainage can be temporarily or permanently blocked, requiring structural adaptation or energy-intensive pumping. Furthermore, the salinization of sewer systems as consequence of various hazards can lead to a change of chemistry and failure of the system (Bjerklie et al., 2012).

Tourism

Along with ports, military installations, and fisheries, tourism is a major component of the economy in many urban coastal areas. Out of fifteen top tourism destination countries, twelve of them have coastlines (UNEP, 2009). One of the primary climate change concerns for the tourism industry is the impact on tourist flows and seasonality for many destinations (Perry, 2006; Amelung et al., 2007; Bigano et al., 2008). Changing temperatures will mean that destinations have longer shoulder seasons and could change the time of year when more tourists visit (Perry, 2006; Amelung et al., 2007). Studies in Australia and Europe have used the Tourism Climate Index (TCI) and climate projections to determine the future suitability of destinations for certain activities and changes in tourist numbers due to rising temperatures: some popular destinations will become too hot for tourists and others will become more popular because of more agreeable temperatures for activities such as sunbathing (Hein et al., 2009; Coombes and Jones, 2010; Amelung and Nicholls, 2014). These changing weather patterns may increase domestic trips for many tourists (Rossello-Nadal, 2014), which could mean increased pressure for coastal urban areas. This will mean that host communities will need to adapt to the changing climate, increasing or decreasing visitor numbers, and changes in activity types.

However, according to multiple case studies, many tourism stakeholders (primarily business owners) did not see adapting to climate change as an immediate priority. While stakeholders were optimistic about their capacity to adapt to climate change, inadequate technical, human resource, and financial capacities were found to be barriers to adaptation. Tourism stakeholders in the case studies viewed government as the entity responsible for climate change adaptation (Scott et al., 2012).

Health, Education, and Wealth

Inequality and poverty are probably the most important factors of vulnerability due to the precarious conditions of life (in urban environment, housing, income, health, etc.) that are usually imposed by them. Those lead to an unequal and unfair distribution of risks (UN-Habitat, 2011) that can perversely

maintain a very high condition of vulnerability in the poorest urban population. This vulnerability is defined by the sensitivity of building and infrastructure conditions and low adaptive capacity due to lack of financing resources, education, and environmental and personal health, in addition to fragile governance conditions.

Toxic Exposures

Research conducted by the New York City Environmental Justice Alliance (NYC-EJA) has shown that coastal communities in close proximity to former or current industrial uses are especially vulnerable to the potential release of contaminants in the event of extreme weather events (Handmer et al., 2012). Vulnerable residents (e.g., low-income, elderly, children) living/working in industrial waterfront neighborhoods are particularly exposed to the potential release of contaminants in the event of severe weather (Bautista et al., 2015a). These releases can come from current operating sites where toxic materials are used or stored, or from sites contaminated from former industrial processes and/or waste storage practices.

9.2.2.3 Assessment of Vulnerability

To assess the growing vulnerability of coastal populations, settlements, and ecosystems to natural and anthropogenic hazards, various global to regional-scale databases have been developed. Among these is the DIVA Coastal Database for impact and vulnerability analysis to sea level rise (Vafeidis et al., 2008) that integrates information on geography, landforms, topography, bathymetry, tidal ranges, wetlands, surge levels, administrative units, uplift/subsidence, land use, gross domestic product (GDP) per capita, storm surges, and waves. In another approach, a Coastal City Flood Vulnerability Index (CCFVI) has been calculated using three elements: (1) A hydro-geological component (sea level rise, river discharge, soil subsidence, cyclones, storm surge), (2) A socioeconomic component (exposed populations, vulnerable groups), and (3) A politico-administrative component (institutional organizations, flood risk maps, flood protection measures) (Balica et al., 2012) (see Table 9.2).

9.3 Adaptation

9.3.1 Adaptation Strategies

Many strategies to manage risks in coastal cities are present (Aerts et al., 2012). Some of these can be implemented readily and rapidly, whereas others may require large investment or long-term planning and implementation. Actions to reduce exposure to natural hazards and consequent vulnerability include moving people and infrastructure, building “hard” engineering protection, and also adopting “soft” solutions, such as planting and protection of mangroves and other natural vegetation (e.g., Möller et al., 2014). These actions directly influence the sensitivity of the system or the adaptive capacity to build resilience (Allenby and Fink, 2005; Adger et al., 2005).

Case Study 9.3 Coastal Hazard and Action Plans in Miami

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Keywords	Sea level rise, flooding, salt water intrusion, coastal, community based adaptation
Population (Metropolitan Region)	2,693,117 (U.S. Census Bureau, 2010)
Area (Metropolitan Region)	4,915 km ² (U.S. Census Bureau, 2010)
Income per capita	US\$56,180 (World Bank, 2017)
Climate zone	Aw – Tropical savannah (Peel et al., 2007)

Southeast Florida enjoys a subtropical climate with relatively dry, sunny winters and hot, wet summers. The hurricane season extends from late June through November. Along with rising temperatures, south Florida can expect increased variability in rainfall – more intense downpours during the summer wet season, also longer droughts (Heimlich et al., 2009). Regional sea level rise lies close to the 20th-century global mean: approximately 2 mm/yr (NOAA, 2016). South Florida is geologically stable with no appreciable land subsidence. The City of Miami, in Miami-Dade County, is especially vulnerable to the effects of sea level rise due to its low topography, large urban population, highly vulnerable water supplies, and its important climate-dependent tourist industry.

Sea level rise projections for southeast Florida are 8–18 centimeters by 2030; 23–61 centimeters by 2060; and 48–145 centimeters by 2100 (Southeast Florida Regional Compact Climate Change, 2011). Large percentages of the urban portions of Miami-Dade could be inundated by sea level rise; for example a 30 centimeter rise would inundate 18.2% of the county; 60 centimeter, 28.2%; and 90 centimeter, 33.6%. More intense hurricanes (e.g., see Knutson et al., 2010) coupled with sea level rise will lead to higher surge levels and stronger waves and winds, causing increased coastal damage.

Major coastal hazards include coastal and inland flooding, storm surge inundation, wind and wave damage from tropical cyclones

(including hurricanes), beach erosion, and saltwater intrusion into the Biscayne Aquifer, which is the city's major water resource.

Water management and the threat of salinization are major concerns in Miami-Dade County. Unique geological features include the low average elevation of under 10 meters; a highly porous and permeable limestone bedrock; the shallow, near-surface Biscayne aquifer; and infiltration of saltwater into existing aquifers during heavy storms or at times of low rainfall. Farther north, due to ongoing saltwater intrusion, the city of Hallandale Beach, Florida, plans to relocate its water well field inland, to the west (City of Hallandale Beach, 2013).

The Southeast Florida Regional Climate Action Plan (2012; 2014) recommends regionally coordinated water management plans to address stormwater use and disposal, future water resources, wastewater treatments, and water conservation. The Action Plan urges a unified effort among government, businesses, and consumers in order to implement near- and long-term strategies to lessen adverse climate change effects on water supplies while diversifying existing water supplies. Water conservation and development of less vulnerable, new water resources are given high priority. Implementation may require changes in policy and regulatory frameworks, additional funding for infrastructure, development of alternative water supplies, and public education.

The Action Plan further advocates development of regional inventories of water management infrastructure and additional requirements to prepare for anticipated climate change. It also recommends development of improved saltwater intrusion models and refined inland and tidal inundation maps for increased sea level. The Plan also advises the consideration of climate change impacts in site selection and design of new water and wastewater facilities, as well as in the relocation of existing wellfields and other water management infrastructure (Southeast Florida Regional Compact Climate Change, 2014). Improvements in efficiency of flood/control/drainage infrastructure, recycling of stormwater, reclamation of wastewater, protection of ecosystems, and expansion of green infrastructure are also urged, as well as greater coordination with other federal agencies, such as the U.S. Army Corps of Engineers, U.S. Geological Survey, and NOAA. The ultimate goal is a regional Integrated Water Management Plan.

Miami-Dade County, as an active member of the Southeast Florida Regional Climate Change Compact, has adopted the Unified Sea Level Rise Projection (see above), initiated a county-wide vulnerability assessment, and increased regional collaboration. Near-term goals are development and implementation of a sustainability plan that also includes community stakeholder and general public inputs (Hefty, 2011; Miami-Dade County, 2015).

9.3.1.1 Shoreline Protection: Hard Solutions

Shoreline protection derives from engineering structures or enhanced natural features designed to withstand current and anticipated shoreline retreat, storm surge, and sea level rise. Protection includes “armoring” the shoreline with “hard” defenses and “soft” defenses that mimic natural processes (e.g., NRC, 1995; Titus and Craghan, 2009; Gornitz, 2013). Shoreline armoring is typically applied to defend important assets. Hard structures include seawalls, bulkheads, boulder ramparts (revetments, riprap), groins, jetties, and breakwaters (see Figure 9.2). The first three types of structures strengthen the existing shoreline by

preventing slumping or erosion of soft, poorly consolidated sediments. While resisting flooding from average storm surges and wave heights, they can still be overtopped by extreme events. Seawalls and revetments may, however, intensify basal erosion. This can be reduced by careful placement of rubble. Groins and jetties project outward and trap sand, widening the beach (but often intensify erosion downdrift). Breakwaters shelter a harbor or beach from extreme wave action but, if poorly designed, can also induce erosion.

Other structures such as dikes, tidal gates, and storm surge barriers protect against extreme floods or permanent

Table 9.2 *Adaptation strategies for coastal cities. Source: Adapted from Dawson et al., 2011b*

INTERVENTION	EFFECT OF ACTION	POTENTIAL MODIFICATION OF CLIMATE RISKS
River and Coastal engineering measures	Hard engineering structures (e.g., river diversions, levees, dikes, breakwaters, seawalls, riprap, barrages) reduce the probability of flooding by providing greater protection against higher water levels, increasing capability of excess water removal or storage. Soft engineering measures (e.g., beach nourishment, vegetation management) reduce the vulnerability of defenses through dissipation of wave energy.	The effectiveness of flood defenses may be assessed by calculating changes in the probability of flooding upon implementation.
Rural runoff reduction and storage	Reduce flood severity from altered runoff properties through changing the infiltration, storage, and conveyancing properties of catchments and floodplains.	Decreases the probability of flooding.
Urban runoff reduction and storage	Reduce the probability of flooding using a combination of storage, infiltration, routing, and drainage capacity management.	Decreases the probability of flooding.
Incident management	Improved flood forecasting and early warning systems provide information to flood risk managers, local authorities, and emergency services to give the public sufficient time to take effective mitigative actions before actual flooding occurs. Proactive pre-incident activities ensure adequate public, emergency services, and other key stakeholder preparation to undertake appropriate actions.	Most flood incident measures act to change the depth–damage relationship of floods (if followed by appropriate action by the public) and increase public safety and reduced health impacts of flooding. However, some flood-fighting actions (e.g., reinforcing failing defenses) can reduce the probability of flooding, and their success is tied to timely responses to specific flood events.
Flood-proofing	Reduce flood damage	Flood-proofing measures change the depth–damage relationship for the properties in which they are implemented. These could be retrofitted to old properties or designed into new builds.
Land-use planning	Limit construction of buildings and infrastructure in the flood plain, hence decrease vulnerability.	Appropriate land-use planning measures lessen overall potential damages through time by reducing floodplain development.
Building codes	Reduced flood damage. Improved flood-proofing measures in new buildings will be more reliable than those in retrofitted properties. For example, raising buildings on stilts.	Flood-proofing measures change the depth–damage relationship for newly built properties in which they are implemented.
Risk spreading (e.g., insurance)	Redistribution of the cost of damage across the population and through time	As well as redistributing risk, insurance is a potent means of communicating flood risk through an economic signal in order to reduce overall future damages by discouraging development in high risk-areas.
Health and social measures	Reduced social, health, and associated economic impacts of flooding	Health, social measures could be incorporated if an appropriate health/social or secondary economic impacts damage function were available.

inundation. While dikes hold back the sea, low-lying terrain behind the dike may need to be pumped dry. Tide gates open and close with the tides, allowing water to drain out at low tide. Storm surge barriers close only during extreme surges or tides, permitting water flows and shipping to continue at other times (e.g., Gilbert, 1986; London’s Thames barrier; Environment Agency, 2012); the MoSE system in Venice (Venice Water Authority, Consorzio Venezia Nuova, 2012; private communication); and the Maeslant Barrier, protecting Rotterdam (Delta Committee, 2008; Deltawerken online). However, most present coastal defenses designed for current sea level and storminess will eventually need to be retrofitted, for example by raising the height of seawalls, dikes, tidal gates, and the like or by reinforcing them to resist stronger and higher waves. New

structures should be built to withstand anticipated higher water levels (i.e., relative sea level rise plus storm surge, high tides, and waves).

