Policy Research Working Paper 8745

Beyond the Gap
How Countries Can Afford the Infrastructure They Need While Protecting the Planet

Background Paper

Global Investment Costs for Coastal Defense through the 21st Century

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WORLD BANK GROUP
Sustainable Development Practice Group
Office of the Chief Economist
February 2019

Policy Research Working Paper 8745

Abstract

Sea-level rise threatens low-lying areas around the world's coasts with increased coastal flooding during storms. One response to this challenge is to build or upgrade coastal flood defenses. This report examines the potential investment costs of such an adaptation strategy applied globally over the 21st century for sea-level rise scenarios consistent with three Representative Concentration Pathways and 3 Shared Socioeconomic Pathways. For all the protection models considered, much less than half of the world's coast is protected. The total defense costs are significantly higher than earlier estimates, amounting to as much as US$18.3 trillion. With cost-benefit analysis, there are large uncertainties and empirical observations of protection standards are limited. Hence, the estimates should be considered as indicative, and this remains an important topic for future research. Further, building defenses is not a one-off capital investment. Over the 21st century, the cost of a comprehensive protection strategy is dominated by maintenance costs in all the cases considered in this report. This indicates that in addition to capital investment, the development of appropriate institutions and governance mechanisms to deliver maintenance, as well as the necessary funding streams, are essential for such a protection-based adaptation strategy to be effective.

This paper was commissioned by the World Bank Group's Chief Economist office for Sustainable Development Practice Group and is a background paper for the World Bank Group's report: *"Beyond the Gap: How Countries Can Afford the Infrastructure They Need While Protecting the Planet."* It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/research. The authors may be contacted at R.J.Nicholls@soton.ac.uk.

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JEL Classification: Q54

Keywords: Sea-level rise; coastal flooding; adaptation costs; protection

1 Introduction

This report evaluates plausible cost estimates for coastal defense infrastructure against sea and related flooding that reflect present and future risks due to changes in population, the economy and climate-induced sea-level rise and their uncertainties. This includes consideration of a range of different possible defense investment strategies. Hence, this analysis recognizes that there is not a single protection cost estimate and actual protection costs will depend on multiple factors, including the aims of the defense investment. The analysis is reported at the scale of World Bank regions and the globe.

The analysis considers three distinct defense technologies (1) sea dikes, (2) river dikes, and (3) surge barriers. These are combined into two defense approaches which we termed (1) open protection (a combination of sea dikes and river dikes only) and (2) closed protection (sea dikes and the lowest cost option contrasting surge barriers and river dikes. Existing defenses are estimated based on assumptions applied in earlier global estimates of global flood risk. The defense approaches are applied using adaptation strategies (or scenarios) rather than economic optimization approaches and ask what the protection costs would be if we followed a pre-defined strategy at a global scale. Hence, we aim to develop a set of capital investment and maintenance needs for coastal defense infrastructure for coastal flooding that provides a set of protection services for a range of realistic demands/conditions.

All costs are reported in 2014 undiscounted US dollars.

The report is structured as follows. Section 2 briefly reviews previous global assessments of protection costs, including their assumptions and the cost estimates. Section 3 presents the methodology, including the analytical framework, the DIVA model and how it was applied and the cost estimates that are employed. Section 4 presents the results, including the length of defenses and their costs including capital and maintenance costs. Section 5 discusses the implications of the results and the potential next steps, and Section 6 concludes. There are four Appendixes. Appendix 1 contains a range of additional results to augment those in the main report. Appendix 2 presents the new analysis of sea dike unit cost, drawing on all the available experience. Appendix 3 provides the unit dike costs by country. Appendix 4 provides summary details on the DIVA model.

2 Previous Studies

Compared to other issues relevant to adaptation to climate change, there is a long history of assessments of the protection costs against sea-level rise. These go back to the pioneering study of Dronkers et al. (1990) which supported the First Intergovernmental Panel on Climate Change (IPCC) Assessment. This situation probably reflects the long history of coastal defense in places such as Northwest Europe and East Asia against storm-induced coastal flooding. Hence, as the threat of climate-induced sea-level rise emerged there was an evidence base and practical experience to draw upon. Hence, coastal zones were some of the first areas to consider climate adaptation, particularly protection and its costs.

Table 1. A summary of previous estimates of global protection costs against sea-level rise.

Study	Cost Estimate (2014 US dollars)	Comments
Dronkers et al., 1990	$815 billion	For 1-m rise, capital costs mainly reflecting flood protection, but other aspects (e.g. port upgrade) also considered.
Hoozemans et al., 1993	$1,630 billion	For 1-m rise, as Dronkers et al. (1990) with a more realistic consideration of storm surge hazard and resulting protection needs.
Fankhauser, 1995	$284 billion (OECD only)	For 1-m rise, using Dronkers et al. (1990) data and capital costs of optimal protection. Not global.
Bijlsma et al., 1996	At least $590 billion (NOT global)	For 1-m rise. Aggregation of 17 national studies in their Table 9.3, so not globally comprehensive. All types of adaptation considered, but floods dominates protection costs. Capital costs only.
Tol, 2002	$1,524 billion	For 1-m rise applying cost-benefit analysis to the protection decision using the FUND model. Capital costs only. Protects 348,000 km of the world's coastline.
Hallegatte et al. 2013	$50 billion per year (NOT Global; to 2050)	Considers the 136 largest coastal cities to 2050, and scales up from a few recent city examples, rather than using unit cost estimates as most other studies considered here.
Hinkel et al. 2014	$32-$84 billion/year (for RCP8.5) (costs for the year 2100) Accumulated costs: $1.9-$4.2 trillion for 21st century	Based on a demand for safety analysis for protection need (Yohe and Tol, 2002) using the DIVA model. Reports capital costs and maintenance costs of dikes built since 2000. (For RCP2.6 corresponding costs are $14-$37 billion/year in the year 2100 and accumulated costs US$1.3 trillion - US$ 2.8 trillion). Protects about 500,000 km of the world's estimated 1,000,000 km coastline length. Capital and maintenance costs.

