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DEVELOPMENT AND CLIMATE CHANGE

# Economics of **Coastal Zone** Adaptation to Climate Change

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# Economics of **Coastal Zone** Adaptation to Climate Change

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# CONTENTS

**TABLES**

**FIGURES**

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We are indebted the DINAS-COAST consortium who developed the DIVA model that made this work possible. Thanks also go to Gordon Hughes, who provided the socioeconomic scenarios that were used, and to Siobhan Murray, who provided data on the present occurrence and absence of tropical storms in coastal areas. Abiy Kebede assisted with the preparation of the final report.

# EXECUTIVE SUMMARY

This report explores the answer to a difficult question: What are the potential costs for coastal adaptation from 2010 until 2050 in response to human-induced climate change? The work reported here builds on the earlier estimate of the United Nations Framework Convention on Climate Change (Nicholls 2007) of incremental protection costs in 2030. While these have been improved in a number of aspects, the results remain a preliminary first estimate of the possible adaptation needs and they show that significant further analysis of the topic is necessary.

In terms of climate change, sea-level rise is the climate driver that is analyzed; the possibility of enhanced storm impacts due to higher water levels in areas subject to tropical storms and cyclones is also considered as a sensitivity analysis with the high sea-level-rise scenario. The analysis uses the framework of the Dynamic Interactive Vulnerability Assessment (DIVA) model to explore the costs of three main protection responses to climate change:

- Sea and river[1] dike construction and maintenance costs
- Beach nourishment
- Port upgrade.

These adaptation methods are applied using a standard methodology around all the world's coasts using criteria that select optimum or quazi-optimum rule-based adaptation strategies. If we protect following the DIVA approach, the *actual* damages of sea-level rise will be much lower than the *potential* damages of sea-level rise if protection is ignored. The resulting adaptation costs are interpreted in a broad sense based on information on current investment in coastal adaptation and expert knowledge on the level of preparation for sea-level rise and climate change. Selected residual impacts that remain even with adaptation are also reported (e.g., land loss costs, coastal flood costs, and the number of people flooded), stressing that larger investments would be required to avoid all impacts of sea-level rise, if this is even possible or desirable.

Four scenarios of global sea-level rise are considered: a no-rise in sea level and temperature (the reference case of no climate change) and low, middle, and high scenarios embracing a rise to 2100 of between 40 and 126 cm. These scenarios were selected to represent interesting, useful, and plausible scenarios to adopt for the exercise of adaptation planning under uncertainty. They were informed by the Intergovernmental Panel on Climate Change's Fourth Assessment Report (IPCC 2007) and the subsequent debate about the possibility of higher rises in sea level during the twenty-first century, and they should not be interpreted as predictions. Note that they are not specifically linked to temperature rise. The impacts are considered in relation to an Economics of Adaptation to Climate Change socioeconomic scenario that is quite similar to the Special Report on Emission Scenarios A2 scenario. Following best engineering practice for sea and river dikes, sea-level rise is anticipated in terms of additional height for 50 years into the future (i.e., expected extreme sea levels in 2100 determine the dike heights built in 2050). For other adaptation measures, there is no anticipation of future conditions, again reflecting best engineering practice. Ports are treated separately, as

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[1] The impact of sea-level rise on rivers concerns the incremental costs of upgrading river dikes across coastal lowlands where sea-level rise will raise extreme water levels. Additional upgrades may be required if extreme river flows are increased, but this factor is not investigated here.

they are only upgraded at the end of their design lifetime (i.e., estimated here at 2050).

Even without climate change, there are adaptation needs and residual impacts: DIVA provides a minimum estimate of these costs, but some aspects of these costs are not considered. Assuming sea-level rise, global adaptation costs are in the range $26–89 billion a year by the 2040s: the cost depends on the magnitude of sea-level rise. Most of these investments would be sea dike construction, and their maintenance costs would rise with time. Beach nourishment costs are also significant and would also increase with time. Other adaptations, such as river dikes in coastal lowlands and port upgrades, are almost negligible at a global level.

Putting these results in context, it is not clear that all the investments that DIVA suggests are prudent are being made, even under today's conditions: this could be considered an "adaptation deficit" that might usefully be assessed. If there is a large adaptation deficit, then the investment levels estimated here will be insufficient to adapt to climate change and the residual impacts will be much larger than estimated here. Policymakers need to be aware of the adaptation deficit and its implications for climate and development policy. Clearly, a wider range of adaptation options than considered in DIVA are available, and this may lead to successful adaptation strategies of lower cost than estimated here. However, realizing these benefits will require long-term strategic planning and more integration across coastal planning and management on a sub-global scale. Few if any countries have this capacity today and an enhancement of institutional capacity for integrated coastal management would seem a prudent response to climate change (as well as realizing benefits for non-climate issues). While all countries need to develop and enhance such capacity, the need is greater in poorer countries—with small islands, populated deltaic areas, and Africa's coast presenting some of the greatest challenges. In these areas, the need for capacity development of coastal management institutions linked to disaster preparedness is largest, and this is an important issue for development.

These global studies need to be reinforced by national case studies to better understand how adaptation might operate on the ground, including the relationship with wider coastal management and non-climate-change issues.

# 1. CONTEXT

This study estimates the costs of adaptation to climate change in coastal areas and is a background paper for the World Bank Economics of Adaptation to Climate Change (EACC) study. Sea-level rise is one of the issues that brought human-induced climate change to the fore due to the large concentration of settlements and economic activity in low-lying coastal areas. The issue has been extensively assessed since the 1980s (e.g., Barth and Titus 1986; Milliman and others 1989; Warrick and others 1993), with the specter of millions of environmental refugees as a worst-case impact. Adaptation needs and costs were considered from the beginning, drawing on the extensive experience of flood and erosion management, including on subsiding coasts. The global costs of protecting developed coasts against sea-level rise (SLR) were first estimated by the Intergovernmental Panel on Climate Change (IPCC) in 1990, with improvement by Hoozemans and others (1993) (see also Nicholls and Hoozemans 2005). There have been updates of these costs based on several different methodologies, as outlined below. However, other dimensions of climate change in coastal areas have received less quantitative assessment and could raise damage and adaptation costs, most especially more-intense hurricanes and tropical storms, which are investigated here (Nicholls and others 2007a).

## 1.1 WHAT ARE THE POTENTIAL IMPACTS OF CLIMATE CHANGE, INCLUDING EXTREME WEATHER EVENTS, ON THE SECTOR?

Coasts contain high and growing concentrations of people and economic activity (Sachs and others 2001; Small and Nicholls 2003; Nicholls and others 2007a; McGranahan and others 2007). Hence, there is a significant and expanding exposure to coastal hazards associated with climate variability such as storms (as well as non-climate events such as tsunamis). As an example, about 120 million people are on average exposed every year to tropical cyclone hazard (UNDP 2004). At least 300,000 people were killed in Bangladesh in 1970 by a single cyclone. Worldwide, from 1980 to 2000 a total of more than 250,000 deaths have been associated with tropical cyclones, of which 60 percent occurred in Bangladesh. Most recently, in 2008, Cyclone Nagris in Myanmar caused at least 138,000 fatalities. Exposure and asset loss is also significant, especially in the industrial world, and there has been significant growth in losses, driven largely by the increase in exposure (e.g., Pielke and others 2008). The growth of population and especially asset exposure is expected to continue to grow, with the developing world contributing the most change (Nicholls and others 2008a; Hanson and others 2009). Without appropriate adaptation, this will translate into growing losses.

Climate change will exacerbate these hazards and threaten much greater losses in the future, as summarized in Table 1. Rising sea levels due to global warming have received most attention to date, with thermal expansion and the melting/disintegration of the small glaciers and the large ice sheets of Greenland and Antarctica being the underlying cause. Changing water levels are already an issue, and in the twentieth century global mean sea levels rose an estimated 17–19 cm (Bindoff and others 2007; Jevrejeva and others 2008). This was primarily due to thermal expansion and the melting of the small land-based glaciers.

Human-induced global warming is expected to cause a significant acceleration in sea-level rise throughout the twenty-first century due to continued thermal expansion and the melting of land-based ice. There is some debate about the potential magnitude of these changes,

TABLE 1. MAIN CLIMATE DRIVERS FOR COASTAL SYSTEMS, TRENDS DUE TO CLIMATE CHANGE, AND MAIN PHYSICAL AND ECOSYSTEM EFFECTS (*ADAPTED FROM NICHOLLS AND OTHERS 2007A*)

| *Climate driver (trend)* | | *Main physical and ecosystem effects on coastal systems* |
|---|---|---|
| $CO_2$ concentration (↑) | | Increased $CO_2$ fertilization; decreased seawater pH (or "ocean acidification") negatively impacting coral reefs and other pH-sensitive organisms |
| Sea surface temperature (↑, R) | | Increased stratification/changed circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality; poleward species migration; increased algal blooms |
| Sea level (↑, R) | | Inundation, flood and storm damage; erosion; saltwater intrusion; rising water tables/ impeded drainage; wetland loss (and change) |
| Storm | Intensity (↑, R) | Increased extreme water levels and wave heights; increased episodic erosion, storm damage, risk of flooding, and defense failure |
| | Frequency (?, R) | Altered surges and storm waves and hence risk of storm damage and flooding |
| | Track (?, R) | |
| Wave climate (?, R) | | Altered wave conditions, including swell; altered patterns of erosion and accretion; re-orientation of beach orientation |
| Runoff (R) | | Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply |

Key: ↑ = increase; ? = uncertain; R = regional variability

with the possible contribution of Greenland and Antarctica being important: the range produced by the IPCC's Fourth Assessment Report (AR4) (Meehl and others 2007) quantified rises of up to 59 cm,[2] but the report is clear that the upper bound of SLR rise remains uncertain and unquantified due to the uncertainty about the response of the large ice sheets (see IPCC 2007). More recent studies have emphasized a range of rises, with the upper limit exceeding the quantified AR4 range (e.g., Rahmstorf 2007; Grinsted and others 2009; Vermeer and Rahmstorf 2009). Hence, it is clear that at present a rise of 1 m or more through this century cannot be excluded (Lowe and others 2009) and needs to be evaluated in impact and adaptation assessments.

The impacts of sea-level rise are produced by relative (or local) SLR, which includes regional sea-level variation and geological uplift/subsidence (Nicholls in press). Subsidence exacerbates climate change, as observed in many subsiding deltas and coastal cities, while uplift counters sea-level rise to some degree, such as observed in parts of Scandinavia (e.g., Helsinki). In this study, global mean SLR is downscaled using local estimates of uplift/subsidence, as explained later. Human-induced subsidence is not considered, but this will lead to local increased values of relative sea-level rise. The physical impacts of SLR are varied and summarized in Table 2.

The other climate factors shown in Table 1 are all potentially important. Of particular significance are changes in storms. It has been suggested that tropical storms may increase in intensity as the world warms (Meehl and others 2007), and the possibility of more-intense storms in the coastal areas experiencing them is analyzed with sea-level rise.

Collectively, the climate effects shown in Tables 1 and 2 can have a range of negative socioeconomic impacts, as summarized in Table 3. This shows that the impacts of climate change on coasts are quite varied. In this analysis, we consider the sea-level rise and the possible increases in the intensity of tropical storms, as they are some of the largest impacts.

Hence, climate change and sea-level rise will have adverse impacts and costs on coastal areas around the world through the twenty-first century and beyond (Nicholls and others 2007a). The impacts of SLR also depend upon future socioeconomic change (e.g., Nicholls 2004). Regardless of climate change, socioeconomic change will result in profound changes in the coastal zone, such as a growth in population and coastal infrastructure (e.g.,

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[2] 76 cm if scaled-up increased ice sheet discharge is included.

## TABLE 2. MAIN EFFECTS OF RELATIVE SEA-LEVEL RISE

This includes relevant climate and non-climate factors that interact with the physical effects; some factors (e.g., sediment supply) appear twice, as they may be influenced by both climate and non-climate factors (adapted from Nicholls 2002).

| | | *Other relevant factors* | |
|---|---|---|---|
| *Physical effect* | | *Climate* | *Non-climate* |
| Inundation, flood and storm damage | Surge | Wave and storm climate, morphological change, sediment supply | Sediment supply, flood management, morphological change, land claim |
| | Backwater effect (river) | Runoff | Catchment management and land use |
| Wetland loss (and change) | | $CO_2$ fertilization<br>Sediment supply | Sediment supply, migration space, direct destruction |
| (Long-term) erosion | | Sediment supply, wave and storm climate | Sediment supply |
| Saltwater intrusion | Surface waters | Runoff | Catchment management and land use |
| | Groundwater | Rainfall | Land use, aquifer use |
| Rising water tables/ impeded drainage | | Rainfall | Land use, aquifer use |

## TABLE 3. SUMMARY OF CLIMATE-RELATED IMPACTS ON SOCIOECONOMIC SECTORS IN COASTAL ZONES

Most are linked to mean or extreme sea level, as indicated (adapted from Nicholls and others, 2007a).

| | *Climate-related impacts* | | | | | | |
|---|---|---|---|---|---|---|---|
| *Coastal socioeconomic sector* | *Temperature rise (air and seawater)* | *Extreme events (storms, sea level, waves)* | *Floods (sea level, runoff)* | *Rising water tables (sea level)* | *Erosion (sea level, storms, waves)* | *Saltwater intrusion (sea level, runoff)* | *Biological effects (all climate drivers)* |
| Freshwater resources | X | X | X | X | — | X | x |
| Agriculture and forestry | X | X | X | X | — | X | x |
| Fisheries and aquaculture | X | X | x | — | x | X | X |
| Health | X | X | X | x | — | X | X |
| Recreation and tourism | X | X | x | — | X | — | X |
| Biodiversity | X | X | X | X | X | X | X |
| Settlements/ infrastructure | X | X | X | X | X | X | — |

Key: X = strong impacts; x = weak impacts; — = negligible impacts or not established

Nicholls and others 2008b). These baseline changes due to non-climate factors need to be considered in addition to the effects of climate change. Investment in adaptation allows these damage costs to be substantially reduced, and all the available analyses suggest that protection is a rational response on populated coasts (although other adaptation strategies might be considered).

This document explains the methods that are being used within the World Bank study to estimate potential protection costs from 2010 to 2050. It explores the costs of protecting the world's coast against sea-level rise using the Dynamic Interactive Vulnerability Assessment (DIVA) model, assuming dike construction and upgrade and beach nourishment where this is optimal or quazi-optimal. Residual impacts after protection are also reported. In the analysis, DIVA has been extended to also consider the costs of port upgrade and the maintenance and operational costs for dikes. In the following treatment, the main focus is the impacts and responses to sea-level rise, with some consideration of more-intense tropical storms in those areas already so affected.

## 1.2 WHO (ACROSS AND WITHIN COUNTRIES) IS LIKELY TO BE MOST AFFECTED?

Both direct and indirect effects are possible due to climate change. Here the direct effects are emphasized.

### 1.2.1 Geographically

In general, all people in low-lying coastal areas are threatened to varying degrees. A range of analyses have consistently found that deltaic areas and small islands are the most threatened coastal settings (e.g., Nicholls and others 2007a). Deltas are by definition at an elevation related to present sea level; many of them are densely populated and are subsiding due to both natural and human causes (Ericson and others 2006; Syvitski and others 2009). Small islands are also threatened (Mimura and others 2007). Atolls, like deltas, are low-lying areas threatened by submergence, with the Maldives being an excellent example of a nation of atolls. However, all islands are threatened, as economic activity is concentrated around the coast and the capacity to respond is nearly always much lower than in continental countries. Lastly, poor regions are problematic as they have a low capacity to adapt.

Geographically, regions with large densely populated deltas in South, Southeast, and East Asia contain the largest concentrations of people threatened by sea-level rise. All small island regions are threatened, including the Caribbean and the Indian and Pacific Oceans. While the absolute impacts in small islands are quite small at a global scale, in relative terms the impacts are highest (Nicholls 2004; Nicholls and Tol 2006). Lastly, Africa is threatened due to its relative poverty, rapid demographic growth, and limited capacity to respond.

### 1.2.2 By income or vulnerability class

The issue of the distribution of the impacts of sea-level rise has been less considered. Anthoff and others (2006) applied equity weighting to the damages of SLR. Taking these distributional issues into account increased the damage estimates by a factor of three, reflecting the fact that the costs of sea-level rise fall disproportionately on poorer developing countries. This is consistent with the fact that Africa is consistently identified as being highly vulnerable to sea-level rise (and other aspects of climate change).