A rising sea level will require periodic strengthening and raising of hard defenses. The timing and extent of work would depend on the rate of sea level rise, which also varies spatially, as discussed earlier. In London, for example, the defenses will likely be reinforced within the next 25–60 years, with the option to build a new barrier after that (Environment Agency, 2012). The Netherlands is already planning to upgrade its sea defense system, taking an integrated approach that includes “building with nature” and allowing “room for the river” (see later discussion and the

Box 9.1 Middle East and North Africa Coastal Cities: Findings from a World Bank Study

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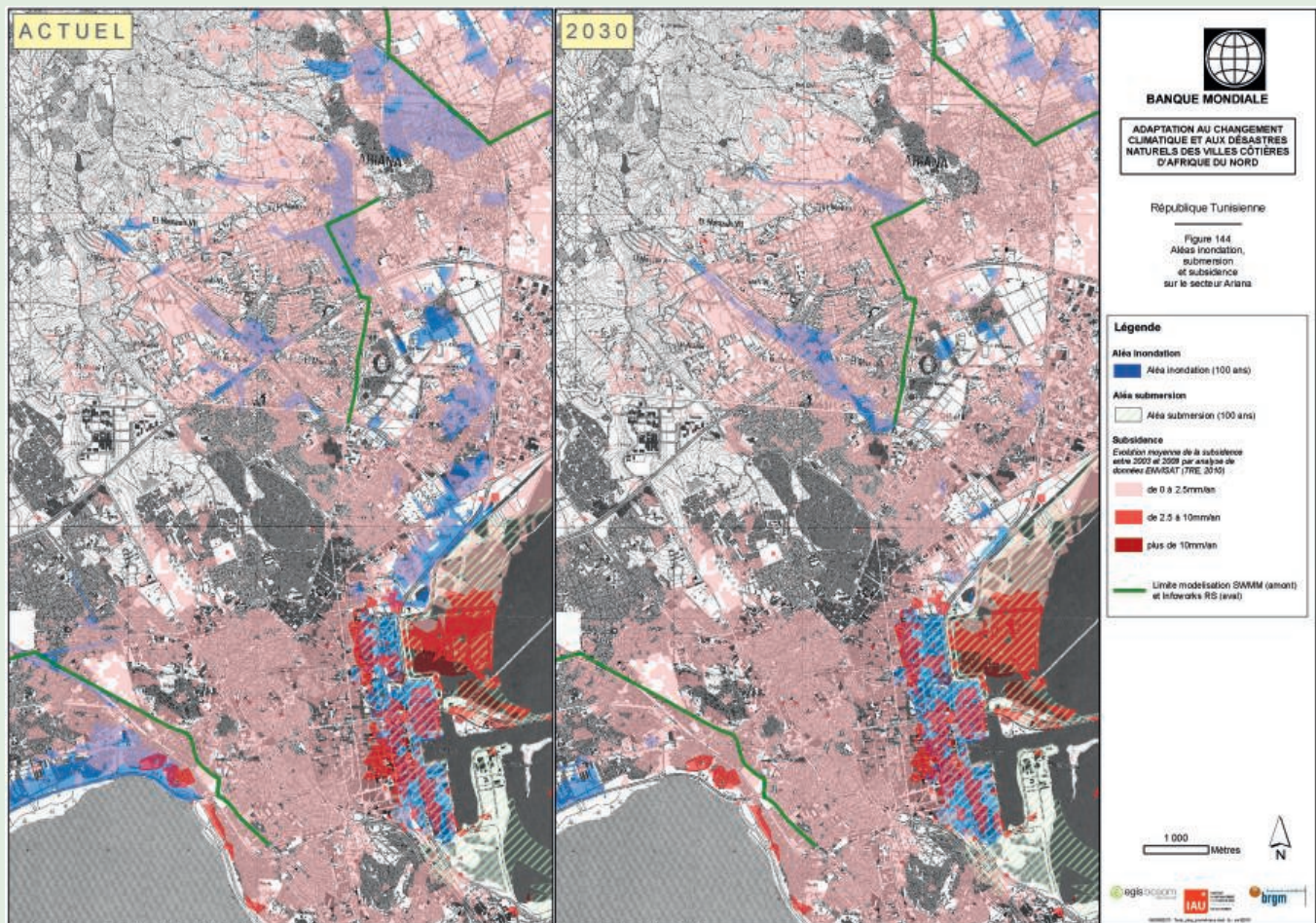
In 2011, the World Bank completed a 2-year study on the vulnerability and adaptation to climate change and natural hazards in the cities of Alexandria, Casablanca, and Tunis in the Middle East and North Africa (MENA) region. It also covered the major urban development project under way in the Bouregreg Valley between the Moroccan cities of Rabat and Salé. The study focused on a relatively short time horizon (2010–2030), considered the most significant for current-day national and local authorities, because it coincided with the timeframe of infrastructure and urban master plans under preparation.

Its major objectives were to provide national and local authorities with an integrated assessment of urban risks facing these major cities, as well as with detailed adaptation and resilience action plans focused on options for priority and no-regret measures to be implemented soon. The study's objectives

were achieved through the active participation of and consultations with scientific, administrative, and civil society organizations in the three countries and at the regional scale.

Under the guidance and supervision of a World Bank team, a consortium of scientific and technical consultants conducted a number of crucial inquiries into the present and projected future levels of urban risk. Climate downscaling was carried out for each location for temperature and precipitations. Probabilistic risk assessment was conducted for seismic and tsunamic activities. Land subsidence was measured via satellite earth observation and spectral interferometry. Digital elevation models of the urban terrain and hydrological models were updated to simulate sea level rise and flooding risks. Economic valuations of the likely cumulative damages and losses due to natural hazards and climatic impacts were carried out.

The *hazards* examined were seismic and tsunamic activities, flooding, land subsidence, coastal erosion, storm surges, and sea-level rise, as well as urban water scarcity in the context of a changing climate. The urban *exposure* was based



Box 9.1 Figure 1 Central Tunis, showing current flooding and land subsidence risks.

on the 2010 urban footprints and characteristics of the built environment and key infrastructure, as well as on the urban projected 2030 footprints resulting from demographic and spatial growth projections. The *vulnerability* analysis took into account the characteristics of the urban fabrics as well as the resilience and adaptation capacity of the urban systems and responsible institutions as of 2010.

Finally, *urban risk* was calculated as the combination of these parameters. Because the same methodology had been applied to the four urban sites at the two distinct points in time, varying degrees of urban risks were assessed for each of the hazards examined, in each urban location, for the current and forecasted scenarios. Overall, the assessments showed a medium to high *current* urban risk in the three cities, with Tunis ranking the highest, followed by Alexandria, and then by Casablanca. *Future* urban risk by 2030 increases to high to very high, with flooding and coastal erosion expected to increase considerably in all locations.

The net present value (NPV) of the likely cumulative damages and losses that each of the cities faces for the 2010–2030 period is more than US\$1 billion. The percentage of such NPV due to climate change impacts was, however, considered very low at the outset of the period and estimated to reach only about 20% by 2030, given the relevance of natural hazards such as seismic activities and land subsidence. This was a sobering finding of the study because it indicated the need for these cities to urgently address current urban risks stemming from natural hazards as a precondition to planning for and implementing further climate adaptation measures. A backlog of unaddressed urban risks dwarfs in the short-term the likely impacts of climate change. Because climatic conditions are expected to worsen by mid-century and beyond, the percentage of cumulative damages and losses due to climate change is expected to increase proportionally.

The adaptation and resilience action plans developed for each of the three cities took into account the specific risks for each of the hazards reviewed and offered implementable responses organized in three areas: institutional and governance responses, urban planning measures, and green and gray infrastructure. The costs of the proposed actions were compared to the value of the potential damages and losses to be avoided through their implementation. The most

cost-effective measures turned out to be those related to the better functioning of the institutions charged with risk prevention, early warning systems, hydro-met services, and the management of climate forecasting and climate adaptation planning. These, however, appeared also as the most difficult ones to implement due to inherent resistance to organizational reform.

Urban planning responses consisted of strategies to prevent urban growth in areas at high risk and to incorporate the detailed knowledge of impacts in the retrofitting of the current built environment and in the planning and design of future urban expansions. Such actions are highly relevant in cities whose populations are expected to grow in the two-decades period from a minimum of 33% in the case of Tunis to a maximum of 65% in the case of Alexandria, with Casablanca at 55%. Such growth and the even faster paced expansion of their urban footprints will expose significantly more population and assets to natural hazards and climatic risks.

Finally, infrastructure responses proposed for the three cities included the provision of additional coastal defenses; beach nourishment; stabilization of buildings in areas subject to land subsidence; the expansion and improvement of drainage systems, including the use of eco-system services and on-site water absorption and retention systems; the “hardening” of critical infrastructure, such as power-stations, water-treatment plants, key roadways, and port systems; and improved water usage management and waste-water reuse.

The study has had a significant impact on the national and local institutions in the three countries involved in terms of focusing on the “clear and present dangers” their cities are facing. Their representatives were able to exchange views and set the stage for regional collaboration via the good offices of the Center for Mediterranean Integration in Marseilles (CMIM), which fosters innovation and exchanges across the Mediterranean region. The study’s reports were widely disseminated across MENA, resonated in the regional media, and have contributed to improving the general understanding of urban risks and climate change. However, due primarily to the political upheaval that has swept across the region following the 2011 Arab Spring, no implementation of the proposed action plans has yet occurred.

Rotterdam Case Study; Delta Committee, 2008; Kabat et al., 2009; Katsman et al., 2011). Likewise, coastal polders in Bangladesh are being raised to provide additional protection against the rising sea level.

Analysis of the costs associated with coastal defense systems to protect against flooding in the context of three IPCC RCP scenarios (2100 with respect to 1985–2005), and under two adaptation strategies, shows that without adaptation, 0.2–4.6% of the world’s population could be flooded each year in 2100, with a sea level rise of 25–123 centimeters, costing 0.3–9.3% of GDP. While coastal protection and maintenance costs are high, amounting to an estimated US\$12–71 billion per year in 2100,

these costs are much smaller than damages arising from doing nothing (Hinkel et al., 2014).

9.3.1.2 Shoreline Protection: Soft Solutions

“Soft” defenses have become a preferred means of shore protection in many places because of the negative impacts of hard stabilization on beaches (NRC, 1995; Bird, 1996; Duarte et al., 2013; Arkema et al., 2013). These include beach nourishment and rehabilitation of dunes and coastal wetlands. Stable beaches and saltmarshes not only provide recreational opportunities and important habitat for a wide variety of wildlife including fish, shellfish, waterfowl, and small amphibians, reptiles, and

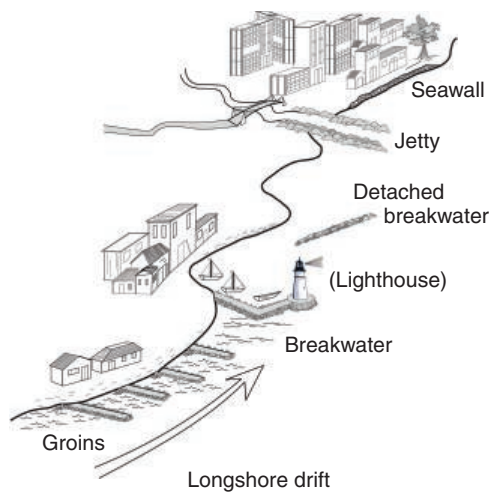


Figure 9.2 Hard structures for shoreline protection.

Source: Gornitz, 2013

mammals, but also protect the hinterlands against storm surges and high waves (e.g., Nordenson et al., 2010; Arkema et al., 2013; IGCI, 2015).