The available protection cost estimates are summarized in Table 1. They nearly all depend on estimates of the length of coast which requires protection and unit costs for that protection. The studies are not independent, and most studies build on earlier studies in terms of adding incremental improvement on issues such as the length of protection, except Bijlsma et al (1996) and Hallegatte et al (2003) which consider different approaches. The unit costs of defense types have often been shared between studies with the original Dronkers et al (1990) costs being influential (see Appendix 1).

While the costs reported in Table 1 are large in absolute terms, in relative terms they are quite modest, especially when compared to the value of assets and the size of population found in the coastal zone (e.g., Hinkel et al., 2014; Diaz, 2016). This shows that coastal protection has a great potential to reduce the human costs of sea-level rise, as the studies in Table 1 all generally conclude. A caveat on that conclusion is the loss of coastal ecosystems which are generally degraded by hard defenses. Assessments such as Hoozemans et al (1993), Tol (2002) and Diaz (2016) attempt to address this issue in their analysis by considering changes to coastal wetlands in addition to protection and other costs.

3 Methodology

Here we follow a similar strategy to the studies in Table 1, and determine lengths of coast that require protection and then estimate the costs of this using unit cost estimates, as appropriate (Appendices 2 and 3). The analysis is conducted within the framework of the Dynamic Interactive Vulnerability Assessment (DIVA) Model (described in Appendix 4) which has been applied in earlier global assessments of coastal flooding (e.g., Hinkel et al., 2014), as well as contributing to global assessments of water security, including multiple forms of flooding (Sadoff et al., 2015). In this section, we first review the DIVA flood module. We then consider the adaptation measures and costs that are considered in the analysis. Then the methods to estimate current protection levels are considered: these define the baseline against which future defense investments occur. Next, we consider the adaptation strategies that we use which guide and illustrate the implications of the different investment choices that we might make, including the population living in the coastal zone and residual damages. Lastly, we consider the climate and socio-economic scenarios that are utilized.

The distinction between defense technologies, defense approaches and adaptation strategies is outlined in Table 2 and explained in detail in the following sections.

Table 2. A summary of the defense technologies, approaches and adaptation strategies employed in this study. Further details are explained in the text.

Defense Technologies	(1) Sea dikes
	(2) River dikes
	(3) Surge barriers
Defense Approaches	(1) Dike only protection
	(2) Dike and barrier protection
Adaptation Strategies	(1) Constant protection levels -- maintain current protection levels
	(2) Constant absolute flood risk -- maintain average

	annual losses
	(3) Constant relative flood risk -- maintain relative average annual losses
	(4) Risk intolerance -- keep relative average annual losses below 0.01% percent of local
	(5) Cost-benefit analysis -- compute the optimum protection level balancing flood damage to assets with protection costs to 2100, including capital and maintenance costs

3.1 The DIVA Flood Module

The methods for assessing global coastal flood risk are taken from Hinkel et al (2014). The impact of coastal extreme events is calculated with the DIVA flooding module (Figure 1) and the key data sets that are defined in Table 3. Impacts are expressed in terms of the mathematical expectation of flood damages under a given protection level for the 12,148 coastline segments defined in the DINAS-COAST database (Vafeidis et al., 2008) which describe the world's coasts with approximately 100 parameters per segment. Population exposure is obtained by overlaying the elevation data with population data (Table 3). Exposed population is translated into exposed assets by applying sub-national GDP per capita rates to the population data, followed by applying an assets-to-GDP ratio of 2.8. Present extreme water level distributions are assumed to be uniformly displaced upwards with relative sea-level rise, following 20th century observations (see Church et al., 2013). In addition to climate-induced sea-level rise, relative sea-level rise includes glacial isostatic adjustment and deltaic subsidence (Table 3). Current protection levels are taken from Sadoff et al. (2015) (see Table 4), who took protection levels for the biggest 136 coastal cities from Hallegatte et al. (2013) and complemented these through expert judgement for segments not associated to one of these cities. Protection level zero is assumed if the population density in the 1-in-100-years floodplain is lower than 30 people per km².

For residual damage and population living in the 100-year flood plain, the methods of Hinkel et al (2014) are used.