## 1.3 WHAT EXPERIENCE IS THERE WITH ADAPTATION IN THE SECTOR?

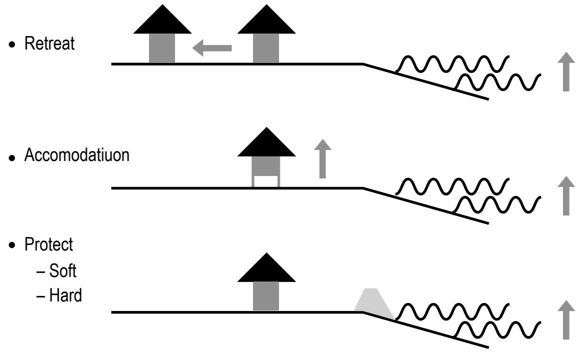
Coastal areas have a long and established tradition of adaptation. While there has often been a focus on protection, the available adaptation measures can be placed in a wider context as one of three generic options (IPCC 1990; Bijlsma and others 1996; Klein and others 2001):

- **(Planned) Retreat** – The impacts of sea-level rise are allowed to occur, and human impacts are minimized by pulling back from the coast via land use planning, development control, set-back zones, etc.
- **Accommodation** – The impacts of sea-level rise are allowed to occur and human impacts are minimized by adjusting human use of the coastal zone to the hazard via increasing flood resilience (e.g., raising homes on pilings), early warning and evacuation systems, risk-based hazard insurance, etc.
- **Protection** – The impacts of sea-level rise are controlled by soft or hard engineering (e.g., nourished beaches and dunes or seawalls), reducing human impacts in the zone that would be affected without protection. However, a residual risk always remains, and complete protection cannot be achieved. Managing residual risk is a key element of a protection strategy that has often been overlooked in the past.

The three approaches are illustrated in Figure 1.

Throughout human history, improving technology has increased the range of adaptation options in the face of coastal hazards, and there has been a move from retreat and accommodation approaches to hard protection and active seaward advance via land claim. This is illustrated

## FIGURE 1. POTENTIAL RESPONSES TO COASTAL HAZARDS



*Source*: van Koningsveld and others, 2008.

by the changing approaches to managing coastal flooding and erosion in the Netherlands (van Koningsveld and others 2008). More recently, there has been a move from hard to softer protection in the Netherlands, based on large-scale beach nourishment with sea-dredged sand—now amounting to 12 million $m^3$/yr. There are also concerns about making adaptation multifunctional such that environmental impacts are minimized while ensuring human safety: this suggests, for example, moves from fixed to mobile surge barriers to allow water and biotic exchanges. Looking to the future, the Deltacommissie (2008) has considered the national response of the Netherlands to sea-level rise over the twenty-first century. Hence, the Netherlands illustrates how thinking about adaptation is rapidly evolving. Looking more widely, there is an important debate concerning the appropriate mixture of hard and soft protection, accommodation, and retreat.

In terms of costing, most experience is available concerning traditional hard engineering approaches and protection. There is much less understanding of retreat and accommodation costs, reflecting the much more limited experience of these measures. Most of the available cost estimates are bottom-up ones based on a long history of coastal management and engineering experience. This mainly assumes protection via dikes (for flood management) and nourishment (to preserve beaches). The costs of these measures were documented globally using a series of country cost factors by IPCC (1990) and Hoozemans and others (1993), based on the global experience of Delft Hydraulics (now Deltares). Hence, the cost estimates are grounded in coastal engineering experience and are reasonably robust.

The United Nations Framework Convention on Climate Change (UNFCCC) assessment (Nicholls 2007) used the DIVA database and focused on dike construction and upgrade and on beach nourishment. The dike costs are derived from Hoozemans and others (1993), while nourishment costs are derived from the recent experience of Deltares, among others, in beach nourishment projects around world. Residual damages are also estimated in terms of land values, depth-damage curves, and the costs of relocating people. The computations are conducted on 12,148 coastal segments (average length of about 70 km) that collectively make up the world's coast, except for Antarctica (McFadden and others 2007; Vafeidis and others 2008). The DIVA database is based on extensive experience and a realistic description of the adaptation measures, which are informed by empirical experience. It is much more detailed than any earlier assessment tool in terms of the impacts and adaptation responses considered as well as the spatial resolution of the computations: the nearest assessment tool is the FUND model, which has a national resolution and considers both impacts and protection costs (e.g., Nicholls and Tol 2006).

### 1.3.1 Autonomous adaptation

Autonomous adaptation describes the spontaneous adjustments that occur in response to climate (or other) change without any active policy intervention. Hence autonomous adaptation has negligible cost. There is some autonomous adaptation in response to climate change in coastal areas, such as increased accretion of salt marshes or market adjustment to the price of land or properties after a coastal disaster. However, human impacts in terms of flooding and erosion are little reduced by autonomous adaptation in coastal areas. Hence, it has been concluded for the last decade that significant planned adaptation is essential to manage the growing risks from sea-level rise (e.g., Klein and Nicholls 1999).

### 1.3.2 Public sector investment

There is considerable experience of adaptation in coastal zones to a range of drivers, of which climate change is only one. Unlike adaptation in many other sectors, coastal adaptation measures usually represent a collective government-led activity, reflecting that the coast is a shared resource (Klein and others 2000). Hence while some adaptation will need to be funded by private investment (e.g., port and harbor upgrade), much of the cost falls on government finances. However, individual adaptation measures are also apparent. Insurance is a mechanism that helps private individuals gain resources to recover from disasters such as coastal flooding and is potentially an important response mechanism (Clarke 1998; Grossi and Muir-Wood 2006). The availability of appropriate insurance varies greatly between coastal countries; it is unavailable in many developing countries and in mainland Europe (as the government is the insurer of last resort), while in the United Kingdom and the United States it is the norm.

While there is significant interest in elaborating coastal adaptation measures and understanding their costs (e.g., UNFCCC 1999; Klein and others 2001; Bosello and others 2007), hard numbers on investment in coastal adaptation are difficult to identify as there is never a single "Ministry for Coastal Adaptation" with published accounts in any country. The reality is that coastal adaptation costs fall between government and the private sector, and different ministries are responsible for different aspects of the process. For instance, in England and Wales, the major investment in coastal adaptation is in flood and erosion management, but the budget covers all flood and erosion management—that is, management of all flood mechanisms, including inland flooding. Integrated coastal management in England and Wales is covered by a separated budget, and this investment is quite small compared with that in flood and erosion management.

Nicholls (2007) identified the following national/regional estimates of current investment in coastal adaptation (reflecting many drivers, including climate change):

- *European Union.* The total annual cost of coastal adaptation for erosion and flooding across the European Union was an estimated 3,200 million euro's (in 2001).
- *England.* The flood and coastal management budget for coasts is roughly £250 million per annum and growing. New estimates show expenditure on all flood defense (rivers and coasts) rising from £575 million per annum in 2011 to more than £1 billion in 2035, with the increase being primarily due to climate change (Environment Agency 2009).
- *Japan.* 120 to 150 billion yen per year from 2003 to 2006.
- *Netherlands.* $600–1,200 million (in 2006 prices), or 0.1–0.2 percent of gross domestic product (GDP). This is expected to double or triple from 2020 to 2050 as the recent recommendations of the Deltacommissie (2008) are implemented. This represents a combination of climate change adaptation, looking 100– 200 years into the future, and increasing safety to much higher levels (risk of failure will be $\leq$ 1 in 100,000 in any year).

For individual projects, Nicholls (2007) identified the following costs:

- *The Maldives.* "Safe Island" Projects for tsunamis—the cost of reclamation and coastal protection including harbor works for the Vilifushi project was about $23 million.
- *Venice, Italy.* The MoSE Project to manage flooding of Venice cost roughly 4,000 million euro's. The project is mainly addressed to solve current flood problems.
- *St Petersburg, Russia.* The Flood Protection Barrier was started in the 1980s, and was 65 percent completed, when construction was halted until about 2002. Then completion was funded by the European Bank for Reconstruction and Development, costing about 440 million euros. Again, the Barrier is mainly designed to solve current flood problems.
- *London, UK.* The Thames Estuary 2100 Project is investing £15 million on appraising the flood management options for London for the twenty-first century and beyond, including building a completely new downstream barrier. Unlike the previous two cases, this is mainly a response to climate change. While nothing has been decided, costs of £4–6 billion for this century have been mentioned for upgrade, while £10–20 billion has been mentioned for a new downstream barrier, which would be the response to a large rise in sea level (several meters).

In conclusion, the present investment in coastal engineering is significant, and any investment in adapting to climate change will be building on a portfolio of existing activity in many parts of the world. In many parts of the developing world, however, the major investment to date in coastal engineering are port and harbor assets, and the types of investments considered in the analyses in this report will represent a significant departure from established practice.

### 1.3.3 "Soft" adaptation—policies and regulations

As well as the hard infrastructure considered here, and this includes soft engineering such as beach nourishment, there is much "soft" infrastructure that constitutes an important component of the adaptive capacity that is essential for coastal adaptation to take place (Smit and others 2001; Adger and others 2007). Institutions are fundamental to manage the coast, including addressing the challenges raised by climate change and other activities such as warning services. For instance, storm tide warning services are an important component to an integrated management response to potential flood events in low-lying coastal areas, as demonstrated in areas as diverse as the United States, the southern North Sea, and Bangladesh.

There is also the issue of the context in which adaptation occurs. Traditionally, coastal management has been sectoral in nature, and the focus of management has been a single goal rather than addressing multiple issues. Integrated coastal management is an attempt to address this problem that is receiving widespread support in coastal areas both academically (e.g., Cicin-Sain and Knecht 1998; Brown and others 2002; Kay and Alder 2005; Williams and Micallef 2009) and in policy terms (e.g., European Union 2010). However, the application and success of this approach remains uncertain. In general, all of these "soft" measures are low cost in terms of application compared with hard protection measures, although there are many other barriers to application. However, the difficulty in developing these capacities where they do not exist should not be underestimated, and this is an important issue for the wider development agenda and sustainable development in general.

### 1.3.4 Reactive (and proactive) adaptation

Reactive adaptation is adaptation that occurs in response to actual (or observed) change and impacts, as opposed to proactive adaptation that takes place in anticipation of expected change (such as projections of rising sea levels or model outputs of future impacts). We mainly observe reactive adaptation in coastal zones at present (e.g., Tol and others 2008; Moser and Tribbia 2008), with the history of New Orleans illustrating this well. Each major flood there triggered major investment in better defenses, including after Hurricane Betsy in 1965 and Hurricane Katrina in 2005. Roughly $10 billion is being spent to upgrade the defenses post-Katrina, but this will only achieve the design standards thought to exist before that storm. Substantial additional investment would be required to achieve Category 5 hurricane projection. Anecdotally, numbers as high as $50 billion have been suggested.

The dynamic nature of the risks due to changing climate means that a more proactive approach to assessment and adaptation planning is essential for coastal areas; otherwise these risks will reach unacceptable levels (Nicholls and others 2007a). Even without climate change, growing populations and economic wealth in coastal areas suggests that substantial investment in coastal adaptation would be required throughout the twenty-first century (e.g., Nicholls and others 2008a), again demanding proactive assessment and responses. In a few limited cases, present adaptation investment includes anticipating climate change (e.g., in the United Kingdom and the Netherlands). Some of the limited cases of anticipatory adaptation have been highlighted in Section 1.3.2.

## 1.4 WHAT IS THE NATURE AND EXTENT OF ADAPTATION/DEVELOPMENT DEFICIT IN THIS SECTOR?

Analysis of climate change often implicitly assumes that the current state is optimal, while the current state is often far from optimal, as shown by Hurricane Katrina in 2005 and Cyclone Nagris in 2008. This gap has been termed the adaptation deficit (Burton 2004; Parry and others 2009). In coastal areas, the adaptation deficit is an important issue due in part to a reactive approach to adaptation, a general under-recognition of the risks in many coastal areas, and the rapid expansion of the population and economy in many areas, which means that historic hazard events are little guide to the level of contemporary (or future) exposure or risks from hazard events (e.g., Nicholls and others 2008a). As just noted, New Orleans is spending $10 billion post-Katrina, while the actual investment required to make New

Orleans' defenses sufficient to survive a Category 5 hurricane is on the order of $50 billion. Defense standards also give an indication of the adaptation deficit. For instance, New York City has much lower standards of protection by one to two orders of magnitude than European cities with a similar or lower exposure to coastal flooding (Nicholls and others 2008a). It can be argued that this represents an adaptation deficit as was seen in New Orleans, although others may interpret it as differing attitudes to risk.

Apart from these industrial world examples, the adaptation deficit in coastal areas is poorly quantified and our understanding of it is essentially qualitative. However, it is a significant issue, as many developing countries have few organized defenses or flood management systems comparable to those in the developed world. This is an important deficiency that future assessments need to address.

## 1.5 HOW WILL EMERGING CHANGES IN DEVELOPMENT AND DEMOGRAPHICS INFLUENCE ADAPTATION?

Coastal populations and economies are presently growing rapidly with little regard to the growing risks of coastal locations. For instance, population is increasing at rates that often double global trends. As such, the exposure of coastal areas is growing rapidly. This is illustrated in the coastal scenarios of Nicholls (2004), Nicholls and Lowe (2004), and Nicholls and others (2007b), where population growth of up to fourfold may occur in the coastal zone. If this development continues in a business-as-usual manner, this growth will strongly reinforce the need for protection, as demonstrated by Anthoff and others (2010). The use of retreat and accommodation options could reduce the need for protection, but these policies have a long lead time, and they require proactive implementation to be fully effective.

# 2. LITERATURE REVIEW

## 2.1 PREVIOUS STUDIES RELEVANT TO THE SECTOR

### 2.1.1 Nature and extent of damages

The focus in the literature is overwhelmingly on sea-level rise impacts and adaptation costs as summarized in a series of IPCC assessments (Bijlsma and others 1996; McLean and others 2001; Nicholls and others 2007a). Actual impacts in coastal zones are a product of relative SLR: this is the sum of climate-induced changes and non-climate effects causing land uplift/subsidence due to natural and human processes (Nicholls in press). Uplift/ subsidence processes include tectonics and glacial-isostatic adjustment as well as human-induced processes, such as subsidence due to fluid withdrawal, and drainage of coastal soils susceptible to subsidence and oxidation. Hence, relative sea-level rise varies from place to place. It is generally higher than the global mean in areas that are subsiding, which includes many populated deltas (e.g., the Mississippi delta) (Ericson and others 2006; Syvitski and others 2009), while many coastal cities have also subsided.

The major impacts of sea-level rise have already been summarized in Table 2. No published impact analysis considers all of these impacts (Nicholls in press). Historically, analyses have either focused on flooding or land loss and have not considered both issues together, while salinization has received the least investigation. Synthesis across the available literature suggests that "inundation, flood and storm damage" has the largest impact potential. All coastal lowlands are threatened to varying degrees, and hence hundreds of millions of people are threatened around the world today. Further, these areas are the nexus for population and economic growth and a strong urbanizing trend in many parts of the world (e.g., Small and Nicholls 2003; McGranahan and others 2007); see Section 1.5. The threat is particularly strong in populated deltas and on small islands. The abandonment of coastal islands due to sea-level rise appears a quite plausible outcome unless appropriate adaptation can be mobilized. Hence, there is a strong consensus that the potential impacts of SLR are large.

Until recently, no study has addressed the impacts of changing storms, in part due to the lack of credible scenarios. Nicholls and others(2008a) did consider more-intense tropical and extra-tropical storms (following the regions identified by Meehl and others 2007) as one factor in the potential increase in exposure of coastal cities to coastal flooding: the effect was significant and comparable in magnitude to changes due to climate-induced sea-level rise, and human-induced subsidence, but much smaller than socioeconomic changes. Narita and others (2009) examined historical damages due to tropical storms and concluded that future changes are likely to be small. Dasgupta and others (2009a) also investigated the impacts of more-severe tropical storms and sea-level rise and found that severe impacts are likely to be limited to a relatively small number of countries and a cluster of large cities at the low end of the international income distribution. Hence, sea-level rise appears a bigger threat globally than more-intense storms, although in certain regions the impacts may be more comparable.