“Ecological engineering” is emerging as a no- or low-regret approach to coastal zone management, recognizing that shorelines are vulnerable to multiple sources of change including climate change, urbanization, and development (Cheong et al., 2013). One such approach replaces traditional engineering with ecological solutions. For example, a successfully restored oyster reef, when fully grown, acts as a shoreline protection system by damping incoming wave energy and reducing erosion. The new reef furthermore removes algae and suspended organic matter, thereby curbing turbidity, and creates suitable habitat for fish, crabs, and other marine wildlife (Cheong et al., 2013). This approach is closely related to that of *living shorelines*, which are an example of coastal management that maintains or simulates natural processes (Titus and Craghan, 2009). Strategic

Case Study 9.4 Venice: Human-Natural System Responses to Environmental Change

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Keywords	Sea-level rise, subsidence, erosion, coastal floods, ecosystem-based adaptation, storm surge barriers, salt marsh restoration
Population (Metropolitan Region)	863,133 (ISTAT, 2015)
Area (Metropolitan Region)	2,462 km ² (Comune di Venezia, 2015)
Income per capita	US\$31,590 (World Bank, 2017)
Climate zone	Cfa – Temperate, without dry season, hot summer (Peel et al., 2007)

ABSTRACT

The artistic and historical patrimony of Venice is part of humanity's global heritage. Its preservation involves issues related to global environmental change, environmental protection and sustainability, economic development, and cultural heritage preservation. The city and its lagoon have been transformed by human interventions over more than a millennium and are now a powerful symbol of the coexistence

of the natural and the built environments, of the tension between sustainable and unsustainable uses of natural resources. To preserve the lagoon, the Venetian Republic diverted three major rivers directly out to the sea over the course of about three centuries (1330–1664) (D'Alpaos, 2011). These massive works did invert the increasing sedimentation trend of the lagoon but caused the current state of diffuse erosion. In more recent years, industrial development left its marks on the lagoon water quality and has contributed to the city's subsidence, while increased tourists fluxes and cruise ship navigation are exerting an ever-growing pressure on the city and its environment as a whole. Overall, ancient and more recent human interventions have greatly increased the vulnerability of the city and of its lagoon to climatic changes, in particular sea level rise acceleration.

The protection of the city from increasingly more intense and frequent high tides, the MoSE system (Modulo Sperimentale Elettromeccanico, i.e., Experimental Electromechanic Module) is a complex engineering project that has required a complex decision-making process involving a large number of local and global stakeholders and a difficult equilibrium between a large number of often-conflicting uses of environmental resources. The project's far-reaching environmental consequences have perhaps not yet been fully understood, but will certainly be felt for several generations to come.

VENICE AS A NATURAL–HUMAN SYSTEM

The very origin of the city of Venice lies in the lagoon surrounding it – a natural defense, a means of transportation, and a source of food. Naturally destined to silt up due to fluvial sediment inputs, the lagoon sediment balance has been deeply changed by major river diversions carried out by the Venetian Republic in the 14th and 15th centuries. These diversions have transformed the lagoon into a sediment-starved environment, thus setting up the stage for the modern conservation issues. The sediment balance was definitively compromised by the completion, in the early 20th century, of three jetties to maintain navigable depths at the inlets connecting the lagoon and the sea. The jetties created a circulation asymmetry between flood and ebb tidal phases that causes sediments to be ejected far into the Adriatic Sea during tidal ebb, such that they cannot be transported back into the lagoon during the tidal flood (D'Alpaos, 2011). The

current sediment loss is between 500,000 and 700,000 cubic meters per year, corresponding to a layer of about 0.9–1.3 millimeters per year, if uniformly distributed throughout the lagoon.

The preindustrial rate of sea level rise in the Adriatic Sea in the 20th century amounted to about 1.2 millimeters per year. However, groundwater withdrawals, mainly between 1950 and 1971 (when industrial artesian wells were closed), have induced additional loss of about 9 centimeters over 30 years (Carbognin et al., 2010). Relative sea level rise has been approximately 25 centimeters since the start of the 20th century (Carbognin et al., 2010).

The historical and, particularly, the recent relative sea level changes have had significant implications for flooding in the city. Flooding starts at a water level of about 80 centimeters above mean sea level (AMSL) – the lowest pavement level in St. Mark’s Square – whereas significant flooding is considered to occur above 110 centimeters AMSL. The frequency with which this flood threshold is exceeded has already significantly increased since the start of the 20th century, from one event every 2.2 years to four events per year. Such frequency is expected to further increase, due to projected sea level rise and subsidence, to between 20 and 250 flooding events per year (Carbognin et al., 2010). This circumstance poses a serious threat to the conservation of the city of Venice and has spurred the development of “hard” protection measures in the form of a tidal-storm surge barrier, the MoSE project.

ENVIRONMENTAL MANAGEMENT

Defending the City from High Tides: The MOSE Project

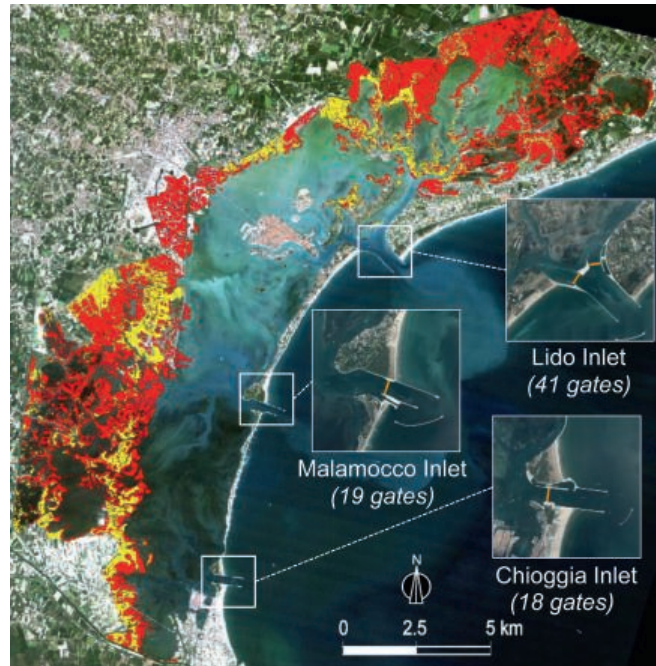
After a disastrous flooding event in November 1966 that lasted for two days with sustained water levels above 2 meters AMSL, a governmental panel of experts suggested the construction of gates to close the lagoon from the sea as the only effective solution to preserve the city. The design, developed several years later by a designated consortium of private companies, is known as MoSE and is based on a system of seventy-eight planar gates that can be raised to close the three inlets of the lagoon. The project has been highly controversial, particularly because of its potential associated environmental impacts. The realization of the MoSE system may also have major impacts on the viability of the Venice harbor, currently the second most important commercial harbor in the Adriatic (after Trieste).

Managing the Lagoon Environment

Human interventions on the lagoon have greatly changed the lagoon sediment balance and induced net erosion throughout its extent. In particular, the lack of sediment input has had a primary role in determining marsh lateral erosion and elevation loss, such that more than 50% of the marsh area has been lost in the past century (see Case Study 9.4 Figure 1) (Marani et al., 2007).

Mitigation strategies to offset this erosive trend have been put in place. Material obtained from dredging navigable channels has been used (when levels of pollution allowed it) to restore and build salt marshes for about 30 years (more than 20 million cubic meters of sediments have been reused to build about 11 square kilometers of salt marshes). This effort has partially compensated for the loss of ecosystem services, but has also spurred controversy over the methods of restoration and the location of the reconstructed marshes.

In 2010, a panel appointed by the Venice Water Authority to develop a Master Plan for managing the lagoon and its environment made the following recommendations: (1) Construction of artificial salt marshes along the main channels to limit the transport of eroded sediment to the sea; (2) Protection, using green engineering methods, of marsh margins



Case Study 9.4 Figure 1 The MoSE project for the defense of the City of Venice from high tides (see insets). In yellow, marsh areas surviving at the beginning of the 21st century. In red, marshes that have disappeared over the course of the 20th century.

Source: Modified from Consorzio Venezia Nuova – Servizio Informativo; www.salve.it; accessed in 2010

to stop the lateral erosion due to boat and wind waves; (3) Experimental artificial tidal flats to boost sediment availability and sustain marsh growth; and (4) Protection and partial reintroduction of water and sediment from the Brenta River toward the restoration of a neutral sediment balance. The Master Plan has not been acted upon as of early 2015.

OUTLOOK

Considering the recent IPCC scenarios for sea level rise, the further increase in tidal/storm surge flooding of Venice and the associated potential damage can only be addressed through hard measures regulating flows between the lagoon and the sea. Soft measures are unlikely to significantly control high tides in the city, essentially because the historical – and current – states of the system are not compatible with current environmental forcings. The current erosional trend experienced by the lagoon and its landforms is irreversible through sustainable solutions. Balancing the elevation deficit of the lagoon (i.e., stopping net erosion and balancing the elevation loss associated with sea level rise and subsidence) requires about $2\text{--}10 \times 10^6 \text{ m}^3/\text{yr}$ of sediments. It has been estimated that the reintroduction of the Brenta River into the lagoon would only yield about $70 \times 10^5 \text{ m}^3/\text{yr}$. Hence, the delivery to the lagoon, through “natural” and sustainable means, of an amount of sediment sufficient to offset the effects of climatic changes is hardly possible. The only alternative is the transport and subsequent distribution of extraneous sediment through mechanical means. Whether this is a viable and desirable solution remains to be determined. Finally, an alternative method to balance the effects of sea level rise would be raising the city and its lagoon by means of water injections into the deep subsurface. This solution has been theoretically evaluated and experimented on a small scale (Comerlati et al., 2004), but its feasibility in the context of a fragile urban fabric, such as that of the city of Venice, is far from established. Economic and technical feasibility also remain to be determined.



Figure 9.3 Widening and extending the dune ridges seaward and replanting with native vegetation along the Delfland coast, The Netherlands, 2013.

Source: Vivien Gornitz

emplacement of plants, stone, sand, and other materials trap sediments and reduce wave energy, thereby cutting beach erosion and wetlands losses. These measures also protect the coast against future sea level rise. The restored broad beach and dune ridges, replanted with native vegetation between the Hague and Hoek van Hollan along the Delfland coast, has created a whole new nature district (see Figure 9.3). The Dutch also employ ecological engineering methods in protecting inhabited areas, such as in the coastal town of Scheveningen. There, multifamily dwellings stand behind a raised levee, fronted by a broad sand beach that is widened by beach nourishment (see Case Study 9.5).

Because of the protection provided by tidal wetlands, their integrity should be preserved as much as possible. Saltmarshes generally keep pace with current sea level rise, except for rapid subsidence (e.g., Louisiana and parts of the Chesapeake Bay), low sediment supply, or altered natural biogeochemical cycles (e.g., Jamaica Bay, New York) (Hartig et al., 2002; Cahoon et al., 2009; Kirwan and Megonigal, 2013). Nevertheless, most marshes would likely submerge when exposed to rapid sea level rise, except under macrotidal regimes or in regions of high sedimentation rates (Kirwan et al., 2010). Saltmarsh restoration involves adding sediment and replanting marsh grasses, sedges, or rushes. Marsh replanting, often with native vegetation, can be combined with engineered structures or submerged stone sills to reinforce the marsh. Coastal uplands should be preserved as buffer zones for future landward saltmarsh migration.

In tropical regions, intact mangroves, which shield the hinterland from severe storm surges, should remain protected from development, and cleared areas should be reforested (McIvor et al., 2012; Van Lavieren et al., 2012). Increasing soil salinity affects the Ganges-Brahmaputra delta of Bangladesh, exposed to both river and coastal flooding. Bangladesh's Char Development

and Settlement Project Phase III aims to provide protection for the coastal regions of the country, including the Sundarbans – world's largest mangrove forest – from saltwater intrusion and flooding by building embankments, sluice gates, drainage channels, protective tree belts, and cyclone shelters, as well as by improving local economic opportunities (Heering et al., 2010). *Char* is newly accreted land in the delta formed by sediments deposited by rivers. Although the Bangladesh Forest Department imposes a 20-year period for replanting and growth of mangroves on the char, new forests are often cut and settled before then. Replanting of mangroves on newly accreted land reduces erosion, stabilizes the soil, and shields against cyclone damage. Adaptation measures include planting of more salt-tolerant crops and conversion to shrimp farming. However, most of the low-lying urban coastal areas like Khulna remain vulnerable to flooding and drainage congestion due to rising high tide levels (see Case Study 9.2).