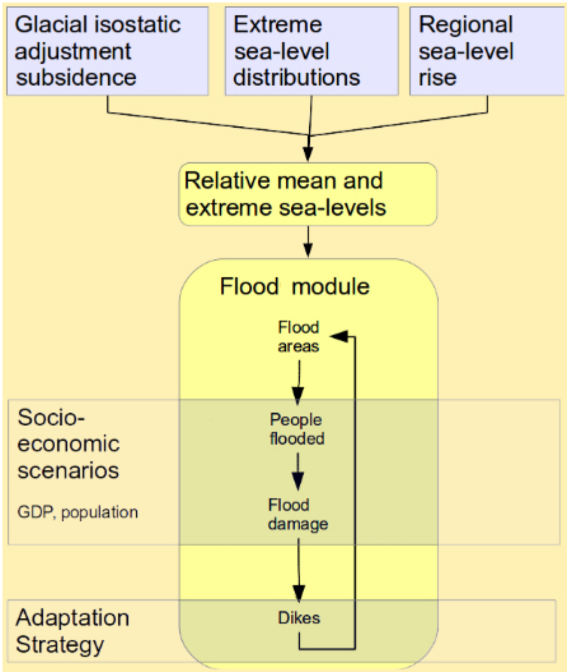

Figure 1. The DIVA Flood Module (following the approach of Hinkel et al., 2014).

Table 3: Data sets used within the DIVA flooding module in this study.

Data	**Dataset**
Elevation data	Shuttle radar topography mission (SRTM) (Rabus et al., 2003)
Population data	Global Rural-Urban Mapping Project (GRUMP) (CIESIN 2011)
Extreme water levels	Global Tide and Surge Reanalysis (GTSR) (Muis et al., 2016)
Glacial isostatic adjustment	ICE-5G (VM2) model (Peltier, 2004)
Delta subsidence	The DIVA delta dataset, taken from Ericson et al. (2006) where available (with some corrections such as Brown and Nicholls, 2015) and 2 mm/yr for deltas where no value is reported

3.2 Adaptation measures and costs considered

This report considers three main adaptation measures against coastal flooding due to current and future conditions, including sea-level rise:

a. **Sea dikes**: these are rigid coastal barriers built along the open coast and around lagoons to stop flooding as widely applied in Northwest Europe (e.g., the Netherlands), East Asia (e.g., China) and parts of North America (e.g., New Orleans). Synonyms include terms such as levees. They have been considered as the primary adaptation against coastal flooding in many earlier global assessments, including those described in Table 1.

b. **River dikes:** In addition to sea dikes we consider the protection that is required along rivers that are influenced by coastal extremes and sea-level rise, and might be flooded due to the backwater effect of the sea (Dronkers et al., 1990; Nicholls, 2010). Thus, rivers need to be protected in the area of their river mouth as illustrated by numerous dikes in coastal areas such as along the Rhine in the Netherlands or along the major rivers in coastal China. Only dikes that are required to address sea-level rise are considered here.
c. **Surge barriers:** This is an alternative approach to flood defense along rivers, and involves closing off rivers from the sea during an extreme event (Gilbert and Horner, 1984; Jonkman et al., 2013; Mooyaart and Jonkman, 2017). Globally storm surge barriers are quite limited in extent at the present time, only being found in a few places such as London (Thames Barrier), Rotterdam (Maeslantkering), Venice (Project MOSES) and New Orleans. However, there are many other places where surge barriers have been considered such as New York City (Hill et al., 2012), with these discussions intensified post Superstorm Sandy in 2012. Hence for the first time in global analysis of costs we consider surge barriers.

Protection on the open coast is always provided by sea dikes. River protection can be provided either by river dikes to the upstream limit of coastal effects (termed open protection), or by storm surge barriers (termed closed protection, Figure 2). In this report we analyze two different defense approaches, with the difference reflecting how river reaches are protected (where protection is applied):

a. ***dike only protection*** - all protection along all river mouths uses river dikes only, combined with river dikes on the open coast;
b. ***dike and barrier protection*** - for river mouths, a least cost selection is made between open and closed protection. For the least cost analysis, accumulated surge barrier costs (construction and maintenance cost) through the 21st century are considered versus the accumulated river dike costs (construction and maintenance cost) through 21st century.

The costs of each measure are assessed in terms of **capital costs** and **annual maintenance costs**. These costs are not discounted and are explained below.