### 2.1.2 Nature of adaptation and its cost, private and public

Adaptation has been a feature of assessments of sea-level rise since the 1980s (e.g., Barth and Titus 1986; IPCC 1990). Initially, this largely built on the experience of coastal engineering, but as the need for adaptation and interest in it increased, it has broadened to the protect, accommodate, and retreat options defined in Figure 1. However, most policy analyses consider a choice of protect versus retreat to examine the economics of SLR, and accommodation has not been considered as extensively as yet. Most analyses that have considered protection at the global scale have considered one of two distinct approaches:

(1) Arbitrary protection of all "developed areas,"[3] as in IPCC (1990), the Global Vulnerability Assessment (Hoozemans and others 1993), and the Fast Track Analyses (Nicholls 2004)

(2) An optimization approach in which "economically worthwhile areas" are defended, as in Fankhauser (1995), Tol (2007), Sugiyama and others (2008), and Anthoff and others (2010); this is normally based on comparing avoided damage and protection costs.

In both cases, the costs of the required protection and the residual impacts in areas that are not protected can be determined. This is not always done in economic terms.

A fundamental result is that protection based on benefit-cost approaches greatly reduces the impacts of sea-level rise, at least for people and assets, and the residual damage is as much as two orders of magnitude lower than the potential impacts (e.g., Nicholls and Tol 2006; Nicholls and others 2007b). This reflects that most coasts remain undeveloped, and hence coastal infrastructure and people are concentrated in smaller areas that are more easily protected. Hence, a greater rise in sea level translates into greater protection costs, and while residual impacts also increase, they remain a small fraction of the potential impacts.

It should be noted that the success or failure of protection is highly controversial, and the different views concerning this aspect of adaptation explain much of the differences between different estimates of actual (as opposed to potential) impacts of sea-level rise (Nicholls and Tol 2006; Nicholls in press). Pessimists expect protection to either be unavailable or to fail, and hence potential impacts translate into actual impacts and the world faces tens of millions of environmental refugees due to sea-level rise alone (e.g., Myers 2001; Dasgupta and others 2009b). Optimists expect widespread protection for sea-level rise and actual impacts that are much less than potential impacts. Both views tend to be caricatures of real responses, but they do stress that the inevitability of worst-case impacts should not be accepted, and they point to the importance of studies like the EACC Project to better understand adaptation and its costs. One important message is the importance of continued economic growth to support the investment in adaptation. Protection is much harder to justify if a no-economic-growth scenario is considered (Anthoff and others 2010). This shows that coastal adaptation is strongly linked to wider development goals and issues, and it has been argued that assistance for adaptation is critical in the developing world in the coming decades, while they develop the capacity to adapt (Patt and others 2010).

The UNFCCC conducted the most recent assessment of the adaptation costs for sea-level rise (Nicholls 2007; Parry and others 2009). This was based on assumptions of protection using dike construction and beach nourishment. The investment costs were estimated for 2030, assuming a range of AR4 sea-level rise scenarios from Meehl and others (2007). As the rate of sea-level rise is similar between scenarios, the range of uncertainty for adaptation costs for reactive adaptation measures (beach nourishment) is small, but it is larger for dikes that anticipated future sea level. The UNFCCC estimated additional costs in 2030 of $4–11 billion a year, assuming a 50-year planning horizon and no adaptation deficient. However, the costs may be underestimates if we consider responses to high-end SLR and other climate changes such as more-intense storms. The additional residual damage attributed to sea-level rise in terms of sea flood and land loss is estimated at $1–2 billion a year. Environmental damages such as loss of coastal wetlands would be in addition to this, and the costs and methods of adaptation are less certain.

### 2.1.3 Strategic conclusion (timing, sequencing, policy, etc.).

The results of these studies suggest that impacts could be disastrous for coastal areas unless there is significant adaptation. The available literature also demonstrates a significant debate about adaptation and its likely success. These differing views can be seen as caricatures,

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[3] Usually based on an arbitrary definition, such as all areas with a population exceeding 10 persons/km$^2$.

but it appears that protection is a rational response on most developed coasts around the world, especially under scenarios of greater economic growth. This is counter to many people's intuition about the response to sea-level rise, which is often seen as a widespread retreat. However, this view fails to appreciate the development of coastal engineering technology and the relatively low cost of these responses compared with what is threatened. To better understand the issue of adaptation, research such as the EACC Project is fundamental.

## 2.2 HOW THIS STUDY COMPLEMENTS EXISTING WORK

This study builds on all the earlier assessments, including the recent UNFCCC assessment of adaptation costs in 2030 (Nicholls 2007). A number of significant improvements have been made compared with previous studies:

- A time series of costs from 2010 to 2050, rather than a single snapshot
- Consideration of a wider range of sea-level rise scenarios, reflecting the post-AR4 debate on this issues
- Inclusion of more-intense tropical cyclones as a sensitivity analysis
- Improved estimates of protection costs, including maintenance costs for dikes and port upgrade
- Consideration of the consequences of avoiding future coastal population growth, reflecting stringent land use planning
- More explicit consideration of the adaptation deficit.

# 3. METHODOLOGY

Following existing practice, the EACC study is focused on preserving the human uses. The methodology is based on the DIVA model, including some new extensions. DIVA is an integrated model that estimates impacts for given climate and socioeconomic scenarios and for stated adaptation options (Figure 2). Given that it can provide adaptation costs in coastal areas, it is well suited to the EACC Project. First the socioeconomic and climate change scenarios are considered, followed by the different impacts. The adaptation option choices are then considered, followed by their implementation in the EACC project.

The DIVA model is an integrated model of coastal systems that assesses biophysical and socioeconomic impacts of sea-level rise and socioeconomic development. One important innovation introduced by DIVA is the explicit incorporation of a range of adaptation options; impacts depend not only on the selected climatic and socioeconomic scenarios but also on the selected adaptation strategy. DIVA is driven by climatic and socioeconomic scenarios. The climatic scenarios consist of the variables temperature change and sea-level rise. The socioeconomic scenarios consist of the variables land-use class, coastal population growth, and GDP growth.

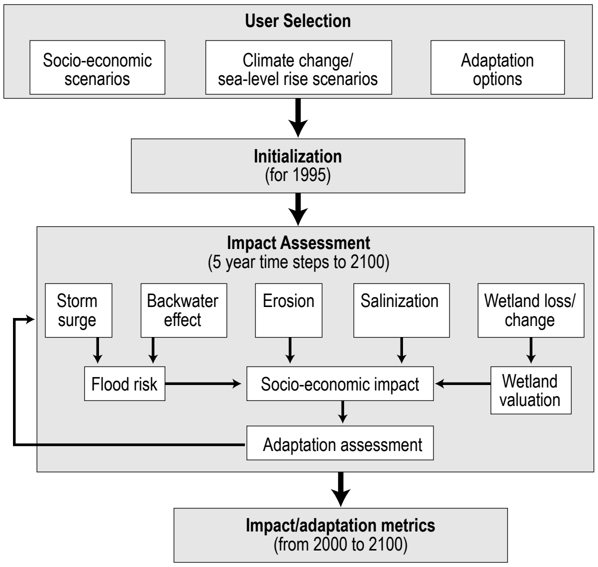
## 3.1 HOW WE REPRESENT THE FUTURE—2010 TO 2050

### 3.1.1 The baseline

In the baseline, climate is constant (i.e., maintained at 1995 levels), but non-climate changes do occur, most especially population and GDP growth. Most existing studies hold developing countries at their current level of development when estimating adaptation costs for both the near and medium term. Over the medium term these countries will, however, become more developed and wealthy and this, in turn, will change the impact of climate change on their economies and the type and extent of adaptation that is required, as well as their capacity to adapt. The EACC study accounts for the impact of development on estimates of adaptation costs by establishing its own development baselines sector by sector (see Appendix 1). These baseline scenarios establish a population and GDP growth path

FIGURE 2. SCHEMATIC OF MODULE LINKAGES IN THE DIVA MODEL

Adaptation decisions are implemented at the next time step (after five years).



*Source*: Authors data utilizing the DIVA model.

in the absence of climate change that determines sector-level performance indicators such as the stock of infrastructure assets, level of nutrition, water supply availability, etc. Climate change impacts and costs of adaptation are then examined relative to this evolving baseline, with no climate change.

Baselines, in turn, are established across sectors using a consistent set of future population and GDP projections. The population trajectory has been developed to be consistent with United Nations Population Division middle fertility population projections for 2006 (UNPD 2006). In order to ensure consistency with emissions projections, the GDP trajectory is based on the average of the GDP growth projections from five sources that provide growth estimates at a reasonable regionally disaggregated level: three main Integrated Assessment Models of global emissions growth—FUND (Tol 2008), PAGE2002 (Hope 2006), and RICE99 (Nordhaus 2001)—and the growth projections used in the energy demand forecasts by the International Energy Agency and the Energy Information Administration at the U.S. Department of Energy[4].

The resulting global average real GDP per capita growth rate is 2.1 percent per year, which is similar to global growth rates assumed in the Special Report on Emission Scenarios (SRES) A2 emissions scenario used in the IPCC AR4 (Nakicenovic and Swart 2000). The study chose not to use the regionally downscaled GDP projections from the different IPCC scenarios (available from the Center for International Earth Science Information Network, Columbia University) because these are based on data that do not include recent changes, such as the continued rapid growth of China.

### 3.1.2 Climate change scenarios

The main climate factor considered here is climate-induced sea-level rise, with some consideration of changes in tropical storms. The SLR scenarios published by the IPCC AR4 Report (Meehl and others 2007) have been widely contested since they were published: many papers have indicated the potential for larger rises than included in the AR4 range (e.g., Rahmstorf 2007; Vermeer and Rahmstorf 2009), and this has been included in some national SLR scenarios (e.g., Lowe and others 2009). These insights are acknowledged here, and a high scenario to describe sea-level rise is included for this purpose.

Several approaches were considered to analyze the impacts of global SLR, and initially it was proposed that we would construct response surfaces across a wide range of SLR scenarios. However, this led to difficulties when we considered different time frames for adaptation: as explained later, beach nourishment and port upgrade costs are based on the actual sea-level rise (to 2050), while dike upgrade anticipates sea-level rise 50 years into the future (to 2100) (i.e., proactive adaptation). Therefore we need self-consistent scenarios that evolve over time to 2050 (for socioeconomic change) and to 2100 (for proactive adaptation to climate change). Hence, after a debate within the wider project, the three SLR scenarios proposed by Neumann (2009) were adopted, in addition to a no-SLR scenario as a reference case. These scenarios assume that sea-level rise is effectively independent of temperature, precipitation, and other climate parameters of interest to the EACC study over the timescale of interest, in the sense that the scenarios not derived directly from specific Global Circulation Model runs.[5] Because the main temperature scenarios for the EACC Project are roughly consistent with the IPCC SRES A2 scenario, the SLR projections considered here are also consistent with the A2 emissions trajectory.

The four SLR scenarios are defined as follows:

- No-rise scenario – no climate change, so sea-level rise only results from vertical land movements; only the vertical movements considered in the DIVA database are considered (see Vafeidis and others 2008) and the potential for human-induced subsidence is not considered
- Low scenario – based on the midpoint of the IPCC AR4 A2 range in 2090–99 (Meehl and others 2007); it is consistent with a MAGICC TAR A2 mid-melt 3°C sensitivity run
- Mid scenario – based on the Rahmstorf (2007) A2 trajectory)[6]

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[4] http://www.eia.doe.gov/

[5] Of course, higher future temperature outcomes are correlated with higher future sea-level rise outcomes. Temperature is the main driver of both thermal expansion of the oceans and melting of land-based ice, which in turn drive sea-level projections. However, there is a decoupling over decades due to the uncertainty of the response of the two major continental ice sheets: Greenland and West Antarctica.

[6] This is similar to the DEFRA (2006) SLR scenario used for planning and design of flood defenses in Great Britain.

- High scenario – based on the "maximum" trajectory of Rahmstorf (2007).

It is important to note that these are scenarios (or plausible futures), and they do not represent our judgment of the most likely global SLR outcomes. Rather they represent interesting, useful, and plausible scenarios to adopt for the exercise of adaptation planning in coastal zones under uncertainty.

The SLR scenarios give a climate-induced global-mean rise in sea level of 16–38 cm by 2050 and 40–126 cm by 2100, respectively (Table 4). The scenarios as used in the impacts and adaptation analysis are defined in Table 5: after 2050, sea-level rise only influences dike costs, as from 2010 to 2050 all the dikes are proactively upgraded to anticipate sea levels in 2100. The "no-rise" scenario allows us to explore the evolving baseline of no climate change combined with socioeconomic change.

## TABLE 4. CLIMATE-INDUCED GLOBAL MEAN SLR SCENARIOS USED IN EACC STUDY

*In cm above 1990 levels*

| | *Sea-level rise (SLR) scenario* | | | |
|---|---|---|---|---|
| *Year* | *No rise* | *Low* | *Medium* | *High* |
| 2010 | 0.0 | 4.0 | 6.6 | 7.1 |
| 2020 | 0.0 | 6.5 | 10.7 | 12.3 |
| 2030 | 0.0 | 9.2 | 15.5 | 18.9 |
| 2040 | 0.0 | 12.2 | 21.4 | 27.1 |
| 2050 | 0.0 | 15.6 | 28.5 | 37.8 |
| 2060 | 0.0 | 19.4 | 37.0 | 50.9 |
| 2070 | 0.0 | 23.4 | 47.1 | 66.4 |
| 2080 | 0.0 | 28.1 | 58.8 | 84.4 |
| 2090 | 0.0 | 33.8 | 72.2 | 104.4 |
| 2100 | 0.0 | 40.2 | 87.2 | 126.3 |

Air temperature rise is also required for the Hamburg Tourism Module (HTM) (Hamilton and others 2005a, 2005b), which is used with DIVA to simulate tourist demand for beaches: an A2 temperature scenario was used.

Intensification of tropical cyclones (or storms) in areas that currently experience them is of widespread concern (Meehl and others 2007; Nicholls and others 2007a). As there is no scientific consensus as to whether storms will or will not intensify, we consider an arbitrary 10 percent increase in extreme water levels for the 100-year event in addition to the high SLR scenario in these areas by 2100[7] (see Section 3.2 for more details). This again influences dike costs and residual flood damage (assuming a 50-year anticipation of future conditions). This aspect of the analysis constitutes a sensitivity analysis. Last, a scenario of no population growth in the coastal zone is considered. While rather an artificial scenario, it illustrates the implications of a land use policy where all

## TABLE 5. SEA-LEVEL RISE AND IMPACT/ADAPTATION ASSESSMENT DECISIONS

Based on the SLR scenarios (in cm above 1990 levels) being used in the EACC study for flooding and erosion impacts and beach erosion/nourishment and port upgrade (no proactive adaptation) and for dike costs (proactive adaptation over 50 years). (See Table 4.)

| | *Impact/adaptation assessment* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | *Flooding, beach erosion, nourishment, port upgrade costs* | | | | *Sea and river dike costs* | | | |
| *Year* | *No rise* | *Low* | *Medium* | *High* | *No rise* | *Low* | *Medium* | *High* |
| 2010 | 0.0 | 4.0 | 6.6 | 7.1 | 0.0 | 4.0 | 6.6 | 7.1 |
| 2020 | 0.0 | 6.5 | 10.7 | 12.3 | 0.0 | 14.9 | 29.8 | 40.8 |
| 2030 | 0.0 | 9.2 | 15.5 | 18.9 | 0.0 | 24.7 | 51.4 | 72.6 |
| 2040 | 0.0 | 12.2 | 21.4 | 27.1 | 0.0 | 33.2 | 70.8 | 101.5 |
| 2050 | 0.0 | 15.6 | 28.5 | 37.8 | 0.0 | 40.2 | 87.2 | 126.3 |

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[7] Note that other impacts of more-intense storms, especially increased wind damage, are not considered.

development is prohibited in areas vulnerable to erosion and inundation/flooding and steered instead to less vulnerable areas. Again, this should be considered a sensitivity analysis. The scenario combinations that are being considered can be summarized in Table 6.

## 3.2 HOW CLIMATE CHANGE IMPACTS ARE CALCULATED

The impacts in terms of both physical change (and adaptation) are calculated using the DIVA model. DIVA first downscales to relative sea-level rise by combining the SLR scenarios due to global warming with the vertical land movement. The latter is a combination of glacial-isostatic adjustment according to the geo-physical model of Peltier (2000a, 2000b) and an assumed uniform natural subsidence in deltas of 2 mm/yr. Human-induced subsidence (due to ground fluid abstraction or drainage) is not considered due to the lack of consistent data or scenarios. Based on the relative sea-level rise (and the influence of the selected adaptation option), several types of bio-physical impacts are assessed, including long-term coastal erosion[8] and damage from inundation, floods, and storms.[9] The following impacts are evaluated in the EACC study (with units in parenthesis):

- Land loss due to erosion ($km^2$/yr)
- Land loss due to submergence ($km^2$/yr)
- Forced migration (thousands/year)
- People actually flooded (thousands/year)
- Land loss costs (million dollars/year)
- Forced migration costs (million dollars/year)
- Sea-flood costs (million dollars/year)
- River flood costs (million dollars/year)

For long-term coastal erosion due to sea-level rise, the impacts of both direct and indirect effects are assessed. The direct effect of sea-level rise on coastal erosion is estimated using the Bruun Rule (e.g., Zhang and others 2004; Nicholls in press). Sea-level rise also affects coastal erosion indirectly as tidal basins become sediment sinks under rising sea level, trapping sediments from the nearby open coast into tidal basins. This indirect erosion is calculated using a simplified version of the Aggregated Scale Morphological Interaction between a Tidal basin and the Adjacent coast model (Stive and others 1998; Van Goor and others 2003). About 200 tidal basins around the world are considered in DIVA.