A broad beach with an elevated dune ridge provides the first line of defense against high seas. Dunes are stabilized by planting grasses and installing fences to trap sand. Beach nourishment also serves as an important means of shoreline protection. Sand from offshore or inland deposits is added to replace erosional losses and to widen and raise the beach. Because of historical erosion, sand needs periodic replacement along the U.S. East and Gulf Coasts. For example, the East Coast from New York to Key West, Florida, has undergone numerous beach nourishment projects since the 1920s. Approximately US\$1.3 billion (in 1996 dollars) has been spent on beach stabilization along the East Coast between 1960 and 1996, with a cumulative cost in the United States of US\$2.4 billion since the 1920s (Valverde, 1999).

Sea level rise will likely worsen erosion, creating shorter sand replacement cycles and increased beach nourishment costs. For example, by the second half of this century, beaches in the New York metropolitan region will need as much as a 26% additional volume of sand for a 60 centimeter to 1 meter rise in sea level (Gornitz, 2002). Beach nourishment will ultimately become economically and physically nonviable for significant increases in sea level.

9.3.1.3 Accommodation

Coastal populations will need to accommodate the anticipated upward climb of sea level and consequent increase in storm floods, as well as other anthropogenic and climate-induced stressors. Various planned and autonomous adaptation measures are possible. For example, building codes can help strengthen structures to make them more storm-resilient. Providing adequate space for water reduces flooding risks. In flood-prone areas, buildings can be raised above the current (or projected) 100-year flood zone, constructed on stilts or pilings, or have ground floors used for nonresidential purposes, such as business, parks, or recreation. One approach is to create “green infrastructure” – planting trees and grass along sidewalks or expanding parks to improve drainage and enhance water infiltration into

the ground (e.g., Aerts et al., 2009; Enarsson, 2011). Another approach is to design neighborhoods around floating buildings and houseboats (e.g., Rotterdam, Seattle, Sausalito, Bangkok; Dircke et al., 2012). Innovative multiuse flood defenses (such as dikes) combine surge protection with housing, parking, parks, and commercial activities (see later discussion; Aerts et al., 2009; Stalenberg, 2012). Underground garages provide storage space for excess water at times of high river or ocean levels (Rotterdam Climate Proof, 2010). Multipurpose examples from Dordrecht, the Netherlands; Hamburg, Germany; and Tokyo, Japan, can serve as models for other coastal cities (Stalenberg, 2012). Preserving community freshwater ponds, harvesting rainwater, floating vegetable gardening, and other community-based practices are commonly seen in coastal Bangladesh.

9.3.1.4 Retreat

Defensive measures, and even accommodation, may provide increased protection against sea level rise and storm surges in the short term, but may offer a false sense of security about changes in the long run, thus serving to encourage further development in inherently high-risk areas. It may ultimately become impossible to defend even the most heavily developed shorelines, particularly on barrier islands lined with high-rise condos outside of major urban centers (Jin et al., 2013). Beyond a certain point, repeated rebuilding after storms, massive protection, or even raising land may become too expensive or ineffective, necessitating a retreat option. As resources available for coastal protection become increasingly stretched, densely populated coastal megacities will probably continue to be defended, whereas smaller settlements are already being considered for realignment. For example, defenses protecting the cliff top village of Happisburgh on the east coast of the United Kingdom are being allowed to fail in order to restore natural coastal processes that will protect downdrift floodplains (Dawson et al., 2009).

Long-term, prudent, coastal management may avert some of the adverse consequences long before a rising sea renders many coastal areas uninhabitable. For example, appropriate land use would limit housing density and building size in flood-prone areas, replacing them instead with natural “buffer zones” of parks, restored wetlands, or recreational facilities. A number of options exist to limit development in flood-prone areas and to plan for eventual retreat. Governments may acquire title to the property at risk through eminent domain, or the property can be donated voluntarily to a conservation organization. Other measures include the creation of erosion setbacks and easements that establish buffer zones for coastal wetlands or beaches. *Buyout programs* reimburse shorefront landowners for abandoning property in high-risk zones. In such cases, the public bears the cost. *Setbacks* restrict shore construction based on erosion or elevation thresholds. In the United States, regulations vary by state. In North Carolina, single-family houses and small structures must be set back thirty times the historic average annual erosion rate or a minimum of 60 feet (18.2 m). For larger structures such as condominiums, the setback is sixty times the historic erosion rate. In Florida, Coastal Construction Control Lines (CCCLs),

based on the 100-year storm surge zone, are intended to protect upland property and control coastal erosion. Construction is limited seaward of CCCL (Florida DEP, 2006). In addition, no new construction is permitted seaward of the projected 30-year erosion line (based on historic trends), with some exceptions, such as building as far landward as possible or behind the barrier dunes. However, numerous loopholes exist in the regulations that do not exclude all forms of development. Setbacks based on historic erosion rates presuppose a future continuation of those rates – unlikely, given anticipated sea level rise. Significantly, accurate historic erosion data may not always exist.

Implementation remains a challenge: setbacks have faced challenges in courts from landowners who claim that they constitutes a “taking” (i.e., government seizure of private property without due compensation) when a property cannot be developed or construction is limited by the setback. In response, some U.S. states, such as Maine, Massachusetts, Rhode Island, South Carolina, and Texas have therefore adopted variants of *rolling easements* (Titus and Craghan, 2009), which allow landowners to keep and develop their property, but prevent shoreline armoring. In *conservation easements*, a conservation organization such as the Nature Conservancy buys the right to prevent further development, but permits the landowner to still remain on the land. Since easements are voluntary, adjacent land can still be armored, but greater erosion downdrift may cancel any conservation benefits. However, easements may not be practical for already heavily developed shorelines. Although designed for present conditions, many coastal management programs can be strengthened by anticipating increased future erosion rates and wider flood zones.

The most extreme option is managed relocation. Extensive use of coastal structures and beach nourishment is expected to become infeasible under future sea level rise (Pilkey and Young, 2009), and transition policies should include coastal retreat and ending financial incentives to rebuild after storms. Individual structures can be moved landward, as has been done most impressively for the historic Cape Hatteras Lighthouse, North Carolina, in 1999 (Bodzin, 1999; National Park Service, 2016). More frequently, houses are moved some tens of meters landward within a given shorefront property, or other buildings threatened by imminent collapse due to coastal erosion are torn down.

Some countries are beginning to take landward relocation seriously. Great Britain now views “managed realignment” as a long-term planning tool, especially for estuaries and relatively undeveloped land (De la Vega-Leinert and Nicholls, 2008). The UK government recognizes that, in the long term, it will become uneconomic to defend many small communities along eroding coasts. “Realignment” involves moving existing coastal defenses inland. However, because most people tend to be unaware of coastal hazard and risk until after damages occur, setbacks and managed realignment are generally highly unpopular and politically contentious. Greater stakeholder involvement from the onset may, however, encourage increased public acceptance (De la Vega-Leinert and Nicholls, 2008).

9.3.2 Adaptive Capacity

A diversity of adaptation measures and practices, ranging from hard and soft solutions to accommodation and retreat, is seen in urban areas around the world. Although these measures are mostly needs-based, the emerging diversity also results from the variation in adaptive capacity of communities and nations.

In coastal urban areas, seen as socio-ecological systems, adaptive capacity refers to the ability of individuals or communities to utilize their resources and capitals to resist and adapt to the present and future hazards (Brooks and Adger, 2004). This capacity varies across and within societies, conditioned by the degree to which the geophysical, biological, and socioeconomic systems are susceptible to the adverse impacts of climate change (Adger et al., 2006; Fussler and Klein, 2006) while being dependent on several factors such as economic wealth, technology, information and skills, infrastructure, institutions, and equity (Smit et al., 2001). In many low-income coastal areas, economic conditions are important for not only affordability of adaptation measures but also for social vulnerability caused by poverty and inequality. In general, adaptation choices are largely influenced by access to technology and information that enhances risk recognition and creates alternative choices for strategies and tools, whereas the effectiveness and appropriateness of adaptation actions depend on the equitable distribution of infrastructure and services. The adaptive capacity of communities is enhanced by increased stability, integrity, and reliability of institutions and governance, a working relationship among local communities and actors (Brooks and Adger, 2004; Smit and Pilifosova, 2003; Smit et al., 2001), high social capital, strong social networks, and community empowerment (Adger, 2003).

Coastal cities often face situations where adaptive capacity and financial capital are enhanced at the cost of increasing climatic risks. The oil exploration and petroleum industry in Hammerfest on the northern coast of Norway triggered economic growth since 2002, which also enhanced the local adaptive capacity by improving institutional capacity, elevating employment and education, and increasing city government investment in schools and urban facilities. However, these transformations were accompanied by a huge increase in GHG emissions due to the industrial activities (Angell and Stokke, 2014).

The importance of information and skills in raising adaptive capacity has been highlighted in Jakarta, the capital of Indonesia, on the northeast coast of Java Island. An environmental vulnerability assessment carried out by Yoo et al. (2014) show that the greatest difficulty in implementing adaptation policies in the city is the local people's lack of awareness and the lack of professionals and experts. Environmental awareness, environmental policy foundation, regional GDP, and infrastructure are the key indicators for adaptive capacity that have positive influences on the city's vulnerability. The less vulnerable region of the city has flood warning system, environmental education programs, and support program for low-income communities after environmental disasters.

Considering the rising risk of coastal flooding and storms, coastal cities will need to invest not only in the spread of information but also in building the autonomy and commitment of local communities for adaptation. Many contingency plans around the world are playing important roles in increasing local adaptive capacity. Rio de Janeiro, a coastal city of around 6.5 million inhabitants, is built over wetlands and mountains on which prevail the poorest population and precarious buildings highly susceptible to landslides. A contingency plan of the city includes preparing local community leaders, mobilizing voluntary groups, and acting through simulation, awareness, and educational programs in primary and secondary schools that function as strategic points for shelter during emergency situations. The whole process fosters awareness and knowledge of risks and the dissemination of information and contributes to community empowerment (Prefeitura da Cidade do Rio de Janeiro, 2013).

9.4 Mitigation Strategies in the Coastal Zone

Mitigation here refers to the reduction in anthropogenic GHG emissions that are a major driver of anthropogenic climate change (as opposed to mitigation of flooding or wave impact energy, which is sometimes used within coastal management terminology). Several mitigation strategies unique to the coastal zone are considered. Although these mitigation options are not necessarily implemented within a coastal city, they usually require supporting urban infrastructure for their maintenance and operation.

9.4.1 Coastal Energy Infrastructure

The coast can provide excellent renewable energy resources and is convenient for siting more traditional power plants due to the availability of cooling water that is not exposed to the risk of low flows, as can be the case for power plants sited next to rivers (Byers et al., 2014). Brown et al. (2014) analyzed nonrenewable coastal energy infrastructure in Europe and identified 158 major oil, gas, liquid natural gas, and tanker terminals (40% on the North Sea coast), and 71 (37% of the European total) operating nuclear reactors on the coast and noted that the United Kingdom has three times more coastal energy facilities than any other European country. Ensuring the security of this infrastructure is important for reducing risks, but, as efforts to mitigate GHG emissions advance, the nature of coastal energy infrastructure is changing. For example, as alternative energy sources such as wind, solar, or tidal power become more prevalent, the need to locate nuclear or conventional power plants at the shore will diminish.

Tidal and wave energy can provide non-fossil fuel energy sources to assist global mitigation. Marine renewables could theoretically provide fifteen times global energy demand, but technical constraints mean it could deliver 1–10% of this (Resch et al., 2010). Potential for marine renewable varies around the world (Arinaga and Cheung, 2012; Moriarty and Honnery, 2012) according to tidal range and wave climate.

Tidal energy technologies include barrages and turbines. The former are damlike structures that capture tidal energy as water flows into and out of a bay or river. Turbines installed next to or within the barrage turn generators that produce electricity. However, tidal barrages may impact estuary ecology and sediment movement (Wolf et al., 2009; Kadiri et al., 2012). Tidal turbines, similar to wind turbines, operate underwater, driven by strong tidal currents.