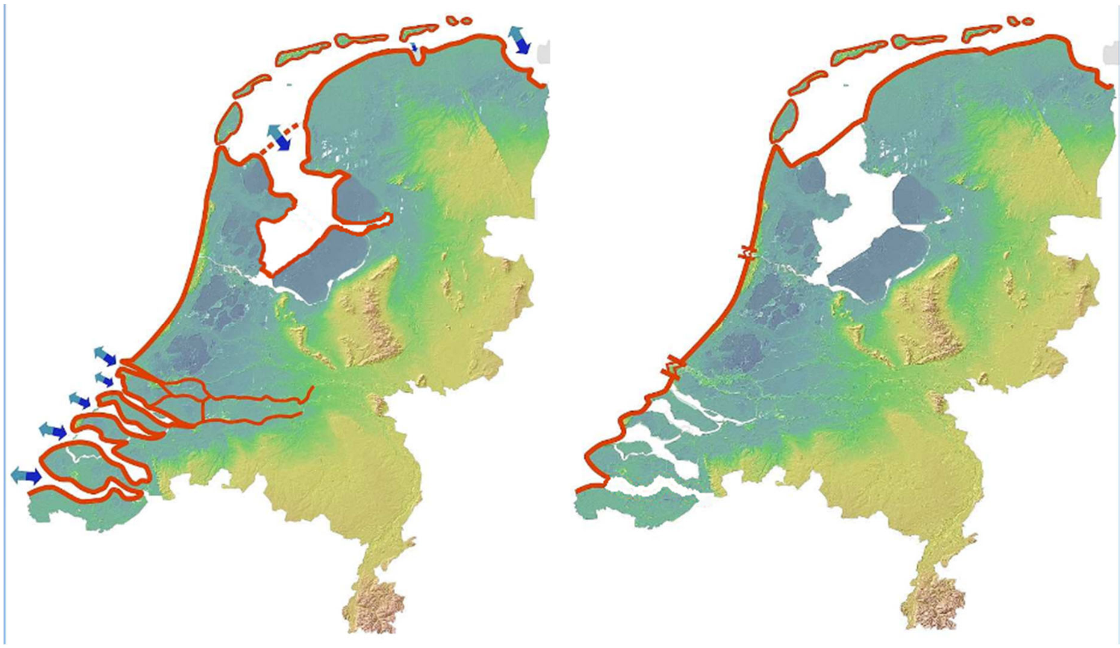

Figure 2: A comparison of open protection (left) versus closed protection (right), illustrated in the case of the Netherlands.

3.3 River and river distributary data set

For this report we consider, for the first time in such analyses, surge barriers as an alternative to river dikes. To support this, we developed an improved spatially explicit data set of river distributaries and potential barrier positions with a focus on the large coastal cities where a large proportion of the economic coastal risk (and protection demand) is located (Nicholls et al., 2008; Hallegatte et al., 2013). The data set was based on the original DIVA river data set (Vafeidis et al., 2008), which was extended to a 245-river data set. For each river we identified the main distributaries using Google Earth, defining a total of 434 distributaries (Figure 3).

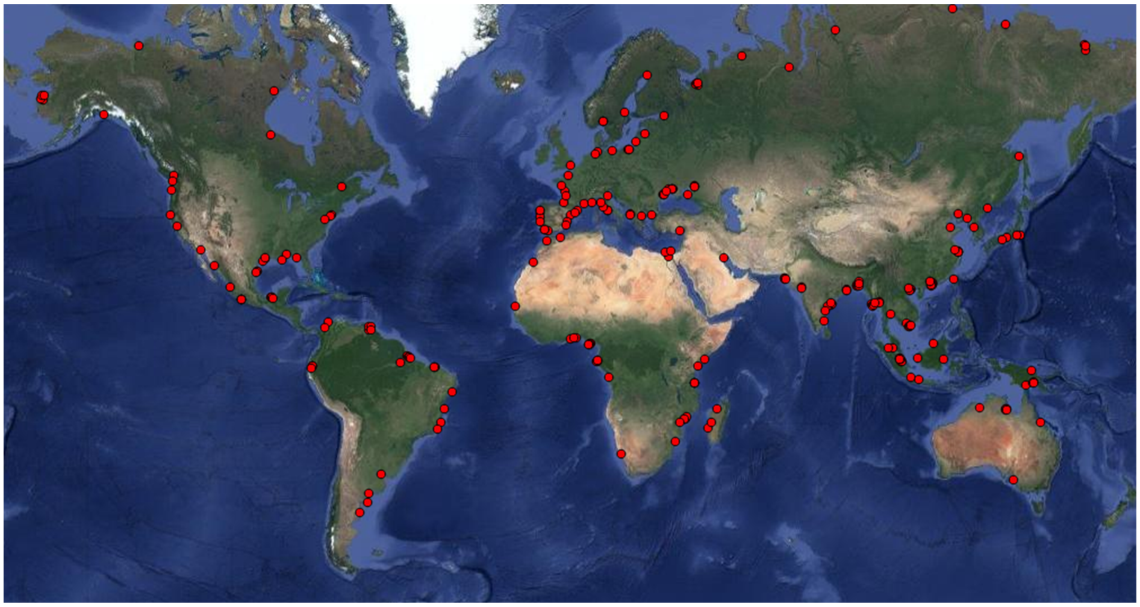

Figure 3: The river mouths (red dots) considered in this study.

Each river distributary is linked to one coastline segment, which was selected so that it captures as much as possible of the exposure connected with the river. The protection decision for the river distributary is linked directly to the protection decision for the coastline segment. Hence, if the coastline segment needs to be protected, we assume that the river distributary also needs protection. The same protection levels are assumed for the associated river distributary as used on the open coast.

3.4 Sea and river dike costs

3.4.1 Sea dikes

Sea dikes are built along the open coast where required using the length of the coastal segments in DIVA (Appendix 4). We estimate capital costs and also maintenance costs (1.0% of the capital cost per year) (Nicholls et al., 2010). In this work we updated our estimates of sea dike costs using new information on dike costs, as explained in Appendix 2.

Unit costs of dikes vary within and between countries. Dike costs in earlier studies such as Hinkel et al. (2014) are based on older studies (Dronkers et al. 1990; Hoozemans et al. 1993), who multiply a point estimate of Dutch unit dike costs with a country-specific factor that was based on expert judgement. There are two main problems with this approach: (i) recent case study results suggest that the Dutch unit costs were underestimated, and (ii) some of the country-specific factors are inaccurate. A pragmatic approach to improve the dike unit cost estimates is to update the previous Dutch unit cost point estimate with the interval estimate for rural areas given by Jonkman et al. (2013). This improves cost estimates and stresses the uncertainty of defense costs, but individual national costs can be substantially in error. Hence the cost estimates an improvement for regional and global cost estimates, but at the national level significant errors may occur.