## TABLE 6. COASTAL SCENARIO COMBINATIONS USED IN EACC STUDY

| | *Sea-level rise scenarios* | | | | |
|---|---|---|---|---|---|
| | *No rise* | *Low* | *Medium* | *High* | *High* |
| *EACC socioeconomic scenarios* | *Tropical Cyclones Constant* | | | | *Tropical cyclone Intensification* |
| Population and GDP growth | X | X | X | X | X |
| GDP only growth (i.e., constant coastal population) | X | — | — | X | X |

DIVA includes beach/shore nourishment—i.e., the replacement of eroded sand—as an adaptation option for coastal erosion. In beach nourishment, the sand is placed directly on the intertidal beach, while in shore nourishment the sand is placed below low tide, where it will progressively feed onshore due to wave action, following current Dutch practice (van Koningsveld and others 2008). Shore nourishment is substantially cheaper than beach nourishment, but the benefits are not felt immediately. The way these options are applied is discussed in more detail in Section 3.3. For a more detailed account of the erosion impact and adaptation methods see Nicholls and others (in prep).

Inundation and flooding of the coastal zone caused by mean SLR and associated storm surges is assessed for both sea and river floods. Large parts of the coastal zone are already threatened by extreme sea levels produced during storms, such as shown by Hurricane Katrina in 2005 and Cyclone Nagris in Myanmar in 2008 (Nicholls in press). Extreme sea-level events produced by a combination of storm surges and astronomical tides will be raised by mean sea level: the return period of extreme sea levels is reduced by higher mean sea levels (e.g., Haigh and others in press). The magnitude of this effect depends on the slope of the exceedance curve. Sea-level

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[8] Only erosion due to sea-level rise is considered. Short-term erosion due to individual storms when the beach is expected to largely recover is not considered. Autonomous adaptation is not relevant to considerations of beach erosion.

[9] Extreme events are an explicit part of this analysis. They are considered via the return periods of extreme events as explained below. Autonomous adaptation is not relevant to considerations of flooding.

rise also raises water levels in the coastal parts of rivers (via the backwater effect), increasing the probability of extreme water levels. DIVA considers both these flooding mechanisms. Due to the difficulties of predicting changes in storm surge characteristics (e.g., von Storch and Woth 2008) in the standard DIVA method, the present storm surge characteristics are simply displaced upward with the rising sea level, following twentieth century observations (e.g., Zhang and others 2000; Woodworth and Blackman 2004; Haigh and others in press). In the EACC Project, increased extreme water levels due to the possibility of more-intense tropical cyclones are considered. We assume that the 100 year event increases by 10 percent in 2100 due to climate change, and to simplify the analysis we assume a linear change with time. Based on this assumption, we rotate the existing exceedance curve upwards by 1 percent per decade. This method means that the lower the probability of the event, the greater the increase in water level. This differs from the effect of sea-level rise, which is uniform.

DIVA assumes the construction and upgrade of dikes as the adaptation option for inundation and flooding, drawing on the experience of Deltares, including its application in the global analysis of Hoozemans and others (1993). Since there are no empirical data on actual dike heights available at a global level, a demand for safety is computed and assumed to be provided by dikes (Tol 2006; Tol and Yohe 2007). DIVA is not able to apply benefit-cost analysis as it was too computationally expensive. Hence, dikes consistent with the demand for safety are applied based on population density. There are no dikes where there is very low population density (< 1 person/km$^2$). Above this population threshold, an increasing proportion of the demand for safety is provided. Half of the demand for safety is applied at a population density of 20 persons/km$^2$, and 90 percent at a population density of 200 persons/km$^2$. This is akin to providing isolated dikes around individual settlements at lower population densities and more-continuous dikes at higher population densities. Based on the selected dikes, land elevations, and relative sea level (including more-extreme sea levels if appropriate), the frequency of flooding is estimated over time. This is further converted into flooded people and economic flood damages based on population density and GDP (see below). River flooding is evaluated in a similar fashion along approximately 115 major global rivers. The distance that requires dike is determined by the backwater effect, which relates to the river depth width and slope. For a more detailed presentation of the flooding model, see Tol (2006) and Tol and others (in prep).

DIVA translates these physical changes into social and economic consequences. Social consequences are expressed in terms of various indicators. The indicator "people actually flooded" gives the expected number of people subject to annual flooding. The indicator "forced migration" gives the number of people who have to migrate from the dry land permanently lost due to erosion and areas submerged by sea level. For inundation it is assumed that all areas subject to flooding more often than once per year are abandoned by people. For the base calculation of these population numbers (in 1995), the Gridded Population of the World dataset, version 3 was used (CIESIN and CIAT, 2004).

The economic consequences are expressed in terms of damage costs (and adaptation costs as outlined in Section 3.3). The cost of (dry) land loss is estimated based on the land use scenarios and the assumption that only agricultural land is lost. Agricultural land has the lowest value, and it is assumed that if land used for other purposes (e.g., industry or housing) is lost, then those usages would move and displace agricultural land. The value of agricultural land is a function of income density. The cost of floods is calculated as the expected value of damage caused by sea and river floods based on a damage function logistic in flood depth. The costs of migration are calculated on the basis of loss of GDP per capita. For a more detailed account of the valuation of impacts, see Tol (2006) and Tol and others (in prep).

## 3.3 HOW COSTS OF ADAPTATION ARE DEFINED AND CALCULATED

We are addressing the adaptation options defined in Table 7. This includes land use planning where we limit the coastal population to current levels to illustrate what an extreme land use planning policy might accomplish. All these results are developed with the global DIVA model of impacts and adaptation to sea-level rise, except for the costs of port upgrade and dike maintenance, which are developed offline in new extensions of the DIVA method.

Beaches and shores are nourished according to a cost-benefit analysis that balances costs and benefits (in terms

## TABLE 7. SEA-LEVEL RISE EFFECTS, IMPACTS, AND ADAPTATION OPTIONS CONSIDERED

| *Sea-level rise effect* | *Impacts considered* | *Adaptation Response considered* |
|---|---|---|
| (Long-term) beach erosion | Land loss and its costs; forced migration and its costs | Beach/shore nourishment<br>Land use planning |
| Increased flooding due to storm surges and the backwater effect | Expected flood damage costs; expected people flooded | Sea and river dikes, including maintenance<br>Port upgrade (raising elevation)<br>Land use planning |
| Submergence | Land loss and its costs; forced migration and its costs | Sea and river dikes, including maintenance<br>Land use planning |

of avoided damages) of protection. Shore nourishment has a lower unit cost than beach nourishment, but it is not widely practiced at present and has the disadvantage of not immediately maintaining the intertidal beach. Beach nourishment is therefore chosen as the better adaptation option, but only if the tourism revenue is sufficient to justify the additional costs. Tourism revenues are derived from the Hamburg Tourism Model (HTM), an econometric model of tourism flows (Hamilton and others, 2005a; 2005b). In HTM, tourism numbers increase with population and income. Rising temperatures pushes tourists toward the poles and the tops of mountains in search of the optimum temperatures. Hence, there is a change in the spatial pattern of tourism. However, while some present tourist hotspots such as the Mediterranean countries might see their market share fall as a result of climate change, there is a significant increase in absolute tourism numbers driven by the population and GDP scenarios.

For adaptation to flooding/inundation, the changing demand function for safety is computed over time (Tol 2006; Tol and Yohe 2007). This increases with per capita income and population density and decreases with the costs of dike building. As with the initial case outlined in Section 3.2, dikes are not applied where there is very low population density (< 1 person/km$^2$), and above this population threshold an increasing proportion of the demand for safety is applied. Half of the demand for safety is applied at a population density of 20 persons/km$^2$ and 90 percent at a population density of 200 persons/km$^2$. It is assumed that any increase in demand for safety is provided by a new or increased dike height, and the incremental costs of dike construction are determined. Explicit in these calculations is the assumption that all existing dikes can be raised incrementally, which is increasingly the norm due to sea-level rise and subsidence. The unit costs for dikes are provided by Hoozemans and others (1993). It is assumed that river dikes are on average half the cost of sea dikes, and the distance inland that they need to be constructed is determined by the backwater effect, which includes the effect of sea-level rise. This provides an estimate of the annual capital investment. It also develops a stock of dikes that require maintenance and operation, but the standard DIVA does not consider these costs.

We have made three extensions to the DIVA method for the EACC research compared with Nicholls (2007): land use planning, dike maintenance and operation costs, and port upgrade. These are outlined in Sections 3.3.1 to 3.3.3.

### 3.3.1 Land use planning

Land use planning to limit growth in vulnerable coastal areas can be simulated simply by holding population constant over time. The individual wealth would still follow the GDP scenario. It is almost inconceivable that we could achieve such a population trajectory based on current trends, even with stringent and persistent government action. Hence, this is an extreme best case and is mainly illustrative of sensitivity analysis of what such a policy might accomplish.

### 3.3.2 Dike maintenance and operation

The capital costs of building and upgrading dikes as sea level rises is calculated within DIVA. There are additional costs required to take account of dike maintenance and operation throughout the lifetime of the dike, as outlined in more detail in Appendix 2. Operational costs reflect the costs of drainage landward of the dike, such as drain clearance and pumping costs:

without drainage, this land would often become waterlogged or flooded due to rainfall and rising water tables, combined with the lack of natural drainage.

Most of the data that were found came from the Netherlands (IPCC 1990; Verhagen 1998; Kok and others 2008), with some additional data from Canada (RSBC 1996; Dike and Channel Maintenance and Habitat Subcommittee 2001). A range of estimates of maintenance and operational values were identified, with river dikes being consistently lower in cost, reflecting the lack of wave loadings. Maintenance costs as high as 2 percent were identified in some cases (UNCTAD 1985; Smedema and others 2004). Taking a conservative view, maintenance and operation costs were assumed as follows: river dikes at 0.5 percent and sea dikes at 1 percent. These costs could be in error by a factor of 100 percent. Full details of the methodology and data sources can be found in Appendix 2.

Note that beach nourishment requires no consideration of maintenance, as these costs are built into the ones produced by DIVA.

### 3.3.3 Port upgrade

Data from the World Bank[10] show that there has been a 6 percent growth per year between 1990 and 2007 in total global exports, a trend also shown by the volume of seaborne trade, which has tripled globally over the past 30 years (UNCTAD 2008). The ability of ports to maintain their future role in the supply chain requires that port infrastructure is adapted to changes in sea levels. The goal of this investigation was to estimate the costs associated with port adaptation to sea-level rise at World Bank regional levels—with adaptation being the raising of existing port ground level to offset the future effect of sea-level rise. Based on discussions with port operators, this is a reasonable approach that ports are likely to adopt. The estimated costs do not include explicit cost/benefit considerations—it is assumed that these strategic and valuable areas will need to be maintained to 2050 (and beyond). The costs that will be estimated are those associated with maintaining current port areas in response to a total SLR projected to 2050.

The methodology to estimate the costs of upgrade is based on that used in the IPCC (1990) report (produced by Delft Hydraulics), which identified global costs of protecting against a 1-m rise in sea level. In the 1990 report, primary data on port areas were found to be limited, and a methodology based on statistics of the tonnage moved was developed to estimate port areas that would require raising. As primary data on port area have not significantly improved, this statistical approach has been adapted here based on Lloyds List (2009) *Ports of the World 2009* directory. This contains information on 1,220 ports located in the regions of interest, of which 501 in 85 countries reported usable data. Where countries had ports recorded in Lloyds List (2009) but no usable data, assumptions based on the IPCC (1990) study were made. This increased the number of countries included in the analysis to 108.

For the purposes of this study, no change in port area by 2050 is included. The methodology was developed to cost the upgrading of existing areas, preserving current risk levels for inundation; any new development is assumed to be designed for future changes in sea level to 2050. The unit cost estimates are based on those used in the IPCC (1990) report, translated into current monetary value.

Full details of the methodology and data sources can be found in Appendix 2.

## 3.4 DATA (SOURCES, ASSUMPTIONS, AND SIMPLIFICATIONS)

The analysis is mainly based on the DIVA database, which was developed specifically for the DIVA model (McFadden and others 2007; Vafeidis and others 2008). This is a one-dimensional database that divides the world's coasts (excluding Antarctica) into 12,148 linear segments and associates about 100 pieces of data with each segment concerning the physical, ecological, and socioeconomic characteristics of the coast. The segments have a variable length, with an average length of 70 km. Hence the spatial resolution is two orders of magnitude higher than any other integrated assessment models that can conduct coastal analyze. As an example, FUND operates at national scales, so resolves approximately 200 coastal units (Tol 2007).

While some data in DIVA are stored in other forms, such as those associated with rivers, lagoons/basins, administrative units, and countries, and on a raster grid

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[10] http://econ.worldbank.org

(Vafeidis and others 2008), the segment is the fundamental spatial unit of DIVA. Most calculations operate at the segment scale, and this defines the fundamental resolution of the model.

The offline calculations for dike maintenance and operation use the DIVA results directly, while the estimate of the costs of port upgrade is based on a range of data, as explained in Appendix 2.

# 4. RESULTS

The results are all given in 2005 U.S. dollars with no discounting. Appendix 3 gives the results by World Bank Region for each of the scenarios that were considered.

Globally and regionally, with the high, medium, and low sea-level rise scenarios, there is a wide range of results for all parameters considered. Protection dramatically reduces land loss, the expected number of people flooded and those forced to migrate, and their associated costs compared with a scenario of no protection. Hence the focus of these results will be on the associated costs of adaptation: the construction and maintenance of sea and river dikes, the costs of beach nourishment, and the costs of port upgrade.

In Section 4.1 (the baseline scenario) global adaptation costs are reported, and the World Bank regions that have the highest costs are discussed. Section 4.2 provides discussion of global costs across the three sea-level rise scenarios, the adaptation costs (including ports) of the medium SLR scenario across World Bank regions, the adaptation costs associated with an increase in surge heights due to more-intense tropical cyclones and with no population growth in the coastal zone, and a synthesis.

## 4.1 INVESTMENT COSTS (UPFRONT AND MAINTENANCE) IN THE BASELINE SCENARIO

Under a scenario of no climate change, DIVA still estimates that there are adaptation investment costs, most especially for improved dikes and to a lesser extent for beach nourishment (Table 8). This reflects that the demand for safety function of Tol (2006) and Tol and Yohe (2007) will produce a higher demand for safety due to growing wealth and population density without any rise in sea level. This is consistent with changing attitudes to risk during the twentieth century as living standards rose substantially. In some locations, especially deltas, sea levels would be expected to rise due to natural subsidence, and this also drives adaptation needs. In DIVA, the total global adaptation costs for a scenario of no sea-level rise is estimated at from $10.4 billion/yr in the 2010s to $9.5 billion/yr in the 2040s. World Bank regions account for approximately 60 percent of these costs. Two-thirds of the total adaptation cost comes from sea dikes, increasing to over 90 percent when maintenance costs are considered.

Out of the World Bank regions (excluding high-income countries), Latin America and the Caribbean and East

### TABLE 8. INCREMENTAL AVERAGE ANNUAL COSTS (2010S–2040S) OF ADAPTATION FOR COASTAL PROTECTION AND RESIDUAL DAMAGES BY SCENARIO UNDER THE NO-RISE SLR SCENARIO

Billion dollars per year at 2005 prices, no discounting; high-income countries are excluded.

| *Adaptation/Damage measures* | | *Costs* |
|---|---|---|
| Beach nourishment | | 0.2 |
| Port upgrades | | 0.0 |
| River dikes | Capital | 0.1 |
| | Maintenance | 0.1 |
| Sea dikes | Capital | 3.6 |
| | Maintenance | 2.0 |
| Total adaptation costs | | 6.0 |
| Total residual damage costs | | 8.3 |

Asia and the Pacific have the greatest percentage of adaptation costs at 40 percent and 30 percent, respectively. Thus on a global level, more investment is required in these regions compared with other World Bank regions regardless of climate change. In contrast, the Europe and Central Asia region and the Middle East and North Africa region have the lowest adaptation costs, at approximately 5 percent of the World Bank total. Thus less investment would be required in these two regions if sea levels do not rise.