Currently, some of the world’s large tidal power stations include Sihwa Lake Tidal Power Station, South Korea (254 MW) and La Rance Barrage, Brittany, France (240 MW), with

smaller plants in Jiangxia, China; the Kislaya Guba (Barents Sea, Russia); and the Annapolis Royal Generating Station (Bay of Fundy, Canada). In 2013, the Scottish government approved installation of Europe’s largest tidal turbine in the Pentland Firth between Orkney and the Scottish mainland. The Pentland Firth holds tremendous potential for tidal energy, but its remote location and harsh environmental conditions pose significant challenges for tidal development. Engineers estimate that a potential output of 1.9 gigawatts could eventually satisfy 43% of Scotland’s domestic energy needs (Adcock et al., 2013). In 2012, permission was granted to install up to thirty tidal power turbines in the East River, New York, to harness the extremely

Case Study 9.5 Adaptation Benefits and Costs of Residential Buildings in Greater Brisbane

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Keywords	Wetlands, flood control, flooding, resilience, adaptation, ecosystem-based adaptation, coastal
Population (Metropolitan Region)	2,274,560 (Australian Bureau of Statistics, 2014)
Area (Metropolitan Region)	15,826 km ² (Australian Bureau of Statistics, 2011)
Income per capita	US\$54,420 (World Bank, 2017)
Climate zone	Cfa – Temperate, without dry season, hot summer (Peel et al., 2007)

The Greater Brisbane area, Queensland, with a population of 2.1 million, is one of the fastest growing areas in Australia. Since 2010, it has been inundated by storms and rainfalls brought by tropical cyclones in December 2010–January 2011, and again in January 2013, inflicting insured losses of more than AU\$2 billion (US\$1.6 billion) to this area and more than AU\$3.5 billion (US\$2.81 billion) to Queensland. This urban area will remain subject to great risks from coastal inundation as the Intergovernmental Panel on Climate Change (IPCC)’s Fifth Assessment Report (AR5) affirms continuing sea level rise (Rogelj et al., 2012). Furthermore, tropical cyclones under a future climate may become more intense (Knutson et al., 2010), although by how much is not yet clear.

In view of the challenges ahead, the Queensland Government in 2012 adopted the IPCC A1FI projected sea level rise (Meehl et al., 2007) in its coastal development plan and assumed that future tropical cyclone intensity will increase by 10% (DERM, 2012). With these assumptions and the population growth projected by the Australian Bureau of Statistics (ABS) up to 2056 (ABS, 2008), we applied cost-benefit analysis to investigate raising building floors for the adaptation of coastal residential buildings to future coastal inundation events. For houses designed according to the building code, significant damage costs can occur only under extreme

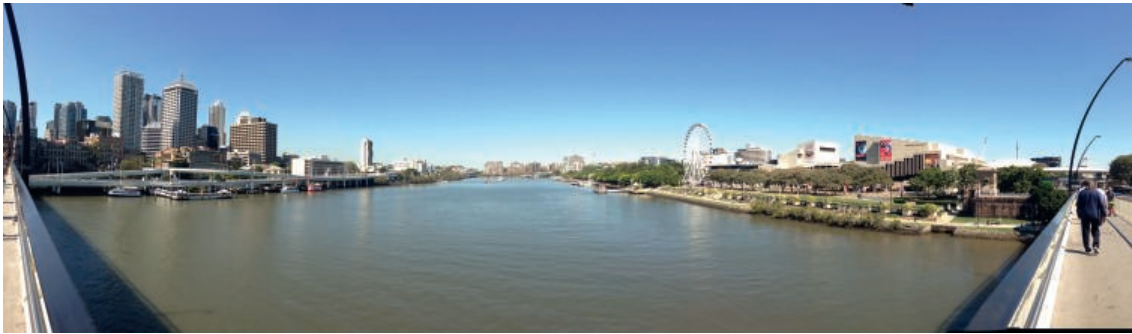
events; therefore, this Case Study investigates the consequence due to annual extreme storm tides.

NEW BUILDINGS ADAPTED VERSUS ALL BUILDINGS ADAPTED

For the inundation analysis, an assortment of data from Australian Bureau of Meteorology, Australian National Tidal Centre, Light Detection and Ranging (LiDAR), Shuttle Radar Topography Mission, Geoscience Australia, and Queensland Government were collected. Ground and building elevations were obtained with average grid spacing of 2 meters from survey data collected by the LiDAR technology. Given a storm-tide height, the areas that are hydrologically connected to the ocean and lower than the water level are projected to be inundated. The number of future residential buildings is assumed to grow at the same rate of population growth projected by the ABS (2008). The spatial distributions of new residential buildings are determined by Monte Carlo simulation under the assumption that they are distributed in accordance with the current distributions of their respective mesh blocks, and the building floor elevations above the Australian Height Datum are determined by the elevation recorded by LiDAR. For damage cost estimation, a discount rate of 4% per annum is assumed to convert future cost to the 2011 value.

The Case Study shows that the increase of future damage costs due to sea level rise is moderate compared to the increase due to building stock growth. This is a result of projected strong growth in the future population of the region. Interestingly, simultaneous consideration of sea level rise and building stock growth results in higher damage costs than the sum of damage costs caused separately by the two. This phenomenon is consistent with the type II extreme value distributions, which exhibit a heavy right tail (i.e., the damage cost is a convex function of the logarithm of average recurrence interval) (Beirlant et al., 2004).

We compare the adaptation options when only new buildings are adapted and when both old and new buildings are adapted. New buildings are regarded as those constructed after 2011. Buildings are adapted by lifting their floors to 1.57 meters above the Australian Height Datum, roughly corresponding to the current 100-year storm-tide level. The adaptation extent is the geographical area inundated by the current 100-year storm-tide events. We found that the benefit of lifting old buildings grows only marginally up to 2056, whereas the bulk of benefit is attributed to the lifting of new buildings. Considering the fact that the modest gain in benefit of lifting old buildings could



Case Study 9.5 Figure 1 *The Brisbane River.*

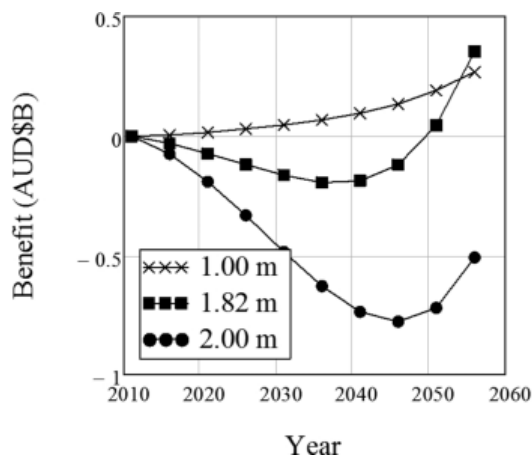


Case Study 9.5 Figure 2 *Buildings developed at waterfront with a high exposure to inundation by extreme storm tides.*

be easily offset by the social cost involved and the high building retrofit cost, lifting new buildings alone appears to be a more cost-effective adaptation policy.

COST-EFFECTIVE ADAPTATION

The larger the adaptation extent, the lower the expected future damage cost. Because of limited resources, however, an infinitely high level of adaptation is untenable. In practical situations, the extent of adaptation is constrained by competing policies and the planning



Case Study 9.5 Figure 3 *Benefit for adaptation extents determined by 1.00, 1.82, and 2.00 meter storm tides.*

time horizon (i.e., the future point in time that the decision-maker sets for achieving the planning objective). A properly chosen adaptation plan can avoid the problem of “underadaptation” that leaves some potential benefits unrealized or that of “overadaptation” that consumes too many resources to the detriment of other policy objectives.

We demonstrate three alternative adaptation extents assuming a planning time horizon of 2056 (the same time horizon for population growth projected by the ABS), as shown in Figure 3. If an adaptation extent determined by a 1.00 meter storm tide is chosen, then it may have the advantage of having an almost always positive net benefit up to the planning time but with modest positive net benefit. For an adaptation extent determined by a 1.82 meter storm tide, it results in negative net benefit during a period of time, but it achieves a higher benefit value than the 1.00 meter storm tide inundation extent. An overaggressive option (e.g., adaptation extent inundated by a 2.00 meter storm tide) requires more resources and may never reach a positive benefit value up to the planning horizon, an example of overadaptation.

Nevertheless, even with limited, suboptimal adaptation, immediate net benefits could be achieved by focusing adaptation on coastal housing with comparatively lower floor height. Similarly, overadaptation in the next decade that lifts more coastal housing to future storm tides gives longer term net benefits, although it incurs higher initial costs. However, too much overadaptation may be undesirable because it incurs unreasonably high initial costs and the benefits of it could only be reaped over a very long time. Therefore, the extent of adaptation should be decided in accordance with the planning time horizon, available resources, and balanced consideration of other policy objectives to avoid either under- or overadaptation.

powerful currents in the tidal strait (Verdant Power, 2014). When fully operational, the turbines will generate 1,050 kilowatts of energy, enough to serve approximately 9,500 local residents (U.S. Department of Energy, 2012).

Marine current power harnesses the kinetic energy of marine currents (e.g., the Gulf Stream) that are generated from a combination of temperature, salinity, wind, bathymetry, and the rotation of the earth. The predictability and potential scale of the resource makes this a potentially significant but not yet widely harnessed source of renewable energy. Wave power harnesses potential energy in the form of water displaced from the mean sea level that has been generated through the transformation of kinetic energy from the wind. However, wave energy varies over short time periods and seasonally making this a less predictable energy source (U.S. Department of Energy, 2010).

Ocean thermal energy conversion exploits gradients in temperature between deep and shallow water to drive a heat engine (Liu et al., 2014). Huge energy resources have been estimated globally, more than any other marine renewable, but currently implementation is limited (Lewis et al., 2011). However, because it can provide a continuous and stable energy source, it is useful for base-load power supply. Similarly useful for base load power supply are salinity gradients, caused by the mixing of freshwater and seawater, which releases energy that could be captured (Scramesto et al., 2009)

9.4.2 Carbon Sequestration

Carbon sequestration is the process of capturing and storing CO₂ emissions. This may involve removing CO₂ from the atmosphere or directly capturing the emissions at their source.

9.4.2.1 Coastal Habitat Restoration

Vegetated coast habitats represent a major terrestrial carbon sink and therefore hold great potential to mitigate climate change (Duarte et al., 2013). Consisting of both submerged (i.e., sea-grass, microalgae) and periodically emerged vegetation (i.e., mangroves, saltmarshes), this habitat is highly endangered, having lost some 25–50% of its area within the past half century, largely due to anthropogenic intervention (Duarte, 2013). Coastal vegetation not only sequesters carbon through its high productivity but also traps sediment, elevates the sea floor through salt marsh accretion and upward growth, and lessens wave energy. Thus, it plays an important dual role in acting as both a CO₂ sink and a natural coastal defense system. Therefore, restoration of degraded coastal wetlands and preservation of existing habitat (e.g., using approaches described in Section 9.3.1.2), offers a safe and cost-effective mitigation strategy.

9.4.2.2 Carbon Capture and Storage

A number of engineering techniques can be used to sequester carbon offshore. These include deep oceanic injection, or converting CO₂ into stable carbonates (such as chalk). These are

not usually directly relevant to coastal, cities but some cities are situated above or provide supporting infrastructure for injection into geological strata. This involves capture, liquefaction, transport, and injection of industrial CO₂ into deep strata including coal seams, old oil wells, stable rock strata, or saline aquifers (Lal, 2008).

9.5 Cross-Cutting Theme Linkages

9.5.1 Governance

Multilevel governance strategies that involve international to local public, private, and nonprofit stakeholders are central to addressing issues such as climate change that extend beyond local administrative boundaries into the social, environmental, and economic systems with which they connect. Climate change hazards pose governance challenges for coastal cities due to the uncertainties associated with the extension of its impact across the territory, thus increasing the complexity of decisions to prioritize adaptation measures. For example, hazards can require population resettlement in retreat adaptation strategies, which can lead to considerable social and economic impacts and thereby demand the empowerment and engagement of all actors involved.