This results in a new range of costs represented by low and high estimates of dike unit costs as documented in Appendix 3. The low costs are similar to the earlier unit costs in DIVA and the high costs are about three times higher. As the stock of dikes grows, so the maintenance costs also grow and can become significant, as shown in Section 4. Hence it is important to track these maintenance costs and make sure they are considered, rather than forgotten or ignored.

The capital costs of existing sea dikes up to 2015 (the base year) are not considered in the analysis. It is simply assumed that defenses corresponding to the standards in Table 4 have been provided. However, the cost of post-2015 maintenance of these pre-existing dikes is considered.

3.4.2 River dikes

River dikes are built on both sides of the lower coastal-influenced reaches of selected rivers (see Figure 2). To calculate the length of river to protect with dikes, it is estimated how far the 1-in-1,000-year extreme sea level event could penetrate inland along the river. This is done by dividing the water level of the 1-in-1,000-year event by the river slope. Hence, the impact length of the 1-in-1,000-year event increases with sea-level rise. For simplicity, we use the same unit costs as sea dikes. Due to geometric considerations, river dikes are on average half the height of sea dikes. This also implies that river dikes are built at sea-level elevation in the river mouth and their base elevation increases with distance from the river mouth. Due to the absence of wave action, the river dike maintenance costs are assumed to be half the maintenance cost of sea dikes (0.5% of the capital cost per year).

As with sea dikes, existing river dikes' capital and maintenance costs in 2015 (the base year) are not considered in the analysis, but post-2015 maintenance is considered.

3.5 Surge barrier costs

Surge barriers require a location. This was developed using expert judgement to define a single potential surge barrier position for each river distributary. The selected position was based on a trade-off between minimizing the barrier length and maximizing the length of avoided river dikes, while considering local conditions (Figure 4). The few existing barriers are not considered, as for most of them there are already plans for substantial upgrade of even the construction of new replacement barriers (Lavery and Donovan, 2005; Tarrant and Sayers, 2012). Hence, all barrier capital (construction) and maintenance costs are considered in the analysis. As with river dikes, the same protection levels are assumed as for the open coast requirement. If surge barriers are built, existing river dikes are kept (maintained) but no longer raised with sea level rise. Surge barriers stay constant in width, but are incrementally raised with rising sea level.

The unit costs for surge barriers are taken from Table 3 of Jonkman et al., (2013). We use the minimal (US$97,000 per meter height and meter width) and maximal (US$374,000 per meter height and meter width) unit costs as the low and high cost scenarios in this study, respectively. Maintenance costs are assumed to be 1%/year following the maintenance costs for sea dikes.

Figure 4: Proposed river distributaries and surge barrier positions as illustrated for the southern Netherlands.

3.6 Initial protection levels

There are no global data sets on current levels of protection and initial protection levels (taken as 2010) have to be estimated in an expert manner. Hence, current protection levels are taken from Sadoff et al. (2015) who applied current protection levels for the biggest 136 coastal cities from Hallegatte et al. (2013) and complemented these through expert judgement for coastal areas not associated to one of these cities (Table 4). Protection level zero (i.e. no protection) is assumed if the population density in the 1-in-100-years floodplain is lower than 30 people per km² and in rural areas in countries with low and low middle incomes. As the socio-economic scenarios assume substantial economic growth, this moves people in rural areas from no protection to protection over the 21st century in these poorer countries, and the global length of protection increases with time.

Table 4: Protection standards adopted in this analysis (following Sadoff et al., 2015).

Wealth Class (annual income per capita) (2014 US$ GDP per capita (PPP))	Urban (>1000 people/km^2)	Rural (30 to 1000 people/km^2)	Uninhabited (<30 people/km^2)
Low income ($\leq$ $1,035)	1:10	no protection	no protection
Lower middle income ($1,035 - $4,085)	1:25	no protection	no protection
Upper middle income ($4,086 - $12,615)	1:100	1:20	no protection

High income (> $12,615)	1:200	1:50	no protection
Special case: Netherlands	1:10,000		
Special case: 136 large coastal cities	taken from Hallegatte et al. (2013)		

Subsequently, protection levels evolve at five-year time steps following the Adaptation Strategies outlined below.

3.7 Adaptation strategies

In this report, we assess the costs for the following five adaptation strategies:

1. **Constant Protection Levels** -- maintain current protection levels as defined in Table 4. As population and GDP change with time in the socio-economic scenario, so the length and standard of protection will increase. Once an area is protected, defenses are maintained to 2100.
2. **Constant absolute flood risk** -- maintain average annual losses for protected areas as defined under Strategy 1 (similar to Hallegatte et al., 2013). This strategy raises the protection level with both rising sea levels and socio-economic development (population, GDP) in order to maintain the current (2015) flood risk level constant in monetary terms.
3. **Constant relative flood risk** -- maintain relative average annual losses for protected areas as defined under Strategy 1**.** This strategy raises protection levels with both rising sea levels as well as socio-economic development in order to maintain the current flood risk constant in terms of percentage of local GDP (considered to be a socially acceptable loss). By local GDP we refer to the fraction of GDP that is produced within the low elevation coastal zone (LECZ -- which is the area below 10 m elevation) associated to a coast-line segment.
4. **Risk intolerance** -- keep relative average annual losses below 0.01% percent of local for protected areas as defined under Strategy 1. The GDP threshold of 0.01% is based on the losses in the cities of Amsterdam and Rotterdam in 2005 as calculated by Hallegatte et al. (2013) and applies this Dutch standard as a risk intolerant world.
5. **Cost-benefit analysis (CBA)** -- compute the optimum protection level minimizing the sum of residual flood damage to assets and protection costs to 2100, including capital and maintenance costs. This follows the methods of Lincke and Hinkel (2018).