However, DIVA is only designed to examine climate change impacts, and there will be adaptation costs in coastal areas that are not linked to climate change. In Section 1.3.2, a number of current adaptation investments are listed; only part of the investment is linked to climate change, as opposed to climate variability, which has been a major driver of coastal investment. The incremental costs of adapting to climate variability post-2010 are included in the DIVA costs as investments in dikes, but the maintenance costs of the dikes built before 2010 are not included, and this cost would be substantial. Investments to address the adaptation deficit discussed in Section 5.1 are not considered, and investments due to non-climatic problems such as subsiding cities and deltas are not considered either. Hence, the DIVA figures are *minimum* estimates of future adaptation without climate change and should not be over interpreted.

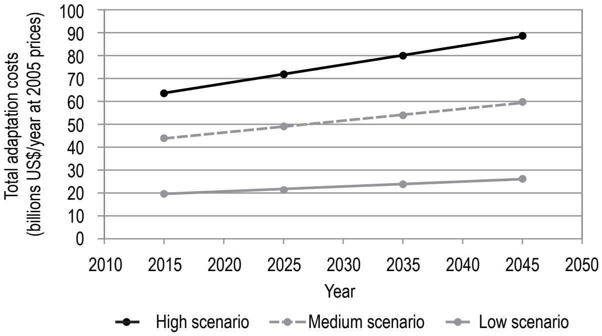
## 4.2 INVESTMENT COSTS (UPFRONT AND MAINTENANCE) DUE TO CLIMATE CHANGE

### 4.2.1 High, medium, and low scenarios: Global adaptation costs

Total incremental global adaptation costs are shown in Figure 3 for sea and river dike construction and maintenance costs, plus beach nourishment. The Figure illustrates that adaptation costs increase linearly with time, with the medium scenario increasing in total adaptation cost from $43.4 billion/yr in the 2010s to $59.5 billion/yr in the 2040s.

Sea dike costs are the main contributor to the global adaptation costs, accounting for $36 billion/yr from the 2010s to the 2040s under the medium scenario. This accounts for 82 percent of the total costs in the 2010s, decreasing to 61 percent by the 2040s as the costs of beach nourishment grow with time.

FIGURE 3. GLOBAL INCREMENTAL ADAPTATION COSTS FOR THE HIGH, MEDIUM, AND LOW SLR SCENARIOS



*Source*: Authors' data.

The distribution of the adaptation costs can be seen in Table 9, which summarizes the costs for the World Bank Regions.

Sea dikes are the dominant adaptation costs, followed by beach nourishment, while river dikes and port upgrade are relatively minor costs. In terms of capital and maintenance costs, the latter grow rapidly with time as the stock of dikes to maintain increases. These maintenance costs only consider the maintenance of dikes required to adapt to climate change; substantial additional investment in maintenance would be required to maintain the overall dike system.

### 4.2.2 Medium scenario: Adaptation costs in World Bank regions

The capital costs for sea dikes under the medium scenario (from the 2010s through to the 2040s) due to climate change are as follows:

| | |
|---|---|
| East Asia and Pacific | $6.4 billion/year |
| Europe and Central Asia | $1.9 billion/year |
| Latin America and the Caribbean | $7.1 billion/year |
| Middle East & North Africa | $0.8 billion/year |
| South Asia | $1.2 billion/year |
| Sub-Saharan Africa | $2.5 billion/year |
| TOTAL | $20.0 billion/year |

### TABLE 9. INCREMENTAL AVERAGE ANNUAL COSTS (2010S–2040S) OF ADAPTATION FOR COASTAL PROTECTION AND RESIDUAL DAMAGES BY SCENARIO

Billion dollars per year at 2005 prices, no discounting; high-income countries are excluded.

| | | Sea-Level Rise Scenarios | | | | |
|---|---|---|---|---|---|---|
| *Costs and damages* | | *Low SLR* | *Medium SLR* | *High SLR* | *High SLR with cyclones* | *High SLR with no population growth* |
| **Adaptation costs:** | | | | | | |
| Beach nourishment | | 1.7 | 3.3 | 4.5 | 4.5 | 4.5 |
| Port upgrades | | 0.2 | 0.4 | 0.5 | 0.5 | 0.5 |
| River dikes | Capital | 0.2 | 0.4 | 0.6 | 0.6 | 0.6 |
| | Maintenance | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 |
| Sea dikes | Capital | 8.7 | 20.0 | 29.9 | 31.8 | 30.0 |
| | Maintenance | 2.2 | 4.9 | 7.2 | 7.7 | 7.2 |
| Total | | 13.0 | 29.0 | 42.8 | 45.2 | 42.9 |
| **Total residual damage costs:** | | | | | | |
| | | 0.7 | 1.5 | 2.1 | 2.1 | 1.5 |

This accounts for 55 percent of the total global costs of dike construction. Sea dike costs are assumed to be roughly uniform over time. The regions with the highest cost are Latin America and the Caribbean, followed by East Asia and the Pacific Region, while Middle East and North Africa has the lowest costs.

Sea dike maintenance costs increase approximately linearly with time as the stock of dikes that require maintenance increases 4.2 times from the 2010s to a total of $7.9 billion/yr by the 2040s. It is important to note that this maintenance cost would continue to grow with time beyond the period of analysis—something that has not been considered in previous analyses and that has important implications for adaptation costs based on hard defenses. For the high scenario, sea dike costs are approximately 1.5 times higher than the medium scenario, whereas in the low SLR scenario, dike costs are 2.3 times lower than in the medium scenario.

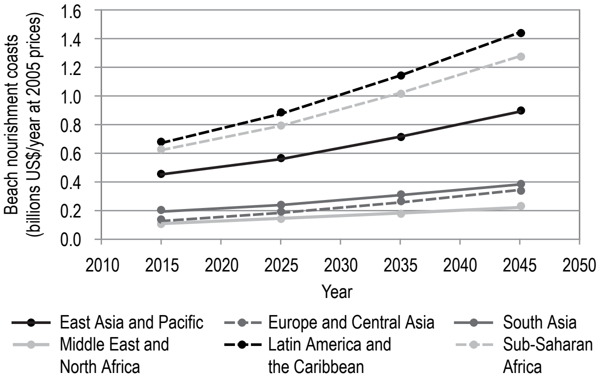
In all regions, the cost of construction and maintenance of river dikes is small in comparison to sea dikes at 1.4 percent of the total adaptation cost, except for Latin America and the Caribbean at 3.5 percent of the total adaptation cost, as there is a large value in investment in initial defenses. Total river dike costs for the World Bank Regions in the 2010s are $0.37 billion/yr, increasing to $0.44 billion/yr in the 2040s (Appendix 3). Maintenance costs increase from $0.02 billion/yr to $0.07 billion/yr over the same time period. Under a high SLR scenario, these costs would be anticipated to increase 1.5 times, whereas for the low SLR scenario costs would expect to decrease by one-third. Maintenance costs become more expensive as time progresses. Some 70 percent of the costs in World Bank Regions occur in Latin America and the Caribbean.

Throughout the regions, beach nourishment is the second highest component of total adaptation costs after sea dikes and their maintenance. The percentage increase in costs is 1.5 to 2.5 times (from the low to the high scenario) from the 2010s to the 2040s. In absolute terms for the medium scenario, the costs of beach nourishment increase from $2.2 billion/yr in the 2010s to $4.6 billion/yr by the 2040s.

Under the medium scenario (Figure 4), Latin America and the Caribbean and Sub-Saharan Africa account for 60 percent of the total cost for the World Bank regions. The region with the lowest beach nourishment costs is the Middle East and North Africa ($0.11 billion/yr in the 2010s rising to $0.2 billion/yr in the 2040s).

Port upgrade costs are relatively minor, as detailed in Appendix 3.

FIGURE 4. BEACH NOURISHMENT COSTS IN THE WORLD BANK REGIONS FOR THE MEDIUM SLR SCENARIO



*Source*: Authors' data.

### 4.2.3 Effect of cyclone activity and of no population growth in the coastal zone on adaptation costs

The effect of a 10 percent increase in tropical cyclones during the twenty-first century is relatively small compared with the high SLR scenario. Globally, an increase in tropical cyclones increases sea dike costs by 8 percent in the 2010s and by 9 percent in the 2040s compared with no tropical cyclones. The effects are felt most in the East Asia and Pacific Region and the South Asia Region, where dike costs could be rise by 13 percent compared to the high scenario in the 2040s. Consequently, dike maintenance costs also increase at a slightly higher rate.

The absolute increase in global adaptation costs due to cyclones becomes greater with time, from $5.1 billion/yr in the 2010s to $7.3 billion/yr in the 2040s.

Limiting population growth in the coastal zone has only a small effect on adaptation costs (around 1 percent). This shows that the existing coastal development leaves a large legacy in terms of the demand for coastal protection. In practice, adaptation costs would be reduced more than calculated here, but the DIVA database cannot resolve such details.

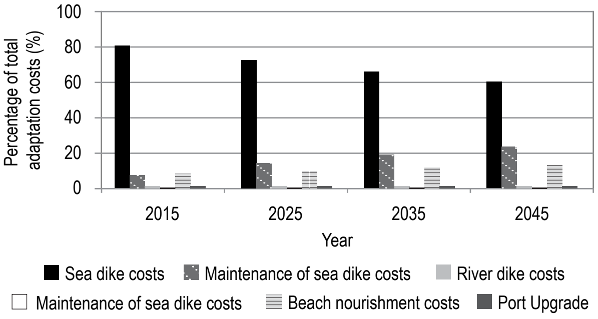
In addition to adaptation costs, damage costs are reduced as fewer people and assets are present to be affected.

### 4.2.4 Adaptation costs: Synthesis

In terms of the adaptation measures considered here, protection by sea dikes is the major contribution to defense costs, followed by beach nourishment. River dike costs and port upgrade costs are relatively small in comparison (Figure 5). For the World Bank Regions, sea dike costs remain similar throughout the study period at $19.8 billion/yr. They are 9.1 times more costly than beach nourishment in the 2010s, decreasingly to 4.4 times more costly in the 2040s (as there is greater investment in beach nourishment). In the East Asia and Pacific and Europe and Central Asia Regions, sea dike costs can be up to 14.1 times more costly than beach nourishment.

In the 2010s, sea dike costs in Europe and Central Asia account for 86 percent of the total adaptation cost, decreasing to 63 percent by the 2040s. In Sub-Saharan Africa they are responsible for 73 percent of total adaptation cost in the 2010s and decrease to 53 percent in the 2040s. This is because beach nourishment costs in both regions increase over time, particularly in Sub-Saharan Africa, where they increase from 19 percent to 26 percent of the total adaptation cost. As sea dikes require maintenance, the regions that have an initial high sea dike cost (such as Europe and Central Asia) also have a high maintenance cost as time progresses. Therefore constructing sea dikes demands continued investment in the future.

FIGURE 5. PERCENTAGE OF ADAPTATION COSTS FROM SEA DIKES, RIVER DIKES, MAINTENANCE COSTS, AND BEACH NOURISHMENT FOR SIX WORLD BANK REGIONS



*Source*: Authors' data.

With a 10 percent increase in surge levels due to cyclones by 2100, sea dike costs increase by 8–9 percent, while limiting population growth in the coastal zone has minimal impact on adaptation costs, as a large amount of wealth is still generated in that area.

# 5. LIMITATIONS

A study of this type inevitably has a number of limitations, as already indicated in the text. This section reflects on the limitations and the next steps to investigate adaptation in coastal areas under climate change.

## 5.1 TREATMENT OF ADAPTATION/ DEVELOPMENT DEFICIT

As with all previous studies, these results only consider the incremental cost of climate change as defined in the UNFCCC. In other words, they assume that there is a good existing adaptation system to upgrade for climate change. This gap between actual and desired adaptation systems has been termed the adaptation deficit (Burton 2004; Parry and others 2009). If there is an adaptation deficit, the total cost of adaptation to achieve the residual impacts presented in this study will be more costly than reported here.

The magnitude of the adaptation deficit for coastal areas has not been systematically investigated, so it is difficult to quantify. Experience shows that current adaptation systems are often inadequate even in the industrial world (e.g., Hurricane Katrina in the United States in 2005 and Storm Xynthia in France in 2010), and analysis points to other cases (Nicholls and others, 2008a), while in developing countries this is a much bigger, although poorly quantified problem.

There are limited cost estimates, which may suggest the order of this adaptation deficit. An example is the $50 billion price tag to upgrade New Orleans for Category 5 hurricanes after the Katrina disaster: given a 30-year period of upgrade, this translates into $2 billion/yr for just one coastal city. As the adaptation costs for the medium SLR scenario (in the 2040s) were only estimated to be about $33 billion/yr for World Bank Regions alone (and $60 billion/yr globally, to include the United States), this single estimate suggests that the adaptation deficit could exceed the incremental costs of sea-level rise estimated here. This issue clearly requires further more comprehensive assessment. This demonstrates that the issues of development and the cost of successful adaptation to climate change are intimately linked.

## 5.2 TREATMENT OF EXTREME EVENTS

Extreme events are an explicit part of the DIVA analysis. The flood analysis explicitly considers extreme water level events and how they might change due to sea-level rise—and for the first time due to increasing intensity of tropical cyclones. However, the treatment of stronger storms is only based on a sensitivity analysis. It should be recognized that coastal storms cause damage by multiple mechanisms, and wind damage, which can be widespread during storm landfall, is not considered here.

There is also always a residual risk for infrastructure behind defenses, and hence in the future we should expect occasional coastal disasters, even if we protect in an efficient manner. Of course, this is a product of climate variability and hence this would be true without climate change—the rise in the mean sea level and possibly more-intense storms will exacerbate this issue and mean that when floods occur they will be deeper, the flow will be faster, and they will be more likely to cause significant infrastructure and loss of life. Infrastructure losses can be reduced by flood-proofing, while loss of life can be minimized by good warning and evacuation systems. They can also be reduced by land use planning to encourage development away from vulnerable areas. Hence, even in city areas a portfolio of adaptation measures is likely to be optimum in response to sea-level rise rather than just depending on defenses.

## 5.3 TREATMENT OF TECHNOLOGICAL CHANGE

It is generally assumed that all the protection technologies considered in the protection analysis using DIVA are mature (cf. Tol 2007), and hence technological change is unlikely to have much influence on the adaptation costs considered here. Important innovations are likely in adaptation technology, especially concerning information technology aspects such as storm forecasts and warnings. It is difficult to forecast how these might change adaptation approaches in coastal areas and hence this is not considered.

## 5.4 TREATMENT OF INTER-TEMPORAL CHOICE

Inter-temporal choice raises the question of the role of reactive versus proactive adaptation. The methods used in this analysis reflect these choices. Beach nourishment and port upgrade are shorter-term decisions where investment can be linked more closely to need, while flood management has a longer lead time. Hence, a more reactive approach was adopted for the first two adaptation measures, and a more proactive approach for the flood protection via dikes. In the United Kingdom and the Netherlands, both land use planning and flood defense design is thinking 100 years (rather than 50 years) into the future (e.g., DEFRA 2006; Deltacommissie 2008; Kabat and others 2009; Environment Agency 2009). This planning is based on a precautionary SLR scenario on the order of a 1-m rise through the twenty-first century and consideration of much larger sea-level rise over the twenty-second century. But these countries are exceptions, and in most locations in Europe and globally there is no proactive adaptation to climate change, even in other industrial countries (Tol and others 2008; Moser and Tribbia 2008). Hence under current behavior there is much less proactive adaptation than considered in the EACC analysis presented here. More proactive preparation for the effects of climate change in coastal areas should be encouraged and supported.

## 5.5 TREATMENT OF “SOFT” ADAPTATION MEASURES

Delivering the “hard” adaptation measures considered in this analysis will require significant institutional and technical capacity in terms of coastal management institutions and coastal engineering expertise. In monetary terms, these institutional costs are relatively small compared with the adaptation measures. However, money alone is not enough to develop the required capacity, and it requires enhancements across the wider issue of adaptive capacity (Smit and others 2001). This is an issue that should be addressed within the development agenda, as the issues are broader than adapting to climate change.