To respond to climate change, governance depends deeply on government's political and institutional capacity to carry out and/or enforce mitigation and adaptation actions. For example, in Mexico City “downsizing and retrenchment of the state, liberalization, decentralization and deregulation” are limiting institutional capacity to adapt (Romero-Lankao, 2007). In many countries the lack of government reliability due to corruption, but also lack of continuity and long-term policies, can be a great barrier for governance, limiting its capacity to respond to all previous challenges. Moreover, in developing countries, climate change adaptation can be delayed by fragile government structures and deficient basic infrastructure (Bulkeley et al., 2011). In the Dar es Salaam Case Study, a port city of 4 million in sub-Saharan Africa, investment requirements to address lack of infrastructure and informal housing and economies, as well as to achieve mobility, solid waste management, and sanitation, deprioritize the need for local-level climate change mitigation and adaptation issues as a public urgency (Kiunsi, 2013).

Coastal cities must build capacity and mobilize the necessary political and financial resources to deliver measures to protect the population and adapt their infrastructure (Bulkeley et al., 2011). Civil society and NGOs play a determinant role in prioritizing climate change adaptation (Bulkeley et al., 2011; Broto and Bulkeley, 2013). This emphasizes that climate change responses cannot be exclusively the responsibility of the public sector (Broto, Obala, and Junior, 2013). As Broto and Bulkeley (2013) have shown, in Asia's economic context, for example, private actors have prevailed in leading urban infrastructure investments seeking climate adaptation.

Case Study 9.6 Adapting to Climate Change in Coastal Dar es Salaam

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Keywords	Adaptation; mainstreaming; peri-urban; vulnerability; seawater intrusion
Population (Metropolitan Region)	4,364,541 (National Bureau of Statistics, 2013)
Area (Metropolitan Region)	1,393 km ² (National Bureau of Statistics, 2013)
Income per capita	US\$820 (World Bank, 2017)
Climate zone	Aw – Tropical savannah (Peel et al., 2007)

Dar es Salaam is located in the eastern part of Tanzania. It is bounded by the Indian Ocean on the east and the Coast Region on the west. The main physical features are the coastal plains, composed of limestone; the alluvial plains, with a series of valleys; and the upland plateau, 100–200 meters in altitude. It is the third fastest-growing city in Africa, the largest one in Tanzania, and the administrative and economic hub of the country. It has the status of a city-region with both a regional administration and four local government authorities (LGAs), the City Council, and the three Municipal Councils of Ilala, Kinondoni, and Temeke.

About 80% of residents live in spontaneous low-density settlements where livelihoods are based on skillful and dynamic combinations of urban and rural activities and resources. Preserving natural resources is fundamental to residents' survival and capacity to adapt to climate change.

RELEVANCE OF THE ACTION TO CLIMATE CHANGE ADAPTATION

The Adapting to Climate Change in coastal Dar es Salaam¹ project is aimed at improving the effectiveness of municipalities supporting coastal peri-urban dwellers who depend on natural resources in their efforts to adapt to climate change (Ricci, 2014). The project was co-funded by the European Union and implemented between 2010 and 2014. It focused on communities in the coastal plain where groundwater salinization, due to the combined effects of urban expansion and climate change, seriously affects local communities because they depend heavily on boreholes for accessing water for domestic and productive purposes (see ACC Dar Papers accessible from the project website; ACC, n.d.).

The project provided Dar's municipalities with enhanced methodologies for mainstreaming climate change adaptation into their Urban Development and Environment Management plans and programs and increased their understanding of adaptation practices. The interplay between climatic and nonclimatic stressors (i.e., developing methodologies for assessing groundwater salinization and urban sprawl) was explicitly recognized. The action aimed to improve the

capacity to integrate climate change concerns at the local level, thus contributing to the implementation of the National Adaptation Programme of Action.²

Three sets of activities were implemented: (1) improve understanding of climate change adaptation; (2) develop methodologies for designing adaptation initiatives; and (3) build the local government authorities' capacity to understand climate change issues specific to peri-urban livelihood in the coastal plain and identify effective measures for supporting coastal peri-urban inhabitants in their efforts to adapt to climate change.

ACTION AND POLICY DRIVERS

Sapienza University of Rome designed and coordinated the project with Ardhi University of Dar es Salaam as a partner and the Dar es Salaam City Council as an associate. The three municipalities were the main stakeholders. The coastal peri-urban residents were involved in the household survey, borehole monitoring, and participatory scenario building (see Case Study 9.6 Figure 1). It ensured that their concerns over environmental change, coping experiences, and future expectations played a major role in the definition of adaptation objectives. Other relevant stakeholders took part in the activities (e.g., the Wami Ruvu Basin Authority was involved in capacity-building to share competences and responsibilities and strengthen the relationships with the municipalities). Nongovernmental organizations (NGOs) (Haki Ardhi, Forum Climate Change, Environmental Engineering and Pollution Control Organization [EPCO]) also took part in the capacity-building program and community-based organizations (CBOs) (Kigamboni Community Centre and Club Wazo) were key players in participatory activities (i.e., community-based scenario exercises combining a backcasting approach and forum theatre) (Macchi and Ricci, 2016; Macchi and Tiepolo, 2014). The whole process of knowledge and methodology development, together with the continual interactions and sharing of the results with local decision-makers, was crucial to improving capacity in adaptation mainstreaming and bridging the gap between knowledge and action (Rugai and Kassenga, 2014).

IMPACT AND SCALE

The actions focused on climate change impacts on peri-urban areas within the coastal plain, slow and incremental environmental changes, and risks to the sustainability of rural-urban livelihoods, rather than on extreme weather events and disasters. Addressing the salinization of the coastal aquifer in connection with seawater intrusion and urban sprawl, the project carried out a detailed analysis of the current situation and future scenarios (Faldi and Rossi, 2014; Congedo and Munafò, 2014). This led to the formulation of amendments for the current Urban Development and Environment Management plans and programs. These amendments were formulated using an ad-hoc methodology to support adaptation efforts through the water conservation and secured access to water resources for domestic and productive uses (see Case Study 9.4 Figure 2) (Shemdoe et al., forthcoming).

LESSONS LEARNED

By strengthening the relationship between knowledge institutions and local government authorities (LGAs), and by involving multiple

¹ www.planning4adaptation.eu

² See http://unfccc.int/national_reports/napa/items/2719.php.

actors and stakeholders, the territorial approach³ proved to be highly suitable for tackling adaptation challenges. The importance of the local dimension in determining the efficacy of adaptation mainstreaming in Urban Development and Environmental Management was confirmed. However, given the poor implementation of many urban and environmental plans, the viability of climate change mainstreaming should be carefully evaluated (Macchi and Ricci, 2014). Moreover, an in-depth analysis of autonomous adaptation strategies and practices is necessary to understand vulnerabilities, their structural causes, and the diverse responses that are emerging. Autonomous adaptation includes strategies to cope with current and future climate-related environmental stresses and changes in coastal peri-urban areas (IPCC, 2014).

At the same time, future uncertainties require the consideration of multiple adaptation strategies to be revised as new challenges and opportunities arise.

The relationships between access to natural resources and climate change vulnerability needs to be deeply investigated and particular attention should be paid to the intersection between uneven access to resources, environmental processes, and human activities affecting the quality and availability of resources such as water. The collaboration among knowledge and research institutions, LGAs, and stakeholders was crucial for integrating different types of knowledge and competences in decision-making to support effective adaptation actions and reduce vulnerability.

Stakeholders in coastal areas can be very heterogeneous, from working waterfronts including small local fishing or industrial businesses to large utility companies, residential and commercial neighborhoods, and stewards of recreational open spaces and ecological sanctuaries. To engage everyone in the resiliency-building process, governance requires transparency in city government actions, inclusive planning, accessibility in the distribution of technical information, and ample opportunities for community oversight (Adger et al., 2006).

9.5.2 Co-Benefits, Barriers, and Bridges

Adaptation efforts in coastal cities provide potential co-benefits for climate change mitigation and local economic development. Although these reflect some of the distinct features of their location in the coastal zone (e.g., marine trade networks, coastal habitats), they are not fundamentally different from other cities although possibly more acute. For example, coastal megacities will experience more intensified conflicts related to land-use due to “squeeze,” whereas coastal erosion, salt water intrusion, loss of habitats for fish and wildlife, and deteriorating marine environment aggravate natural disasters.

A significant challenge for coastal cities will be to develop and grow in a more climate-sensitive manner. It is cheaper and easier to protect a small compact area from rising sea level than a large sprawl, whether by erecting dikes, elevating the urban area, or rebuilding inland. Retreat is less expensive with a dense area because there is less infrastructure (e.g., roads and sewers) that needs to be rebuilt. Furthermore, higher densities can reduce energy use and lower infrastructure costs.

9.5.3 Urban Planning and Design

The challenge to urban planners and designers in coastal cities is to find positive solutions to adapt, resist, or mitigate coastal climate risks while being sensitive to the coastal environment and adding value to the development. A growing body of

innovative architectural and engineering design work is emerging that embraces these challenges within urban design and planning (Building Futures, 2010). Central to these are use of new building design approaches, multifunctional flood defense infrastructures that benefit local people and businesses, and planning systems that enable integrated and long-term local strategies.

Possible secondary functions of flood defenses include housing, transport, shipping, agriculture, habitat, and amenity (Anvarifar, 2013). For example, a flood defense with a road on top is multifunctional. Governance for these structures must be considered because they require maintenance and inspection to ensure safety. It must be noted that there is potential to create conflicts of interest with multiple stakeholders invested in the structure (Voorendt, 2015).

Low-lying coastal or riverine cities often develop around a series of canals (the “Venetian solution”). Venice is best-known, but Amsterdam, Bruges, Copenhagen, Suzhou, and Bangkok also boast extensive canal networks. Although many of Bangkok’s canals have recently been filled and paved over, Rotterdam plans to construct additional moats and canals to store excess discharge at times of high water. The expanded canal system would additionally create a supplementary transportation corridor. Innovative harbor redevelopment proposals include formation of an artificial island archipelago and reefs using dredge material or reconfiguring the shoreline by lowering the seaward gradient, rehabilitating or expanding remnant wetlands, creating new parks, and building a “feathered edge” of piers and slips to lessen storm surge impacts (Nordenson et al., 2010). Some of these inventive ideas have already been implemented or are under consideration. For example, with only a few cruise ships still docking directly at Manhattan piers, New York has built an extensive network of parks and pedestrian and bicycle pathways along the waterfront. Floating buildings (like large houseboats) represent yet a different mode of living with a higher water level. A floating neighborhood of approximately 100 houses has been constructed in Ijberg, eastern Amsterdam, and more are planned (Finney, 2013). Other buildings sit on a

³ The territorial approach for adaptation is a place-based approach in which local authorities interact with a range of other local and multilevel actors (e.g., universities) to make the most of existing political and institutional resources. LGAs also cooperate with national-level institutions to implement National Adaptation Programs of Action (NAPA). Moreover, climate change adaptation mainstreaming of LGAs not only improves the national climate change agenda, but also contributes to the effective use of resources and enhances the potential to attract other resources.

Case Study 9.7 Rotterdam: Commitment for a Climate-Proof City

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Keywords	Sea level rise, river flooding, climate resilience, coastal
Population (Metropolitan Region)	1,175,477 (Statistics Netherlands, 2014)
Area (Metropolitan Region)	782,43 km ² (Statistics Netherlands, 2015)
Income per capita	US\$46,310 (World Bank, 2017)
Climate zone	Cfb – Warm temperate, fully humid, warm summer (Peel et al., 2007)

Like many other major port cities, Rotterdam faces increasing vulnerability to sea level rise. The Delta Committee (2008) anticipates a sea level rise of 0.65 to 1.3 meters for the Netherlands by 2100, as compared with 0.4 to 1.05 meter after Katsman et al. (2011).

Rotterdam has embarked on an ambitious plan to “climate-proof” the city, anticipating up to 1.3 meters higher sea level and greater winter rainfall (causing additional river flooding) by 2100. The

Delta Committee (2008) has therefore proposed to tighten current flood risk standards by creating a “closable yet open” Rhine estuary through new movable flood barriers that would divert water into safer directions depending on hydraulic conditions. Other options include introducing new interconnections within the existing canal and river network or even building entirely new waterways. Added coastal hazard protection from storm surges and sea level rise including reinforcing water defenses – the dikes and the neighborhoods beyond the dikes – as well as undertaking appropriate land-use planning, constructing water-adapted buildings, and allowing water to drain or to temporarily retain excess rainwater. Large areas of unembanked land reserved for future urban expansion will need to be raised by 1–1.5 meters to meet the revised base flood level (the minimum threshold level for new buildings and infrastructure) requirement of 3.9 meters above the Amsterdam Ordnance Datum (Rijcken, 2010; Van Veelen, 2010).