Strategies 1 to 4 are scenarios of how protection might be applied globally and are based on expert judgement, while Strategy 5 is based on economic optimization and balancing the costs of protection to the avoided damages. Under Strategy 1, the defenses are raised with relative sea-level rise, while under the other strategies, the defenses are generally raised more than the rise in sea level. Strategies 1 to 3 take a positive approach, while Strategy 4 takes a normative approach which allows us to consider the adaptation deficit, relative to Strategies 1 to 3. The adaptation deficit can only be assessed with respect to a normative assumption as to what is desirable -- here we ask what is required to give all protected areas following Table 4 the same level of safety as Amsterdam and Rotterdam. Similar analysis can be conducted with Adaptation Strategy 5.

Note that the protected length in 2015 is maintained or grows over time under Strategies 1 to 4. Under Strategy 5 (Cost-benefit analysis) an optimal defended length (and defense standard) is determined in 2015 and maintained to 2100.

3.8 Socio-economic and sea-level rise scenarios

Adaptation costs are assessed for a consistent set of socio-economic and sea-level rise scenarios over the 21st century. These scenarios are summarized in Table 5.

For socio-economic scenarios, we draw on the Shared Socio-economic Pathways (SSPs), version 9 provided by IIASA and use three scenarios: SSP2, SSP3 and SSP5 (IIASA, 2016; O'Neill et al., 2014).

Three global mean sea-level rise scenarios are taken assuming relatively low, intermediate and relatively high emissions, respectively. They are use the HadGEM-ES2 model. These are the 5th percentile of RCP2.6, the 50th percentile of RCP4.5, and the 95th percentile of RCP8.5 (all taken from Hinkel et al., 2014). Henceforth these are just termed RCP2.6, RCP4.5 and RCP8.5, respectively.

Table 5: The socio-economic and sea-level rise scenarios applied in this study. Base year for sea-level rise is the 1985 to 2005 average.

Year		**2015**	**2030**	**2050**	**2075**	**2100**
Global population (billions)	**SSP2**	7.4	8.4	9.4	9.7	9.2
	SSP3	7.4	8.7	10.1	11.6	12.8
	SSP5	7.4	8.2	8.8	8.6	7.7
GDP per capita (US$, global average)	**SSP2**	14,400	20,800	30,000	46,700	72,600
	SSP3	14,300	18,500	20,800	23,000	26,000
	SSP5	14,400	26,200	51,700	97,500	170,000
Sea-level rise (global coastal average, m)	**RCP2.6 5th percentile**	0.02	0.06	0.11	0.17	0.23
	RCP4.5 50th percentile	0.03	0.08	0.16	0.29	0.43
	RCP8.5 95th percentile	0.04	0.13	0.28	0.59	1.03

4 Results

The results are reported globally and for different groups of countries by income as defined by the World Bank in 2015 (World Bank, 2017). They are as follows: (1) East Asia & Pacific, (2) Europe & Central Asia, (3) High Income, (4) Latin America & Caribbean, (5) Middle East & North Africa, (6) South Asia, and (7) Sub-Saharan Africa. In this main report results are provided for the SSP2 and high adaptation unit costs, while in Appendix 1 the other results are reported for SSP3 and SSP5 and low adaptation unit costs. In Section 4.1 we consider the length of open coast and number of rivers/distributaries that require protection. In Section 4.2 the protection costs are presented in terms of annual and accumulated costs, the relative contribution of capital and maintenance costs and the adaptation deficit. There is a focus on the dike and barrier defense approach. In Section 4.3, the population living in the 100-year flood plain and the residual damages are reported.

4.1 Required Length/Quantity of Protection

Based on the assumptions described in Table 4, we estimate that 24.2% of the world's coastline is protected by dikes in 2010 (Figure 5). These comprise (1) East Asia & Pacific: 25.8% of the coast, (2) Europe & Central Asia: 54.3% of the coast, (3) High Income: 23.1% of the coast, (4) Latin American & Caribbean: 27.9% of the coast, (5) Middle East & North Africa: 46.6% of the coast. (6) South Asia: 23.9% of the coast, and (7) Sub-Saharan Africa: 11.8% of the coast (Figure 5). Tables 6, 7 and 8 summarize the length of protection required over time. From 2015 to 2100, the length of protection increases under Strategies 1 to 4. The global increase from 2010 to 2100 is 23% in length, while in Sub-Saharan Africa experiences a 133% increase and in East Asia & Pacific it is a 79% increase in length. Under Strategy 5, the protected length varies with both RCP and SSP scenarios -- it is longest under RCP8.5 and SSP5 (see Tables 7 and 8). This length is often longer than the other Adaptation Strategies in 2015, but this difference diminishes with time. In a few cases it is less than the estimated length of defenses in 2010 (Table 7). These abandoned defenses are assumed to have no costs in the period 2015 to 2100. Note that in all cases the length of protection estimated in this analysis is substantially less than that reported by both Tol (2002) and Hinkel et al (2014) in Table 1.