Protection will tend to degrade coastal ecosystems via coastal squeeze, so this adaptation approach produces secondary impacts that are evaluated in some cases. Hence, protection does not preserve the status quo, but it does preserve the valuable dryland. Coastal ecosystem degradation will be significant due to sea-level rise, and this will be reinforced by protection based on dikes. Nicholls and Klein (2005) identified the twin challenges of maintaining human safety and sustaining coastal ecosystems as a major challenge in a European context. This is also true more widely and constitutes a major challenge for coastal management.

## 5.6 TREATMENT OF CROSS-SECTOR MEASURES

The coastal system is cross-sectoral by definition. In this report, where we can identify significant human activities, they have been protected from the threats raised by sea-level rise and increased storms. Some human impacts have not been considered, however, most relevantly changes in water supply due to salinization (Ward and others 2010). There are also natural system impacts such as coastal wetland loss and change. These natural systems are certainly valued in richer societies, as illustrated by the EU Habitats Directive.

In addition, coastal areas experience significant changes due to non-climate factors (Nicholls and others 2007a, 2009). A major example is subsidence and failure of sediment supply in many deltas, which may locally have consequences as large as climate change, if not larger (e.g., Ericson and others 2006; Woodroffe and others

2006; Syvitski and others 2009). This stresses the need for integrated responses to climate change that address all the issues facing coastal zones, including climate and non-climate drivers (Klein and others 2001).

## 5.7 AREAS FOR FOLLOW-UP WORK AND RESEARCH ADVANCES

- The work raises a number of issues for further research as follows:
- Improved understanding the adaptation deficit for coastal areas
- Better predictive capacity of the future—for coastal changes associated with both climate and non-climate drivers
- Better understanding and accounting of local factors that influence coastal impacts and adaptation needs, such as subsiding deltas and cities
- Improved integrated cross-sectoral assessment
- Improved methods to recognize and prioritize potential coastal adaptation options
- Improved understanding of the best way to adapt to sea-level rise (e.g., soft versus hard options, retreat/realignment) to minimize other impacts
- National adaptation case studies with more local details to reinforce this global analysis.

# APPENDIX 1. EACC POPULATION AND GDP PROJECTIONS

## A1.1 POPULATION PROJECTIONS

The choice of projections of population out to 2050 presents few difficulties. The UN Population Division (UNPD) publishes updated population projections to 2050 every two years using four sets of assumptions about future fertility: constant fertility (CF), based on fertility rates at the date of the projection; low fertility (L), reflecting an assumption that fertility rates will either fall rapidly (in developing countries) or remain low (in industrial countries); medium fertility (M); and high fertility (H). The CF projections largely provide a reference point for measuring the impact of the anticipated profile of future fertility on world/national populations. UNPD consistently uses the M projections as its main projections, while the L and F projections provide a range for plausible outcomes. Further, the M projections are used as the foundation for other UNPD forecasts, such as levels of urbanization, which the study also uses.

The most recent version of the UNPD projections is the 2008 Revision published in March 2009. Derived projections for urbanization and other variables are, however, still based upon the 2006 Revision published in March 2007. For this reason, the EACC Project used the 2006 Revision population projections together with the associated derived figures (UNPD 2006).

## A1.2 GDP PROJECTIONS

There are different requirements for GDP projections in the various elements of the global analysis. The *World Development Indicators* (WDI) provides two main measures of GDP per person in real terms: GDP in dollars at 2000 constant prices and market exchange rates and GDP at purchasing power parity (PPP) in dollars at 2005 prices. Some sectors, such as infrastructure, use GDP per person at PPP as the income variable, as this is standard in work on cross-country comparisons. However, others, in particular the IMPACT model by the International Food Policy Research Institute used for the analysis of agriculture, are calibrated to country incomes measured in dollars at market exchange rates, and they therefore use GDP at constant prices and market exchange rates.

Most of the economic models used to project future emissions and analyze the impacts of climate change rely on economic projections in terms of GDP per person—the International Energy Agency (IEA), the Energy Information Administration (EIA) of the U.S. Department of Energy, Hope, and Tol. Nordhaus's RICE model, on the other hand, seems to be consistent PPP incomes rather than market exchange rate figures. The SRES aggregates and the downscaled estimates from CIESIN use projections starting from 1990 are now very out of date and are therefore not used. Thus, the starting point for the projections is the World Bank's estimates of GDP per person in 2005 at PPP and 2005 prices. Aggregate GDP at PPP is calculated by multiplying total population and is then projected at five-year intervals using the real GDP growth rates for the country/region in each of the economic models. Note that each model relies on different definitions of regions, so that, for example, India is treated as a separate projection unit by the IEA but is included in South Asia by Tol. Thus, it is necessary to map regions to countries separately for each model. One can get back to the implied PPP level of GDP per person by dividing aggregate GDP for the country by its projected population.

Two minor points concern the sample of countries and the treatment of missing values:

- The full set of countries included in the WDI database includes many small countries and territories. Often the data available for such countries are very limited. For this reason, the sample of countries included in the analysis excludes all countries and territories with populations of less than 400,000 in 2005.
- Data on key variables are also missing for a number of larger countries. For example, the WDI database does not have information on either population or income per capita (on any basis) for Afghanistan, North Korea, or Iraq. Since it would be very undesirable to exclude such countries, the WDI data have been supplemented with information from a variety of sources, including the United Nations, the EIA, and non-official sources.

The various models diverge significantly in their projections of world GDP at PPP. Table A1.1 shows the aggregate GDP projections (in billion dollars at 2005 PPP) for the five economic models as well as the equally weighted average of these for each projection period. The rankings are not entirely consistent, but broadly the EIA generates the highest figures while Nordhaus's model generates the lowest. Overall, the average is closest to the figures generated by Hope's model. In the absence of good reasons to give some projections more weight than others, it seems reasonable to use the equally weighted average.

Table A1.2, on the other hand, shows the results of applying the growth rates implied by the downscaled SRES scenarios to the 2005 starting point used for the economic models. Note that there is a very small discrepancy in the aggregates for 2005 because the downscaled SRES projections exclude some small countries that are included in the sample used for the analysis. With the exception of the A2 scenario, the SRES projections show much higher rates of growth of aggregate GDP than the average of the economic models. The A2 scenario is quite similar to the economic average, while the B2 scenario is close to the highest of the economic models (EIA). At the other end of the scale, the A1 scenario shows total GDP in 2050 that is more than double the economic average.

To run the IMPACT model, it is necessary to convert the PPP estimates of GDP per person into GDP at market exchange rates and constant 2000 prices. A standard method of imputing PPP values for countries for which the necessary price comparison data have not been collected is to regress calculated values log(GDP per person at PPP) for the International Comparisons Project countries on the equivalent values of log (GDP per person at market exchange rates) and use the resulting equation for imputation purposes. It is perfectly straightforward to reverse that process—that is, to use log (GDP per person at market exchange rates and constant 2000 prices) as the dependent variable and log (GDP per person at PPP) as the primary independent variable. There is

## TABLE A1.1. AGGREGATE GDP PROJECTIONS FROM ECONOMICS MODELS

In billion dollars at 2005 PPP

| | *Tol* | *Hope* | *Nordhaus* | *IEA* | *EIA* | *Average* |
|---|---|---|---|---|---|---|
| 2005 | 55,303 | 55,303 | 55,303 | 55,303 | 55,303 | 55,303 |
| 2010 | 64,401 | 63,213 | 61,772 | 67,295 | 69,199 | 65,176 |
| 2015 | 73,893 | 72,140 | 69,226 | 83,109 | 83,422 | 76,358 |
| 2020 | 84,949 | 82,683 | 76,025 | 94,981 | 98,769 | 87,481 |
| 2025 | 96,362 | 96,514 | 83,712 | 108,915 | 115,915 | 100,284 |
| 2030 | 109,490 | 113,125 | 92,457 | 125,330 | 135,357 | 115,152 |
| 2035 | 123,085 | 133,139 | 102,387 | 144,743 | 158,474 | 132,366 |
| 2040 | 138,604 | 157,325 | 113,268 | 167,793 | 186,013 | 152,601 |
| 2045 | 154,492 | 172,379 | 125,567 | 195,268 | 218,884 | 173,318 |
| 2050 | 172,519 | 189,024 | 136,221 | 228,144 | 258,190 | 196,820 |

## TABLE A1.2. AGGREGATE GDP PROJECTIONS FROM SRES SCENARIOS

In billion dollars at 2005 PPP

| | *SRES A1* | *SRES A2* | *SRES B1* | *SRES B2* | *Average* |
|---|---|---|---|---|---|
| 2005 | 55,294 | 55,294 | 55,294 | 55,294 | 55,294 |
| 2010 | 69,225 | 63,641 | 67,413 | 66,189 | 65,176 |
| 2015 | 91,142 | 72,993 | 82,557 | 77,802 | 76,358 |
| 2020 | 113,058 | 84,196 | 101,860 | 92,474 | 87,481 |
| 2025 | 154,133 | 97,403 | 124,837 | 109,106 | 100,284 |
| 2030 | 195,208 | 115,475 | 153,185 | 130,138 | 115,152 |
| 2035 | 252,194 | 133,548 | 186,518 | 153,340 | 132,366 |
| 2040 | 309,180 | 151,620 | 226,901 | 182,486 | 152,601 |
| 2045 | 366,166 | 169,692 | 271,825 | 212,840 | 173,318 |
| 2050 | 423,152 | 187,764 | 323,069 | 250,066 | 196,820 |

evidence that the relationship is not linear (see Deaton and Heston 2009), so the fitted equation includes linear and quadratic terms. It is sometimes argued that other variables may influence the relationship between PPP and market exchange rates, but these can only be used in this context if either the variables are constant over time or it is possible to obtain independent projections of the values of the variables up to 2050. None of the possible candidates—country size, population, etc.—yielded a significant coefficient, so the model is a simple quadratic in log(GDP per person at PPP). However, one modification to a simple linear regression was adopted. We have data on the dependent and independent variables for a large sample of countries from 1980 to 2005, though with some missing values. Thus, it is possible to use panel methods of estimation, which can take account of systematic differences across countries over time. This approach produces much better econometric results than standard ordinary least squares and has been used to impute the projected values of GDP per person at market exchange rates.

# APPENDIX 2. ADAPTATION IMPROVEMENTS

## A2.1 DIKE MAINTENANCE AND OPERATION

The capital costs of building and upgrading dikes as sea level rises is calculated within DIVA. Additional expenditures are required for maintenance and operation throughout the lifetime of the dike. Operational costs reflect the costs of drainage landward of the dike, such as drain clearance and pumping costs.

Some of the best cost estimates are available from the Netherlands. Verhagen (1998) estimated that the 3,600 km Dutch primary dike system was worth 26 billion guilders (at 1991 values). This cost was assumed to cover the cost of a total dike rebuild. Unit maintenance costs per km were 25,000 guilders/yr for river dikes and 85,000 guilders/yr for sea dikes. The higher costs for sea dikes reflect the fact that they are subject to wave loading in addition to high still-water levels.

Kok and others (2008) reports the national length of river and lake dikes as 1,441 km and the length of seawalls and delta dikes as 1,880 km. Sandy coasts (which are maintained by beach nourishment) account for the remaining 268 km of defense length. For DIVA calculations, river and lake dikes are jointly classed as river dikes (as they do not take the direct force of waves), while seawalls and delta dikes as jointly classified as sea dikes (as they have to withstand the greater wave impacts).

A proportional relationship was assumed between the value of dikes and the length of each dike type (approximately 40 percent and 60 percent for river and sea dikes respectively). Maintenance cost was multiplied by the length of the dike type to give maintenance cost in guilders/yr.

Percentage of maintenance cost per year =

$$\left(\frac{\text{Maintenance cost}}{\text{Total cost}}\right) \text{x } 100$$

Hence based on this Dutch data, the maintenance costs are estimated as 0.3 percent of the initial construction costs for river dikes and as 1.1 percent for sea dikes.

There are other sources of these numbers, again mainly from the Netherlands. Delft Hydraulics (1990) estimated that a 1-m high sea dike with regular maintenance will be maintained at 50 percent of the construction cost. UNCTAD (1985) estimates that breakwaters have a 50-year design life, so combining these values suggests maintenance costs are about 1 percent per year. UNCTAD (1985) also estimates the maintenance cost as a percentage of the initial cost of port structures: quay steel piling with reinforced concrete deck (1 percent), reinforced concrete piles and deck (0.75 percent), including rock-filled embayment's (0.75 percent) and breakwaters (2 percent).

Prof. Marcel Stive (Professor of Coastal Engineering, Delft Technical University) reports that over the last 10 years Rijkswaterstaat spent approximately €250million on 2,875 km of primary defenses. Estimating construction costs from IPCC (1990), maintenance cost equates to 1.7 percent of the capital cost.

British Columbia's (Canada) Drainage, Ditch and Dike Act (RSBC 1996) states that an annual levy for drainage, ditch, and dike maintenance fund cannot exceed

5 percent of the cost of the original works. It is anticipated that this is an upper limit of the funding required. Furthermore, the Dike and Channel Maintenance and Habitat Subcommittee (2001) of Fraser Basin in British Columbia estimates $5.5million/year for routine maintenance and an additional $4.0million/year for major river dike repairs. Assuming construction costs from IPCC (1990), maintenance cost is at 0.8 percent for minor maintenance and 0.6 percent for major works, combining maintenance for a total of 1.4 percent of capital costs.

For drainage projects, a rule of thumb in that operation and maintenance costs (such as weed clearance and desilting) account for 2 percent of the construction costs.

Hence, a range of estimates of maintenance and operational costs were identified, with river dikes being consistently lower in cost, reflecting the lack of wave loadings. Locally, maintenance and operational costs can be as high as 5 percent, but this is atypical, and a maximum of 2 percent appears a reasonable generic maximum case for sea dikes. Taking a conservative view, maintenance and operation costs were assumed as follows:

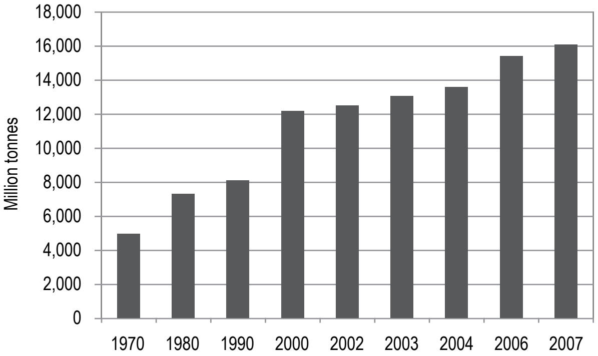
- River dikes: 0.5 percent
- Sea dikes: 1 percent

These costs could be in error by a factor of 100 percent, and further investigation of these costs in more-diverse settings is recommended. This should include how they might be expected to evolve under a scenario of rising sea level.

## A2.2 PORT UPGRADE

In 2007, the volume of international seaborne trade reached 8.02 x $10^9$ tons—with an estimated annual average growth rate of 3.1 percent over the past three decades—representing 80 percent of world trade (UNCTAD 2008). Total amounts for goods loaded and unloaded have increased steadily (Figure A2.1), with trade through the worlds container ports reaching 485 million TEUs[11] in 2007, of which China is estimated to account for approximately 28.4 percent. China has exhibited the largest growth in seaborne trade, notably after joining the World Trade Organization in 2001. Between 1990 and 2004, for example, the annual amount of goods handled for China and North Korea increased almost six times, from 167.7 million to 1,091.5 million tons, representing an increase from 2.06 percent to 8.06 percent of world trade (UNCTAD 2005). More recent figures, which include Hong Kong, Macau, Taiwan, Mongolia, and South Korea (UNCTAD 2008), show a further increase of trade in the region to 19.63 percent of world trade (3,151.3 million tons) by 2007.

FIGURE A2-1. WORLD TONNAGE FOR GOODS LOADED AND UNLOADED, 1970–2007



*Source*: UNCTAD 2005, 2008.

This growth in trade has fuelled the development of significant new port areas and highlights the importance of the world ports for current and future trade. The nature of this trade necessitates the location of ports in coastal areas, which makes them particularly vulnerable to the potential impacts of climate change and sea-level rise. This has been recognized recently with the C40 Climate Leadership Group's World Ports Climate Conference held in Rotterdam in 2008 (http://wpccrotterdam.com/) and studies such as Herberger and others (2009), which noted that the Port of Los Angeles, which handles 40–50 percent of the containers that enter the United States, will be subject to increasing flood risk due to sea-level rise over this century.