The Floating Pavilion, installed in June 2010, previewed other floating districts planned for the Stadshavens section of Rotterdam. It represents a prototype for future floating districts (Aboutaleb, 2009). Floating homes already exist in various places, such as the sampans in Hong Kong harbor and houseboats along the shores of Lake Union, Seattle, Washington, and Sausalito, California. Former barges, now comfortable homes, line the canals of Amsterdam and Rotterdam. Rotterdam even boasts a floating three-star hotel in historic Wijnhaven. Rotterdam foresees entire future floating residential districts, complete with office complexes and parks, and will expand



Case Study 9.7 Figure 1 Multipurpose dike in Scheveningen, a coastal resort near the Hague, the Netherlands.

Photo: Vivien Gornitz

its network of moats and canals. Impermeable concrete or asphalt associated with urbanization prevents rainwater from infiltrating into the soil and recharging aquifers and causes street and basement flooding after heavy rains. In Rotterdam, excess rainwater is temporarily stored beneath municipal parking or in water plazas that also serve as parks or playgrounds when dry. “Green roofs” also helps curb excess runoff (Aerts, 2009).

Following the disastrous North Sea flood of 1953, which left 300,000 people homeless and caused 1,800 deaths, the Netherlands began construction of the Delta Works (a series of dams, surge barriers, dikes, and sluices along the Rhine-Meuse-Scheldt delta), which closed off some of the estuarine outlets to the sea. Approximately 40% of the country lies below sea level, and an even greater proportion is vulnerable to coastal or river flooding. The lowest areas are highly populated and encompass the bulk of the nation’s economic activity. Acceptable risk levels of dike failure were set at 1 in 10,000 years for North and South Holland; other high risk areas are set at 1 in 4,000 years, and South Holland river flooding at 1 in 1,250 years. A movable barrier, the Maeslant Barrier completed in 1997, now closes off the New Waterway (Nieuwe Waterweg) whenever a high storm surge threatens the city of Rotterdam and surrounding dikes. These impressive engineering structures have been designed for a sea level rise of only 20 to 50 centimeter per

century (Delta Committee, 2008), far short of the projected rise. Sea level rise will lead to more frequent barrier closures: three closures per year for an 85 centimeter rise and an average of seven closures per year for a 1.3 meter rise. The Delta Committee (2008) therefore recommended that existing or new storm surge barriers should withstand a worst-case scenario of regional sea level rise of 0.65–1.3 meters by 2100, and up to 2–4 meters by 2200 (using the SRES A1F1 emissions scenario) (Nakicenovic et al., 2000). Present flood protection standards in the diked areas must be raised tenfold by 2050. Dikes, such as a massive new one 1 kilometer long and 12 meters high under construction in the coastal resort of Scheveningen, near the Hague, will serve multiple purposes (see Case Study 9.5 Figure 1). It will be overtopped by a sweeping new boulevard with broad stairways to ensure ready access to the beach, which is also being widened to dampen the power of the waves and buffer against floods.

Rotterdam, like many other delta or tidal river cities, faces inland flooding as well as marine incursions. Dutch winters are expected to grow wetter while summers become drier. Therefore, water management plans will defend against both inland and coastal flooding and also ensure an adequate water supply during dry spells. New developments beyond the dikes will be designed not to interfere with river discharge or lake water levels.

series of artificial islands on the IJsselmeer, accessible by bridges and walkways. To deal with extreme hazards, tsunami-resilient building designs are starting to emerge using principles of performance-based design – rather than try to resist the force of the tsunami, the lower floors can be opened up (given sufficient warning) or designed so the walls easily “blow-through” while the upper floors and main supports remain intact (Designs Northwest, 2015).

9.5.4 Equity and Environmental Justice

Climate change poses risks to urban coastal populations, but the uneven spatial distribution of these risks has not been fully understood (Bautista et al., 2015b). This constitutes a critical gap for communities currently challenged by poverty and/or environmental injustice (and their cumulative impacts), vulnerabilities that can be exacerbated by severe weather and climate change (Milligan et al., 2009; Nicholson-Cole and O’Riordan, 2009). Equity and environmental justice issues are therefore critical factors to assessing local vulnerability to floods and other climate change impacts in urban areas (Maantay and Maroko, 2009; Bautista et al., 2015a). Coastal cities, particularly those in mid- and low-income countries, concentrate the most vulnerable communities in high-risk areas – informal settlements and substandard housing mainly located in flood-prone areas or in landslide susceptible hills. These vulnerable populations experience a cumulative risk effect that adds to the underlying adversities posed by the lack of employment, poor health conditions, and deficient urban services and infrastructure, among others (Satterthwaite, 2013). This is the case in cities like Chittagong, the biggest port city on the coast of Bangladesh, where landslides have caused 400 deaths since 1997 (Ahammad, 2011), or in Rio de Janeiro, the biggest Brazilian coastal city. Rio is

highly threatened by summer storms and had experienced 373 deaths from climate-related disasters from 1966 to 2010, when the city was hit by a huge storm (Prefeitura da Cidade do Rio de Janeiro, 2015). In 2015, the municipal government launched its new resilience plan, Rio Resiliente, that prioritizes reducing the vulnerability of thousands of households under risk of potential landslides (mainly in the slums) by adding to previous plans that were specifically focused on disaster prevention (Prefeitura da Cidade do Rio de Janeiro, 2015).

The challenge posed then is to guarantee that adaptation and mitigation measures do not reinforce inequalities (Olsson et al., 2014). This creates an opportunity for environmental justice advocates, community-based planners, and other local stakeholders to lead efforts in identifying strategies to build climate resiliency and to address the needs of vulnerable populations (Bautista et al., 2015a). The New York City Environmental Justice Alliance’s (NYC-EJA) approach to building community resilience illustrates the potential for innovative, locally driven resiliency planning. This approach “focuses on building healthy, resilient communities while advocating for long-term climate adaptation, mitigation, and resiliency measures in order to ensure that vulnerable communities are stronger and healthier before disaster hits” (Bautista et al., 2015b).

In the aftermath of Hurricane Sandy, there have been extensive conversations regarding opportunities to reduce the vulnerability of the New York region to flooding and storm surge, but government reports had almost exclusively focused on the built environment. NYC-EJA co-convened and facilitated the Sandy Regional Assembly (SRA), an association of grassroots stakeholders from communities vulnerable to severe weather events, in order to address this gap. As a result of this process, the SRA issued a Recovery Agenda, including comprehensive



Figure 9.4 Post Hurricane Sandy community forum in New York.

Photo: UPROSE

rebuilding/resiliency recommendations and capital projects – some of which were incorporated in government plans (Sandy Regional Assembly, 2013). NYC-EJA has also partnered with one of its member organizations, The Point CDC (www.thepoint.org), to create the South Bronx Community Resiliency Agenda and engage local communities in creating a comprehensive climate resiliency agenda to strengthen the physical and social resiliency of five of the most vulnerable communities in NYC – and in the United States (Bautista et al., 2015b; NYC-EJA, 2015). The Climate Justice & Community Resiliency Center that is being developed by the community-based planning organization UPROSE in Sunset Park, Brooklyn, is another example where an environmental justice community is leveraging on-the-ground knowledge and grassroots organizing with advice from urban planners and public health scientists to create strategies for a climate-resilient industrial waterfront community (www.uprose.org/).

Addressing existing vulnerabilities to build community resiliency constitutes a central pivot point for the governance of coastal areas (Paavola et al., 2006). Over the past decade, environmental justice advocates have been striving for the recognition of principles of equity and environmental justice in climate change discussions. In part as the result of these efforts, in 2015, the de Blasio Administration published its sustainability blueprint, “One New York, The Plan for a Strong and Just City,” articulating strategies to address equity as a cross-cutting priority in the city’s long-term economic growth, sustainability and resiliency agendas (City of New York, 2015). Nonetheless, to guarantee that these efforts reach those who need them most, such government initiatives require the direct continued participation of all sectors of civil society in the decision-making process – both during the planning and design phases as well as throughout its implementation (Scholsberg, 2014; Bulkeley, 2014).

9.6 Conclusions, Policy Recommendations, and Areas for Future Research

Climate change, and sea level rise in particular, will likely exacerbate natural hazards to which coastal cities are uniquely exposed (e.g., storm surges, beach erosion, and saltwater intrusion). Urban centers built on low-lying deltas will be especially vulnerable. Many coastal cities face additional risks from river and groundwater flooding, loss of protection from offshore (coral) reefs, and increased wave damage at the shore. These climate-induced changes will, in turn, affect marine ecosystems, aquifers used for urban water supplies, the built environment, and disruption to transportation and economic activities, particularly following extreme storm events. The intensity of the risk will vary from place to place, depending on the extent of local changes in sea level rise, ocean warming, precipitation, or river runoff. In addition to natural hazards, cities face vulnerabilities in exposure of critical infrastructure in flood zones, precariously built housing in poor neighborhoods, and sharp contrasts in income distribution that affect adaptive capacity and personal health.

Various strategies exist to manage climate-induced risks affecting coastal cities. These range from increasing shoreline protection, both by building defensive structures or by adopting “soft,” more natural solutions, such as dune building or wetlands preservation and restoration. Other adaptive strategies include accommodating structures and lifestyles to a more aquatic presence. It may ultimately become impossible to defend further development in extremely high-risk areas. However, a long-term integrated approach to coastal management and inclusive governance is essential to adapt to climate change impacts and manage cities in the coastal zone in the third millennium (Nicholls et al., 2015).

Case Study 9.8 Preparing for Sea-Level Rise, Coastal Storms, and Other Climate Change–Induced Hazards in New York

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Keywords	Sea level rise, coastal flooding, structural adaptations
Population (Metropolitan Region)	20,153,634 (U.S. Census Bureau, 2016)
Area (Metropolitan Region)	17,319 km ² (U.S. Census Bureau, 2010)
Income per capita	US\$56,180 (World Bank, 2017)
Climate zone	Dfa – Cold, without dry season, hot summer (Peel et al., 2007)

New York, with a population of 8.4 million (Metropolitan Statistical Area population 20.1 million [2016]), is the largest city in the United States and is a major center of global finance and commerce. Significant economic assets and a population vulnerable to coastal flooding line its 837 kilometers of shoreline. The city has long led climate change adaptation efforts (NPCC, 2010; Rosenzweig et al., 2011), and new projects have been initiated since Hurricane Sandy in October 2012 (SIRR, 2013; New York City Office of Emergency Management, 2014). The city's population residing within the 100-year flood zone⁴ exceeds that of other vulnerable U.S. coastal cities, including Houston, New Orleans, and Miami (SIRR, 2013). The New York-Newark-New Jersey area ranks among the world's ten port cities most vulnerable to coastal flooding (by assets, not population), not counting future coastal protection (Hanson et al., 2011). This case study highlights major conclusions about accelerated sea level rise and increased coastal flooding and some of New York's ongoing and planned responses.

Underscoring New York's vulnerability to intense coastal storms, Hurricane Sandy, in October 2012, caused forty-four deaths, hospitals and nursing home evacuations, inundation of some subway and other tunnels and 17% of the city's land area, power outages affecting nearly 2 million people, and major transportation disruptions. An estimated 70,000–90,000 buildings were flooded and/or damaged. Storm damages totaled nearly US\$20 billion (New York, PlaNYC, 2014).

Following Sandy, New York developed more comprehensive plans to reduce present and future climate-related risks, drawing upon the scientific expertise of city and regional agencies, universities, the private sector, and the New York City Panel on Climate Change (NPCC), an advisory group inaugurated by Mayor Michael Bloomberg in 2008 from academia, government, and the private sector (SIRR, 2013; NPCC, 2013, 2015; New York City PlaNYC, 2014). Implementation of resiliency measures has already begun. This case study highlights

major NPCC conclusions regarding accelerated sea level rise and increased coastal flooding, with some of New York City's ongoing and planned responses.