Similarly, protection is required for 145 of 345 (42.2%) river distributaries in 2015. Globally, a total length of 8,600 km river dikes is required. Under constant protection levels, dike only protection and the high sea-level rise scenario, the length of river dikes increases to 11,500 km by 2100. This reflects that the dikes need to extend further inland as sea levels rise.

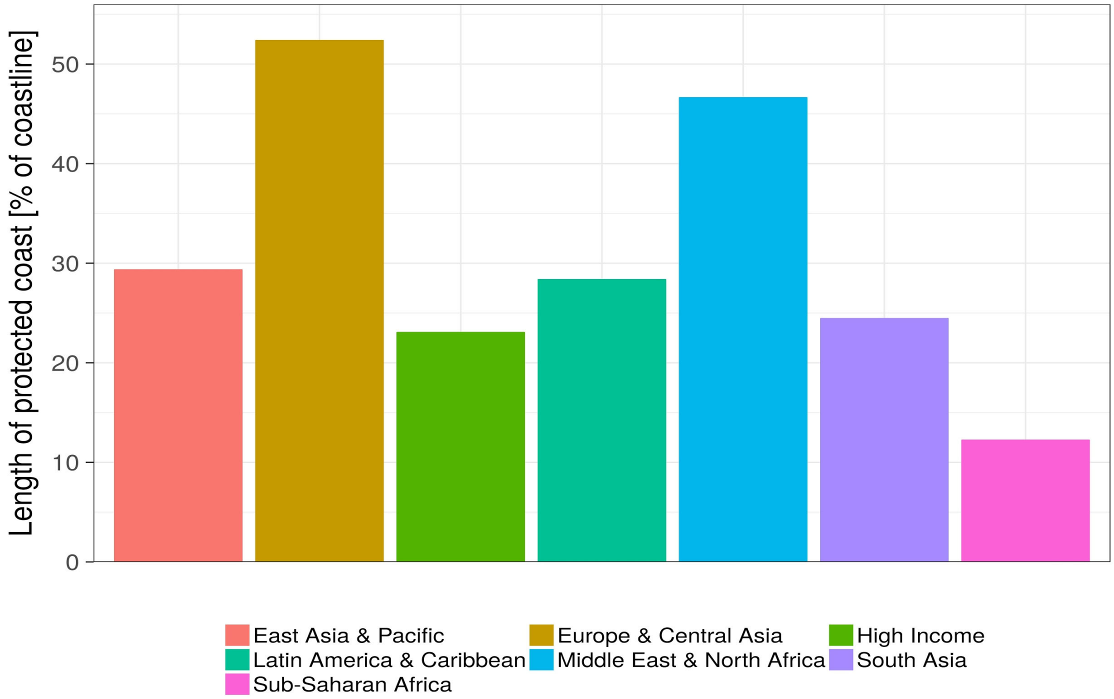

Figure 5: Percentage of protected open coast in 2010 in the seven World Bank regions used in the study for SSP2, following the assumptions in Table 4. The results for SSP3 and SSP5 are almost identical and hence are not shown. Absolute values are given in Tables 6 and 7.

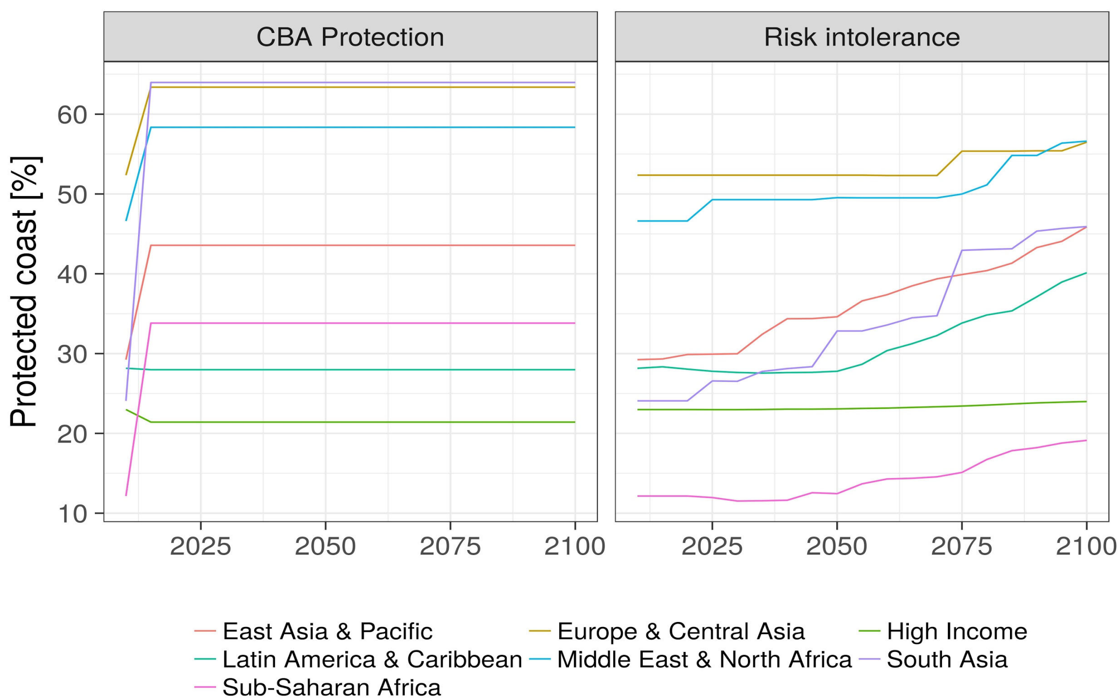

Figure 6: Percentage of protected coast over time for SSP2, high adaptation unit cost and RCP 8.5 sea-level rise. Lengths are almost identical in Strategies 1 to 4 (illustrated here with Risk Intolerant Protection).