Only a limited number of previous assessments of port adaptation to climate change have been carried out at regional and global scales. This is largely because data on ports are fragmented and inconsistent, and the necessary physical parameters are not systematically reported. This lack of information has led to the use of

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[11] TEU is twenty-foot equivalent unit, or a 6.1 m x 2.4 m container.

indicators in order to assess potential impacts and associated costs.

The aim of this work is to estimate the costs associated with the adaptation of ports to sea-level rise at country, World Bank regional and global levels. As the main form of adaptation to sea-level change is assumed to be raising land levels, adaptation costs are assumed to be only those associated with raising current port areas to maintain their elevation relative to sea level and preserving current risk levels for inundation.

### A2.2.1 Methodology

The methodology adopted for this study is based on that developed by Delft Hydraulics (now Deltares) in its report *Sea-Level Rise: A World-wide Cost Estimate of Basic Coastal Defence Measures* (IPCC 1990). This report on global costs of protecting against a 1-m rise in sea level used statistics of maritime tonnage at country level to estimate the port area that would require ground levels to be raised.

In this study, due to the lack of comprehensive data at country level, port-level information was sourced that could then be aggregated to country level. In addition, estimated costs are calculated in response to the sea-level rise scenarios to 2050 (Section 3.1). The costs for raising port areas by 1-m are scaled to determine unit costs for other increments of sea-level rise. It is assumed that all port areas need to be raised, and no formal cost/benefit analysis is conducted; it is assumed that these strategic and valuable areas will need to be maintained to 2050 (and beyond). Only existing port areas are considered and they are assumed to be flat. Any new developments between 2010 and 2050 are presumed to be constructed with an appropriate allowance for sea-level rise.

### A2.2.2 Source data

The most comprehensive data source on ports was found to be Lloyds List's *Ports of the World 2009* directory. This provides port data listed by country, including:

- Port name
- Port activity (if the port is still commercially active)
- Port location (degrees and minutes)
- Port facilities (including which type of cargo the port is able to accommodate)
- Traffic (tonnage and number of containers (TEUs) for a given year)
- Tides (e.g., tidal range/tidal levels)

Traffic data were supplemented, where appropriate, from the *Containerisation International Yearbook* (Fossey 2009).

### A2.2.3 Port selection criteria

Countries included in the analysis were only those classified as upper middle income, lower middle income, or low income in the World Bank list of economies. For China, this meant ports located in Taiwan were included, but those in Hong Kong and Macau were excluded.

Individual port data for the selected countries were recorded on a spread sheet and then transferred into GIS software (ArcGIS), which showed the geographic position of individual ports. This allowed easy classification of the ports as either river, coastal, or offshore. This excluded from the analysis ports located inland on major rivers, such as the Yangtze in China, which may be subject to changes in future water levels due to the "backwater" effect as river waters meet rising sea levels but which are not considered a direct influence of sea-level change in this analysis. To allow the inclusion in the analysis of ports located in deltas or estuaries that are subject to the direct effects of sea-level change, an "up river" limit was established for those classified as coastal using the description of tidal influence in the original data. Ports upstream of this limit were excluded. Ports located on the Caspian Sea were also excluded, as change in global sea level will not have direct impacts.

### A2.2.4 Traffic to area calculations

The methodology for translating reported traffic used values from the IPCC (1990) report. Based on information from the Port of Rotterdam, the IPCC determined tonnage-space ratios for a range of cargo types and an amalgamated ratio that represents the quays, storage areas, roads, general areas (offices, etc.), and industrial areas within the port area. In this report three ratios were used:

- Mixed cargo: $3^* 10^6$ tons handled per $km^2$ of port area
- Bulk/oil: $30 * 10^6$ tons handled per $km^2$ of port area
- Containers (TEUs): $16 * 10^6$ tons handled per $km^2$ of port area

### A2.2.5 Tonnage and containers

Two categories of traffic are recorded in Lloyds List (2009): tonnage and TEUs. The tonnage and TEUs handled reported in the Lloyds List are assumed to represent the current capacity of the port, although it is recognized that this may change over time. Potential changes in traffic to 2050, such as a potential decrease in oil transport, are not considered.

Separate area calculations were undertaken for the two values. Tonnage was transferred directly onto the spreadsheet, and if a range of port facilities was indicated (e.g., general cargo, dry bulk, Ro/Ro, liquid bulk) that was divided by the mixed cargo rate above to generate area for the port.

As TEU is a volume based unit, translation into other units is necessarily imprecise. With reference to the design and specification of containers, the most common dry cargo maximum gross weight is approximately 24tonnes.[12] This value was therefore used in the equation below to determine the area required for the number of reported TEUs:

$$Y = (N *24)/(16^* 10^6) \qquad \text{Eq.1}$$

$Y$ = area ($km^2$)
$N$ = Number of TEUs handled
24 = tonnage equivalent for a container
$16^* 10^6$ = Tonnage equivalent for containers which can be handled in $1km^2$ (IPCC 1990)

### A2.2.6 Oil and petroleum products

It was noted that ports identified in Lloyds List (2009) as being oil terminals or only having facilities for bulk liquid and petroleum did not report any traffic values. As oil forms an important aspect of maritime trade, data from the CIA's *World Factbook* website were used as a basis for calculating area. These data represent the total oil exported in barrels per day (bbl/day) at national level, including both crude oil and oil products, and was translated into area ($km^2$) using the following equation:

$$Y = (\text{bbl/day} * 50)/ 30 * 10^6 \qquad \text{Eq.2}$$

$Y$ = area ($km^2$)
bbl/day = Number of barrels per day as reported by the CIA *World Factbook*[13]
50 = conversion factor of 1 barrel a day is 50 tons a year[14]
30 * 106 = Tonnage equivalent for bulk liquids and petroleum that can be handled in 1km2 (IPCC 1990)

### A2.2.7 Amalgamating data

Areas were derived for individual port areas by adding the tonnage and TEU area equivalent values calculated using the method described in Section A2.2. These were then aggregated to country level and added to the area equivalent for oil exports to provide a total area estimate per country. Small island counties with no area calculated by these methods but that had listed ports were given a nominal area of 0.1 $km^2$; larger countries were assigned the areas from the IPCC (1990) report to represent a minimum area. Country-level data were then summed according to the World Bank geographic regions.

### A2.2.8 Costs of upgrade

The cost of the upgrade to port ground levels is based on that reported in IPCC (1990) of $15 million per $km^2$ to raise ground levels by 1m. This was based on Dutch procedures including design, execution, taxes, levies and fees and the assumption that the operation would take place as one event. It is likely that these costs are overestimated for some countries and underestimated for others. At the scale of this investigation, these discrepancies will largely balance out. To standardize the results, costs were inflated from 1990 to 1995 using the U.S. Retail Price Inflation (Annual Average), which shows a cumulative inflation increase of 22.89 percent over this period. This inflation

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[12] See http://www.emase.co.uk/data/cont.html, http://www.freightraders.co.nz/containerspecs.html,and http://www.bslcontainers.com/products41.php).

[13] https://www.cia.gov/library/publications/the-world-factbook/rankorder/2176rank.html#.

[14] http://www.eppo.go.th/ref/UNIT-OIL.html.

### TABLE A2.1. ESTIMATED REGIONAL COSTS OF PORT UPGRADE COSTS BASED ON ELEVATING PORT AREA FOR HIGH, MEDIUM, AND LOW SEA-LEVEL SCENARIOS TO 2050

(High-income countries are excluded)

| *Region* | *Total port area ($km^2$)* | *Costs of port raising, by Sea-level rise scenario (billion dollars, at 2005 prices)* | | |
|---|---|---|---|---|
| | | *Low (15.6cm)* | *Medium (28.5cm)* | *High (37.8cm)* |
| East Asia & Pacific | 1,124 | 4.4 | 7.3 | 9.7 |
| Latin America & Caribbean | 385 | 1.4 | 2.5 | 3.3 |
| Europe & Central Asia | 251 | 0.9 | 1.6 | 2.2 |
| South Asia | 243 | 0.9 | 1.6 | 2.1 |
| Middle East & North Africa | 134 | 0.5 | 0.9 | 1.2 |
| Sub-Saharan Africa | 127 | 0.5 | 0.8 | 1.1 |
| **Total** | **2,263** | 8.5 | 14.7 | 19.6 |

increased costs from $15 million to $18.5 million per $km^2$ to raise ground levels by 1m, or $0.185 million per $km^2$ to raise ground levels by 1 cm.

### A2.2.9 Results/Discussion

The results shown in Table A2.1 are for the scenarios in Section 3.1.2. They show a total cost for adaptation to projected sea-level rise by 2050 of between $6,855 million and $15,822 million for countries of low, lower middle, and upper middle income as defined by the World Bank. The region with the largest area is East Asia and the Pacific, largely due to the rapid growth in China's maritime trade, as evidenced by rapid port expansion in this country over recent years.

On an individual country basis, estimation errors can have a significant effect on adaptation costs, but the regionalized figure gives a valid indication of the scale of potential costs. However, the values in the table should be regarded as minimums for several reasons:

- The database contains 1,220 identified ports, of which 1,135 are located either on the coast or offshore; only 501 of these reported either tonnage or TEU data. These data are derived largely from imports and exports, excluding port areas mostly linked to domestic trade.
- Port areas for 13 small island states[15] and eight mainland countries[16] were approximated using values from the IPCC (1990) report.
- Traffic values in Lloyds List (2009) and oil values from the CIA *World Factbook* are reported for a single year. These values vary annually, and the number reported may not represent the actual capacity of the port. However, as global maritime trade is expected to continue to increase, any future calculations would be expected to increase port area.

Comparison of port areas with the IPCC (1990) report is difficult due to changes in both the reporting and nature of maritime traffic. However, if China (which shows atypical growth) is excluded, on average port areas are 2.6 times larger; this is commensurate with the increase in the amount of goods handled (see Figure A1-1).

It is important to remember that this report does not include any cost/benefit considerations. It is calculated on maintaining current risk levels and therefore gives no indication of vulnerability.

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[15] Comorros, Fiji, Kiribati, Marshall Islands, Mayotte, Micronesia, Palau, São Tomé and Principe, Solomon Islands, St. Kitts and Nevis, St. Vincent and the Grenadines, Tonga, and Vanuatu.

[16] Gabon, Guinea-Bissau, Guyana, Iraq, Democratic Republic of Korea, Liberia, Myanmar, and Suriname.

# APPENDIX 3. RESULTS BY WORLD BANK REGION (EXCLUDING HIGH-INCOME COUNTRIES)

Tables are presented for each scenario, including (1) no-rise SLR, (2) low SLR, (3) medium SLR, (4) high SLR, (5) high SLR with increased tropical cyclones, and (6) high SLR with constant coastal populations. The following abbreviations are used for the regions:

- EAP – East Asia and Pacific
- ECA – Europe and Central Asia
- LAC – Latin America and Caribbean
- MNA – Middle East and North Africa
- SAS – South Asia
- SSA – Sub-Saharan Africa

## TABLE A3.1. INCREMENTAL ANNUAL COSTS OF ADAPTATION FOR COASTAL PROTECTION AND RESIDUAL DAMAGES BY REGION AND DECADE FOR THE NO-RISE SLR SCENARIO

(Billion dollars per year at 2005 prices, no discounting; high-income countries are excluded.)

| | | *World Bank Regions* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *EAP* | | *ECA* | | *LAC* | | *MNA* | | *SAS* | | *SSA* | | *Total* |
| **Total adaptation costs:** | | | | | | | | | | | | | | |
| Beach nourishment | 2010s | 0.03 | | 0.02 | | 0.04 | | 0.01 | | 0.02 | | 0.05 | | 0.17 |
| | 2020s | 0.03 | | 0.03 | | 0.05 | | 0.02 | | 0.02 | | 0.05 | | 0.2 |
| | 2030s | 0.03 | | 0.03 | | 0.05 | | 0.02 | | 0.02 | | 0.06 | | 0.21 |
| | 2040s | 0.04 | | 0.04 | | 0.05 | | 0.02 | | 0.02 | | 0.06 | | 0.23 |
| Port upgrades | 2010s | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 |
| | 2020s | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 |
| | 2030s | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 |
| | 2040s | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 | | 0.00 |
| | | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | |
| River dikes | 2010s | 0.07 | 0.01 | 0.00 | 0.00 | 0.08 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 |
| | 2020s | 0.02 | 0.01 | 0.00 | 0.00 | 0.07 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.18 |
| | 2030s | 0.02 | 0.01 | 0.00 | 0.00 | 0.06 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.18 |
| | 2040s | 0.02 | 0.01 | 0.00 | 0.00 | 0.05 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.17 |
| Sea dikes | 2010s | 1.79 | 0.37 | 0.22 | 0.08 | 1.54 | 0.74 | 0.22 | 0.04 | 0.34 | 0.08 | 0.62 | 0.22 | 6.26 |
| | 2020s | 1.12 | 0.49 | 0.15 | 0.10 | 1.34 | 0.87 | 0.19 | 0.06 | 0.29 | 0.11 | 0.45 | 0.26 | 5.43 |
| | 2030s | 1.07 | 0.60 | 0.13 | 0.11 | 1.28 | 1.00 | 0.13 | 0.07 | 0.29 | 0.14 | 0.45 | 0.31 | 5.58 |
| | 2040s | 0.91 | 0.70 | 0.10 | 0.12 | 1.03 | 1.11 | 0.10 | 0.09 | 0.27 | 0.17 | 0.39 | 0.35 | 5.34 |
| **Total residual damage costs:** | | | | | | | | | | | | | | |
| Land loss, migration, and sea and river flood costs | 2010s | 3.11 | | 0.13 | | 0.71 | | 0.11 | | 1.18 | | 0.08 | | 5.3 |
| | 2020s | 4.01 | | 0.15 | | 0.87 | | 0.15 | | 1.90 | | 0.12 | | 7.2 |
| | 2030s | 4.89 | | 0.17 | | 1.08 | | 0.21 | | 2.80 | | 0.18 | | 9.3 |
| | 2040s | 6.23 | | 0.18 | | 1.08 | | 0.28 | | 3.15 | | 0.26 | | 11.1 |

*Note*

## TABLE A3.2. INCREMENTAL COSTS OF ADAPTATION FOR COASTAL PROTECTION AND RESIDUAL DAMAGES BY REGION AND DECADE FOR THE LOW SLR SCENARIO

(Billion dollars per year at 2005 prices, no discounting; high-income countries are excluded)

| | | *World Bank Regions* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *EAP* | | *ECA* | | *LAC* | | *MNA* | | *SAS* | | *SSA* | | *Total* |
| **Total adaptation costs:** | | | | | | | | | | | | | | |
| Beach nourishment | 2010s | 0.26 | | 0.06 | | 0.39 | | 0.07 | | 0.11 | | 0.36 | | 1.25 |
| | 2020s | 0.30 | | 0.08 | | 0.48 | | 0.09 | | 0.13 | | 0.43 | | 1.51 |
| | 2030s | 0.35 | | 0.10 | | 0.58 | | 0.10 | | 0.15 | | 0.51 | | 1.79 |
| | 2040s | 0.41 | | 0.13 | | 0.70 | | 0.12 | | 0.17 | | 0.61 | | 2.14 |
| Port upgrades | 2010s | 0.11 | | 0.03 | | 0.02 | | 0.02 | | 0.01 | | 0.01 | | 0.21 |
| | 2020s | 0.11 | | 0.03 | | 0.02 | | 0.02 | | 0.01 | | 0.01 | | 0.21 |
| | 2030s | 0.11 | | 0.03 | | 0.02 | | 0.02 | | 0.01 | | 0.01 | | 0.21 |
| | 2040s | 0.11 | | 0.03 | | 0.02 | | 0.02 | | 0.01 | | 0.01 | | 0.21 |
| | | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | |
| River dikes | 2010s | 0.03 | 0.00 | 0.00 | 0.00 | 0.11 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.17 |
| | 2020s | 0.03 | 0.00 | 0.00 | 0.00 | 0.11 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.17 |
| | 2030s | 0.03 | 0.00 | 0.00 | 0.00 | 0.11 | 0.02 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.18 |
| | 2040s | 0.03 | 0.01 | 0.00 | 0.00 | 0.11 | 0.02 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.19 |
| Sea dikes | 2010s | 2.79 | 0.29 | 0.89 | 0.09 | 3.02 | 0.31 | 0.34 | 0.04 | 0.53 | 0.05 | 1.04 | 0.11 | 9.50 |
| | 2020s | 2.79 | 0.57 | 0.86 | 0.18 | 3.04 | 0.61 | 0.38 | 0.07 | 0.53 | 0.11 | 1.05 | 0.21 | 10.40 |
| | 2030s | 2.80 | 0.84 | 0.85 | 0.26 | 3.07 | 0.92 | 0.37 | 0.11 | 0.53 | 0.16 | 1.07 | 0.32 | 11.30 |
| | 2040s | 2.80 | 1.12 | 0.84 | 0.35 | 3.09 | 1.23 | 0.37 | 0.15 | 0.53 | 0.21 | 1.09 | 0.43 | 12.21 |
| **Total residual damage costs:** | | | | | | | | | | | | | | |
| Land loss, migration, and sea and river flood costs | 2010s | 0.21 | | 0.01 | | 0.04 | | 0.01 | | 0.03 | | 0.00 | | 0.30 |
| | 2020s | 0.42 | | 0.02 | | 0.08 | | 0.01 | | 0.05 | | 0.01 | | 0.59 |
| | 2030s | 0.45 | | 0.03 | | 0.09 | | 0.03 | | 0.18 | | 0.01 | | 0.79 |
| | 2040s | 0.49 | | 0.03 | | 0.21 | | 0.03 | | 0.50 | | 0.02 | | 1.28 |