CLIMATE, SEA LEVEL RISE, AND COASTAL STORMS

New York experiences a hot-summer continental climate (Köppen-Geiger, Dfa), with a mean annual temperature of 12.2°C between 1971 and 2000, climbing 0.2°C per decade between 1900 and 2013 (NPCC, 2015). Rainfall ranges between 109 and 127 centimeters per year, rising by 2.0 centimeters per decade between 1900 and 2013. Variability has increased noticeably over the past 40 years (NPCC, 2015). In the future, the NPCC finds that mid-range temperatures could increase by 2.3–3.2°C by the 2050s, 2.95–4.9°C by the 2080s, and 3.3–5.8°C by 2100 (NPCC, 2015)⁵.

Twentieth-century regional sea level rise ranged between 2.2 and 3.8 centimeters per decade in the New York metropolitan area⁶ (NOAA, 2016), as compared to the global average rise of 1.7 centimeter per decade (IPCC, 2013). The NPCC (2015) finds that mid-range sea level at the Battery (southern tip of lower Manhattan) will increase 28–53 centimeters by the 2050s and 46–99 centimeters by the 2080s, relative to 2000–2004. High-end estimates reach 76 centimeters by the 2050s, 147 centimeters by the 2080s, and 190 centimeters by 2100.

Past winter cyclones and hurricanes have flooded parts of the city. Hurricane Sandy (an extra-tropical-tropical storm in NYC) generated the highest recorded water level (3.38 m) at the Battery (the southern tip of Manhattan) that has been recorded in nearly 200 years due to strong easterly winds, surge amplification,⁷ maximum storm surge at high tide and full moon, plus historic sea level rise (0.44 m since 1856 [NOAA, 2016]).

Using the just noted sea level rise projections, updated Federal Emergency Management Agency (FEMA, 2013) flood return curves, and assuming unchanged storm characteristics, flood heights for the 100-year storm (excluding waves) would rise from the present 3.4 meters in the 2000s to 3.9–4.5 meters by the 2080s (mid-range). The annual likelihood of such a flood would increase from 1 to 2.0–5.4% by the 2080s, with a high estimate of 12.7%. The area potentially at risk to flooding would consequently expand in the future.

VULNERABILITY TO SEA LEVEL RISE AND COASTAL STORMS

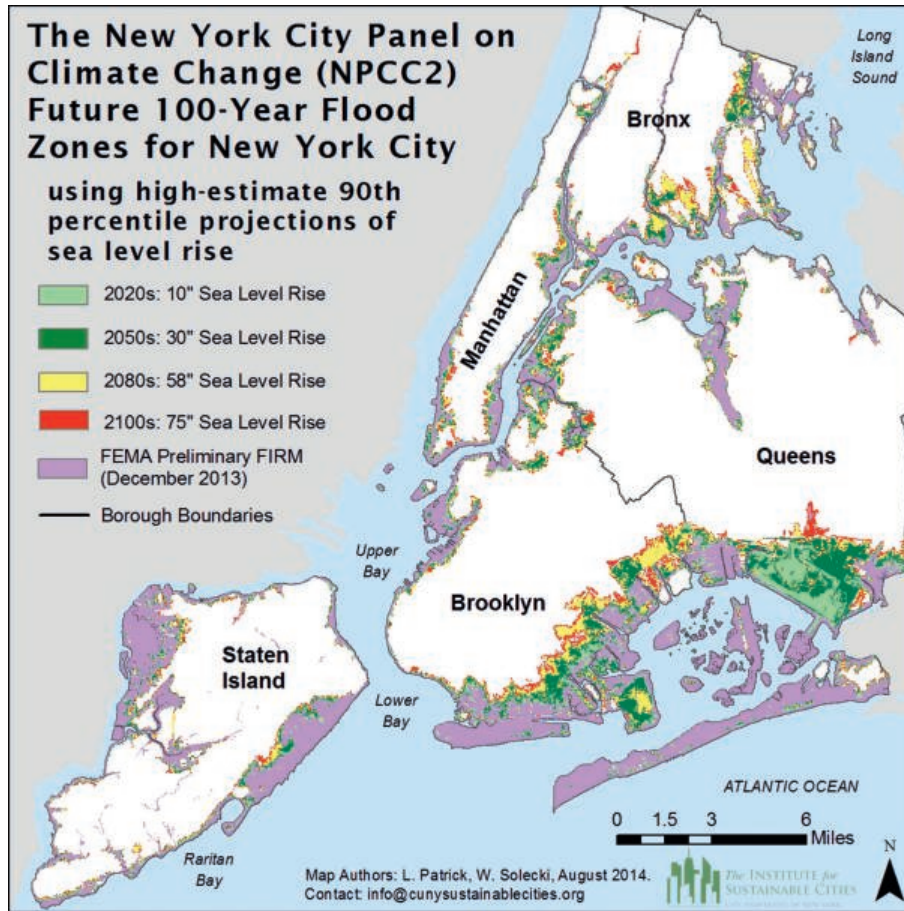
Major critical New York assets, including port facilities, major transportation routes, oil tanks and refineries, power stations, and wastewater treatment plants lie along the waterfront or within the 100-year flood zone. Coastal wetlands in Jamaica Bay that buffer storm surges and waves and provide important wildlife habitat, recreation, and water pollution filtration have deteriorated within the past few decades (Hartig et al., 2002), although a restoration program is under way (New York City Audubon). Wetland restoration to

⁴ The area flooded by a storm having an estimated 1% probability of occurrence per year.

⁵ Future temperature and precipitation projections derive from a suite of 35 global climate models (Coupled Model Intercomparison Project Phase 5, CMIP5) and two GHG emission pathways (RCP 4.5 and RCP 8.5; IPCC, 2013b), which produce a 70-member model-based distribution for risk-based decision-making. The 25th to 75th percentile of the model-based distribution represents the mid-range; the 90th percentile represents a high-end estimate. Projected temperatures and precipitation are averaged over selected 30-year time intervals; 10-year intervals for sea level rise, of 24 GCMs are used.

⁶ Of this, 0.86–1.1 centimeters per decade is due to glacial isostatic adjustments from collapse of the peripheral bulge south of the last ice sheet, following its retreat (NOAA, 2016; PSML, n.d.).

⁷ Landward funneling of storm surge due to near right-angle geometry of New Jersey and Long Island shorelines.



Case Study 9.8 Figure 1 Areas potentially at risk to the 100-year flood by the 2020s, 2050s, and 2080s based on projections of the 90th percentile sea level rise.

Source: NPCC, 2015

preserve habitat and buffer storm surges in Jamaica Bay is ongoing in partnership with the New York City Department of Parks, New York State, and the U.S. Army Corps of Engineers. Continual erosion of the city's sandy beaches requires periodic nourishment with dredged sand by the U.S. Army Corps of Engineers. Although diverse income groups share a similar exposure to coastal flood hazards in New York and surroundings, the poor, aged, and disabled urban populations are more vulnerable and less able to cope with natural disasters (Buonaiuto et al., 2011). Following Hurricane Sandy, the City's Office of Emergency Management (OEM), Center for Economic Opportunity (CEO), and other city agencies worked closely with grassroots community groups, such as the New York City Environmental Justice Alliance and its member organizations, to improve local preparedness and response capacity in extreme weather events (e.g., New York City Office of Emergency Management, 2014; SIRR, 2013).

ADAPTATION TO RISING SEAS AND STORM SURGES

New York intends to strengthen its resiliency to climate change risks (SIRR, 2013; New York City, PlaNYC, 2014). Ongoing and proposed initiatives call for improved coastal flood mapping, continued collaboration with the NPCC to update and refine local climate projections, and strengthening of coastal defenses using a variety of approaches tailored to specific neighborhood needs. These include raising bulkheads and seawalls; enhancing beach nourishment;

building local levees and storm surge barriers; implementing stricter building codes to reduce flood risk; increasing protection of critical infrastructure, including port facilities, utilities, telecommunications, sewer and drainage systems, and transportation arteries; and restoring wetlands and beach dunes. The city also recommends several smaller, strategically placed local storm surge barriers (SIRR, 2013). Many of these adaptations are included in "The Big U," an imaginative proposal for a protective system around the southern part of Manhattan stretching from West 57th Street south to the Battery and up to East 42th Street (Inexhibit, n.d.). An important element of protection for part of lower Manhattan that is now moving forward is the East Side Coastal Resilience Project, which includes flood barriers and other measures to protect the area from East 23rd Street south to Montgomery Street (New York City, PlaNYC, 2015).

CONCLUSION

Global warming in New York is anticipated to increase temperatures, produce more frequent and prolonged heat waves, create more intense downpours, raise sea level, and lead to more damaging coastal flooding. In response, the city has embarked on a comprehensive long-term program to improve its resiliency to climate change, working closely with the NPCC, FEMA, and other state and national agencies. New York City's proposed strategies for enhancing coastal urban resiliency stand as a model for other urban coastal centers to prepare for climate change.

9.6.1 Policy Recommendations

9.6.1.1 Adaptive Management of Coastal Cities

An adaptive management framework for urban coastal adaptation involves assessing climate change risks, implementing various adaptive measures, monitoring outcomes periodically, and refining these successively as more up-to-date climate change data become available (e.g., Environment Agency, 2012; NPCC, 2010, 2015). An adaptive approach maintains flexibility to accommodate to changing conditions over time. While simple, less costly measures can be implemented in the short-term, the door is kept open for major projects needed for long-term protection as needed. Such an approach is already being applied in London (e.g., the Thames Estuary 2100 Plan; Environment Agency, 2012), in New York (New York City Office of Emergency Management, 2014), and across the Netherlands (Delta Commission, 2013).

9.6.1.2 Integrated Coastal City Management

Coastal cities need to develop and adopt integrated management strategies that plan adaptation to climate risks, encompassing where possible co-benefits for the built environment, ecosystems, and human systems. Appropriate land-use planning for sustainable infrastructure development in low-lying coastal areas should become an important priority.

9.6.1.3 Inclusive Governance and Learning from Change

Delivering adaptive and integrated responses will require greater coordination and cooperation on coastal management issues. This must be fostered among all levels of local, regional, and national governing agencies and be participative, engaging with other stakeholders. Learning from experience, especially dealing with change in coastal cities, is challenging. We understand how to defend a coast much better than how we can live in cities on a dynamic coast. Action research should be undertaken on this issue, and the lessons must be captured and incorporated into coastal policy formulation.

9.6.1.4 Integrated Decision-Support Tools and Skills

Central to delivering sustainable and climate-sensitive coastal cities will be the monitoring of critical climate indicators and the development of approaches for integrated assessment of coastal cities to support decision-making. The necessary cross-disciplinary approaches, including the research to support them, require education programs for early career researchers and practitioners to facilitate future development and the implementation of integrated assessment and decision-making in practice (Nicholls et al., 2015).

9.6.2 Knowledge Gaps

- Significant uncertainties remain in understanding climate change processes, but in particular for upper-end scenarios such as ice sheet collapse.
- Information is lacking on the response and long-term behavior of deltas and other complex, dynamic, coastal environments.
- Understanding of interactions between coastal and urban processes is limited: these include atmospheric flows that influence air pollution and human health and biogeochemical processes that can extend the influence of coastal cities into the atmosphere and thousands of kilometers into the ocean.
- There is a need for more systematic integrated assessment to address a limited understanding of and to provide quantitative evidence-based understanding of tradeoffs and co-benefits.
- The costs of coastal climate management choices are poorly understood, thus hindering robust evaluation of the benefits and costs of coastal management.
- Investment decisions and implementation of successful transitions in coastal city management have both technical and social dimensions, and analysis capable of delivering this is needed to develop adaptation pathways under uncertain futures.

Annex 9.1 Stakeholder Engagement

Coastal cities face particular challenges but are no less diverse than other cities. The international authorship of this chapter was therefore augmented with a stakeholder engagement program that involved three main mechanisms: (1) Chapter authors exploited their own networks and attendance at international workshops and conferences in the United Kingdom, France, the United States, Bangladesh, India, Netherlands, China, and Brazil to engage with a multidisciplinary, global group of stakeholders who contributed a broader and holistic perspective to the challenges of coastal cities; (2) Chapter authors worked closely with local actors and stakeholders (e.g., the NYC-EJA, New York City Mayor's Office, Khulna Mayor's Office, and local communities) in the development of detailed case studies; and (3) More formally, the chapter was reviewed by international experts from academia, industry, and international agencies.

Chapter 9 Urban Areas in Coastal Zones

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