*Note*: 2010s=2010–19, 2120s=2020–29, 2030s=2030–39, and 2040s=2040–49; CC=Capital Cost, and MC=Maintenance Cost

## TABLE A3.3. INCREMENTAL ANNUAL COSTS OF ADAPTATION FOR COASTAL PROTECTION AND RESIDUAL DAMAGES BY REGION AND DECADE FOR THE MEDIUM SLR SCENARIO

Billion dollars per year at 2005 prices, no discounting; high-income countries are excluded.

| | | *World Bank Regions* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *EAP* | | *ECA* | | *LAC* | | *MNA* | | *SAS* | | *SSA* | | *Total* |
| **Total adaptation costs:** | | | | | | | | | | | | | | |
| Beach nourishment | 2010s | 0.45 | | 0.13 | | 0.67 | | 0.11 | | 0.19 | | 0.62 | | 2.17 |
| | 2020s | 0.56 | | 0.18 | | 0.87 | | 0.15 | | 0.24 | | 0.79 | | 2.79 |
| | 2030s | 0.72 | | 0.26 | | 1.14 | | 0.18 | | 0.31 | | 1.02 | | 3.63 |
| | 2040s | 0.89 | | 0.34 | | 1.44 | | 0.22 | | 0.38 | | 1.28 | | 4.55 |
| Port upgrades | 2010s | 0.18 | | 0.06 | | 0.04 | | 0.04 | | 0.02 | | 0.02 | | 0.37 |
| | 2020s | 0.18 | | 0.06 | | 0.04 | | 0.04 | | 0.02 | | 0.02 | | 0.37 |
| | 2030s | 0.18 | | 0.06 | | 0.04 | | 0.04 | | 0.02 | | 0.02 | | 0.37 |
| | 2040s | 0.18 | | 0.06 | | 0.04 | | 0.04 | | 0.02 | | 0.02 | | 0.37 |
| | | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | |
| River dikes | 2010s | 0.07 | 0.00 | 0.01 | 0.00 | 0.25 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.02 | 0.00 | 0.37 |
| | 2020s | 0.07 | 0.01 | 0.01 | 0.00 | 0.25 | 0.02 | 0.00 | 0.00 | 0.01 | 0.00 | 0.02 | 0.00 | 0.39 |
| | 2030s | 0.07 | 0.01 | 0.01 | 0.00 | 0.26 | 0.04 | 0.00 | 0.00 | 0.01 | 0.00 | 0.02 | 0.00 | 0.42 |
| | 2040s | 0.07 | 0.01 | 0.01 | 0.00 | 0.26 | 0.05 | 0.00 | 0.00 | 0.02 | 0.00 | 0.02 | 0.00 | 0.44 |
| Sea dikes | 2010s | 6.39 | 0.62 | 2.05 | 0.20 | 6.92 | 0.67 | 0.78 | 0.08 | 1.22 | 0.12 | 2.39 | 0.23 | 21.67 |
| | 2020s | 6.40 | 1.26 | 1.99 | 0.40 | 7.06 | 1.37 | 0.85 | 0.16 | 1.23 | 0.24 | 2.43 | 0.47 | 23.86 |
| | 2030s | 6.42 | 1.90 | 1.96 | 0.59 | 7.15 | 2.09 | 0.84 | 0.24 | 1.23 | 0.36 | 2.47 | 0.72 | 25.97 |
| | 2040s | 6.43 | 2.54 | 1.96 | 0.79 | 7.18 | 2.80 | 0.84 | 0.33 | 1.24 | 0.49 | 2.54 | 0.97 | 28.11 |
| **Total residual damage costs:** | | | | | | | | | | | | | | |
| Land loss, migration, and sea and river flood costs | 2010s | 0.31 | | 0.01 | | 0.12 | | 0.01 | | 0.04 | | 0.00 | | 0.49 |
| | 2020s | 0.60 | | 0.03 | | 0.14 | | 0.02 | | 0.10 | | 0.02 | | 0.91 |
| | 2030s | 1.11 | | 0.05 | | 0.23 | | 0.04 | | 0.28 | | 0.03 | | 1.74 |
| | 2040s | 1.34 | | 0.08 | | 0.45 | | 0.07 | | 0.94 | | 0.04 | | 2.92 |

*Note*: 2010s=2010–19, 2120s=2020–29, 2030s=2030–39, and 2040s=2040–49; CC=Capital Cost, and MC=Maintenance Cost

## TABLE A3.4. INCREMENTAL ANNUAL COSTS OF ADAPTATION FOR COASTAL PROTECTION AND RESIDUAL DAMAGES BY REGION AND DECADE FOR THE HIGH SLR SCENARIO

Billion dollars per year at 2005 prices, no discounting; high-income countries are excluded.

| | | *World Bank Regions* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *EAP* | | *ECA* | | *LAC* | | *MNA* | | *SAS* | | *SSA* | | *Total* |
| **Total adaptation costs:** | | | | | | | | | | | | | | |
| Beach nourishment | 2010s | 0.58 | | 0.16 | | 0.84 | | 0.13 | | 0.25 | | 0.78 | | 2.74 |
| | 2020s | 0.77 | | 0.25 | | 1.17 | | 0.19 | | 0.33 | | 1.07 | | 3.78 |
| | 2030s | 1.00 | | 0.36 | | 1.55 | | 0.24 | | 0.43 | | 1.40 | | 4.98 |
| | 2040s | 1.34 | | 0.50 | | 2.09 | | 0.31 | | 0.58 | | 1.87 | | 6.69 |
| Port upgrades | 2010s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | 2020s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | 2030s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | 2040s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | |
| River dikes | 2010s | 0.10 | 0.00 | 0.01 | 0.00 | 0.37 | 0.02 | 0.00 | 0.00 | 0.02 | 0.00 | 0.02 | 0.00 | 0.54 |
| | 2020s | 0.10 | 0.01 | 0.01 | 0.00 | 0.38 | 0.04 | 0.00 | 0.00 | 0.02 | 0.00 | 0.03 | 0.00 | 0.59 |
| | 2030s | 0.11 | 0.02 | 0.01 | 0.00 | 0.39 | 0.05 | 0.00 | 0.00 | 0.02 | 0.00 | 0.03 | 0.00 | 0.63 |
| | 2040s | 0.11 | 0.02 | 0.01 | 0.00 | 0.40 | 0.07 | 0.00 | 0.00 | 0.02 | 0.00 | 0.03 | 0.01 | 0.67 |
| Sea dikes | 2010s | 9.52 | 0.86 | 3.06 | 0.28 | 10.4 | 0.94 | 1.17 | 0.11 | 1.83 | 0.17 | 3.58 | 0.32 | 32.2 |
| | 2020s | 9.55 | 1.82 | 2.96 | 0.58 | 10.6 | 1.99 | 1.29 | 0.23 | 1.84 | 0.35 | 3.65 | 0.69 | 35.6 |
| | 2030s | 9.58 | 2.78 | 2.94 | 0.87 | 10.7 | 3.06 | 1.25 | 0.36 | 1.85 | 0.53 | 3.73 | 1.06 | 38.7 |
| | 2040s | 9.59 | 3.73 | 2.95 | 1.17 | 10.7 | 4.13 | 1.25 | 0.48 | 1.85 | 0.72 | 3.83 | 1.44 | 41.8 |
| **Total residual damage costs:** | | | | | | | | | | | | | | |
| Land loss, migration, and sea and river flood costs | 2010s | 0.37 | | 0.01 | | 0.14 | | 0.01 | | 0.05 | | 0.01 | | 0.59 |
| | 2020s | 0.79 | | 0.03 | | 0.20 | | 0.03 | | 0.13 | | 0.03 | | 1.21 |
| | 2030s | 1.30 | | 0.06 | | 0.33 | | 0.06 | | 0.36 | | 0.05 | | 2.16 |
| | 2040s | 1.88 | | 0.10 | | 0.63 | | 0.12 | | 1.48 | | 0.07 | | 4.28 |

*Note*: 2010s = 2010–19, 2120s = 2020–29, 2030 s= 2030–39, and 2040s = 2040–49; CC = Capital Cost, and MC=Maintenance Cost

## TABLE A3.5. INCREMENTAL ANNUAL COSTS OF ADAPTATION FOR COASTAL PROTECTION AND RESIDUAL DAMAGES BY REGION AND DECADE FOR THE HIGH SLR SCENARIO WITH CYCLONES

(Billion dollars per year at 2005 prices, no discounting; high-income countries are excluded.)

| | | *World Bank Regions* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *EAP* | | *ECA* | | *LAC* | | *MNA* | | *SAS* | | *SSA* | | *Total* |
| **Total adaptation costs:** | | | | | | | | | | | | | | |
| Beach nourishment | 2010s | 0.58 | | 0.16 | | 0.84 | | 0.13 | | 0.25 | | 0.78 | | 2.74 |
| | 2020s | 0.77 | | 0.25 | | 1.17 | | 0.19 | | 0.33 | | 1.07 | | 3.78 |
| | 2030s | 1.00 | | 0.36 | | 1.55 | | 0.24 | | 0.43 | | 1.40 | | 4.98 |
| | 2040s | 1.34 | | 0.50 | | 2.09 | | 0.31 | | 0.58 | | 1.87 | | 6.69 |
| Port upgrades | 2010s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | 2020s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | 2030s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | 2040s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | |
| River dikes | 2010s | 0.11 | 0.01 | 0.01 | 0.00 | 0.37 | 0.02 | 0.00 | 0.00 | 0.02 | 0.00 | 0.03 | 0.00 | 0.57 |
| | 2020s | 0.12 | 0.01 | 0.01 | 0.00 | 0.38 | 0.04 | 0.00 | 0.00 | 0.03 | 0.00 | 0.03 | 0.00 | 0.62 |
| | 2030s | 0.12 | 0.02 | 0.01 | 0.00 | 0.39 | 0.05 | 0.00 | 0.00 | 0.03 | 0.00 | 0.03 | 0.00 | 0.65 |
| | 2040s | 0.13 | 0.02 | 0.01 | 0.00 | 0.40 | 0.07 | 0.00 | 0.00 | 0.03 | 0.01 | 0.03 | 0.01 | 0.71 |
| Sea dikes | 2010s | 10.4 | 1.04 | 3.09 | 0.29 | 10.74 | 1.01 | 1.17 | 0.11 | 2.01 | 0.20 | 3.68 | 0.34 | 34.0 |
| | 2020s | 10.6 | 2.09 | 3.00 | 0.59 | 11.00 | 2.10 | 1.29 | 0.23 | 2.05 | 0.40 | 3.78 | 0.71 | 37.8 |
| | 2030s | 10.7 | 3.16 | 2.98 | 0.88 | 11.09 | 3.21 | 1.25 | 0.36 | 2.09 | 0.61 | 3.88 | 1.10 | 41.3 |
| | 2040s | 10.8 | 4.24 | 2.99 | 1.18 | 11.13 | 4.32 | 1.25 | 0.48 | 2.12 | 0.82 | 3.99 | 1.49 | 44.8 |
| **Total residual damage costs:** | | | | | | | | | | | | | | |
| Land loss, migration, and sea and river flood costs | 2010s | 0.37 | | 0.01 | | 0.14 | | 0.01 | | 0.05 | | 0.01 | | 0.59 |
| | 2020s | 0.79 | | 0.03 | | 0.20 | | 0.03 | | 0.13 | | 0.03 | | 1.21 |
| | 2030s | 1.30 | | 0.06 | | 0.33 | | 0.06 | | 0.36 | | 0.05 | | 2.16 |
| | 2040s | 1.88 | | 0.10 | | 0.63 | | 0.12 | | 1.48 | | 0.07 | | 4.28 |

## TABLE A3.6. INCREMENTAL ANNUAL COSTS OF ADAPTATION FOR COASTAL PROTECTION AND RESIDUAL DAMAGES BY REGION AND DECADE FOR THE HIGH SLR SCENARIO WITH NO POPULATION GROWTH

Billion dollars per year at 2005 prices, no discounting; high-income countries are excluded.

| | | *World Bank Regions* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *EAP* | | *ECA* | | *LAC* | | *MNA* | | *SAS* | | *SSA* | | *Total* |
| **Total adaptation costs:** | | | | | | | | | | | | | | |
| Beach nourishment | 2010s | 0.58 | | 0.16 | | 0.84 | | 0.13 | | 0.24 | | 0.78 | | 2.73 |
| | 2020s | 0.77 | | 0.25 | | 1.16 | | 0.18 | | 0.33 | | 1.07 | | 3.76 |
| | 2030s | 0.99 | | 0.36 | | 1.55 | | 0.23 | | 0.42 | | 1.40 | | 4.95 |
| | 2040s | 1.33 | | 0.50 | | 2.08 | | 0.30 | | 0.57 | | 1.86 | | 6.64 |
| Port upgrades | 2010s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | 2020s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | 2030s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | 2040s | 0.24 | | 0.08 | | 0.05 | | 0.05 | | 0.03 | | 0.03 | | 0.49 |
| | | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | CC | MC | |
| River dikes | 2010s | 0.09 | 0.00 | 0.02 | 0.00 | 0.40 | 0.01 | 0.00 | 0.00 | 0.02 | 0.00 | 0.02 | 0.00 | 0.56 |
| | 2020s | 0.10 | 0.01 | 0.03 | 0.00 | 0.38 | 0.04 | 0.00 | 0.00 | 0.02 | 0.00 | 0.03 | 0.00 | 0.61 |
| | 2030s | 0.11 | 0.01 | 0.02 | 0.00 | 0.39 | 0.06 | 0.00 | 0.00 | 0.02 | 0.00 | 0.03 | 0.00 | 0.64 |
| | 2040s | 0.13 | 0.02 | 0.03 | 0.00 | 0.40 | 0.08 | 0.00 | 0.00 | 0.02 | 0.00 | 0.03 | 0.01 | 0.72 |
| Sea dikes | 2010s | 9.45 | 0.86 | 3.25 | 0.29 | 10.14 | 0.91 | 1.14 | 0.10 | 1.83 | 0.17 | 3.52 | 0.32 | 31.98 |
| | 2020s | 9.50 | 1.81 | 3.33 | 0.62 | 10.49 | 1.96 | 1.16 | 0.22 | 1.84 | 0.35 | 3.67 | 0.68 | 35.63 |
| | 2030s | 9.55 | 2.76 | 3.39 | 0.96 | 10.54 | 3.01 | 1.18 | 0.34 | 1.85 | 0.53 | 3.72 | 1.05 | 38.88 |
| | 2040s | 9.75 | 3.73 | 3.41 | 1.30 | 10.59 | 4.07 | 1.18 | 0.45 | 1.85 | 0.72 | 3.72 | 1.43 | 42.20 |
| **Total residual damage costs:** | | | | | | | | | | | | | | |
| Land loss, migration, and sea and river flood costs | 2010s | 0.26 | | 0.01 | | 0.10 | | 0.01 | | 0.05 | | 0.00 | | 0.43 |
| | 2020s | 0.62 | | 0.02 | | 0.14 | | 0.02 | | 0.09 | | 0.01 | | 0.90 |
| | 2030s | 1.28 | | 0.05 | | 0.22 | | 0.03 | | 0.20 | | 0.03 | | 1.81 |
| | 2040s | 1.81 | | 0.11 | | 0.39 | | 0.06 | | 0.61 | | 0.04 | | 3.02 |

Note: 2010s = 2010–19, 2120s = 2020–29, 2030s = 2030–39, and 2040s = 2040–49; CC = Capital Cost, and MC = Maintenance Cost

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