Table 6. The length of protected coast (in km) globally and by region over time (for selected years) under Strategies 1 to 4. 2010 is included to illustrate the large increase in protected length in Upper middle income countries in 2015. RCP 8.5 SLR and Risk Intolerant Protection are considered.

Year	**2010**	**2015**	**2030**	**2050**	**2100**
East Asia & Pacific	31,300	31,400	32,100	37,000	49,100
Europe & Central Asia	4,600	4,600	4,600	4,600	5,000
High Income	104,100	104,100	104,100	104,500	108,600
Latin America & Caribbean	17,000	17,100	16,700	16,800	24,200
Middle East & North Africa	6,500	6,500	6,800	6,900	7,800
South Asia	3,500	3,500	3,900	4,800	6,700
Sub-Saharan Africa	4,100	4,100	4,100	4,200	6,400
Total (global)	171,100	171,200	172,300	178,800	207,800

Table 7. The length of protected coast under CBA Protection, RCP8.5 and SSP2 scenarios.

Year	**2010**	**Length of Protected Coast (2015 to 2100) (km) and percentage change relative to 2010**
East Asia & Pacific	31,300	46,600 (+48.9%)
Europe & Central Asia	4,600	5,600 (+21.7%)
High Income	104,100	97,000 (-6.8%)
Latin America & Caribbean	17,000	16,900 (-0.6%)
Middle East & North Africa	6,500	8,100 (+24.6%)
South Asia	3,500	9,300 (+165.7%)
Sub-Saharan Africa	4,100	11,300 (+175.6%)
Total (global)	171,000	195,000 (+14.0%)

Table 8. The global length of protected coast under CBA Protection under all the climate and socio-economic scenarios from 2015 to 2030. Antarctica is not considered.

Scenarios		Length Protected	
Climate	Socio-economic	Distance (km)	Proportion of globe (%)
RCP8.5	SSP2	1.95E+05	28.20%
	SSP3	1.69E+05	24.47%
	SSP5	2.19E+05	31.75%
RCP4.5	SSP2	1.79E+05	25.88%
	SSP3	1.57E+05	22.76%
	SSP5	2.00E+05	28.88%
RCP2.6	SSP2	1.69E+05	24.48%
	SSP3	1.52E+05	22.06%
	SSP5	1.92E+05	27.80%

Of the 434 river distributaries considered in the analysis, we protect 232 of them (53.3%) in 2015. For dike and barrier protection, we protect 145 river distributaries with river dikes and 87 river distributaries with surge barriers. Dike only protection leads to longer lengths of defenses (Figure 2). This is summarized in Table 9.

Table 9. River protection. The length of protected river mouths (in km) and the number of surge barriers globally and by region over time (for selected years) assuming open (dike only) and closed (surge barriers, if appropriate). The first line in each cell shows the length of river dikes and number of surge barriers for open protection and the second line in each cell shows the length of river dikes and the number of surge barriers for closed protection. This assumes RCP 8.5 SLR, SSP2 and Risk Intolerant Protection.

Year	**2010**	**2015**	**2030**	**2050**	**2100**
East Asia & Pacific	3,600/0 3,600/0	4,000/0 3,700/26	4,200/0 3,700/27	4,900/0 4,100/31	5,700/0 4,600/31
Europe & Central Asia	97/0 97/0	100/0 100/1	120/0 110/1	140/0 130/1	260/0 240/1
High Income	6,000/0 6,000/0	6,100/0 6,000/51	6,300/0 6,100/51	6,700/0 6,300/52	8,100/0 7,000/52
Latin America & Caribbean	1,200/0 1,200/0	1,200/0 1,200/12	1,200/0 1,200/11	1,300/0 1,200/12	1,700/0 1,300/14
Middle East & North Africa	170/0 170/0	180/0 180/2	210/0 190/3	250/0 220/3	680/0 340/5
South Asia	1,700/0 1,700/0	1,700/0 1,700/4	1,700/0 1,700/4	1,800/0 1,800/4	2,200/0 2,000/5
Sub-Saharan Africa	160/0 160/0	160/0 160/2	170/0 170/2	180/0 170/2	290/0 170/3
Total (global)	13,000/0 13,000/0	13,400/0 13,100/98	14,000/0 13,300/100	15,300/0 14,000/105	19,100/0 15,800/111

4.2 Protection Costs

Figures 7 and 8 show the annual protection costs including the sum of capital and maintenance costs for the five Adaptation Strategies, the sea-level rise scenarios, the SSP2 scenario and the high adaptation unit costs. These costs are the sum of the capital costs of sea dikes, river dikes and surge barriers, and all maintenance costs. All the Defense Approaches produce similar estimates of annual protection costs rising through the 21st century. In 2100, global costs are about US$40 billion to US$110 billion per year under RCP2.6 and about US$60 billion to more than US$170 billion per year under RCP8.5.

A large spike in the costs occurs in 2015 in all cases, being the biggest of several spikes in simulated cost time series for Strategies 1 to 4. It reflects a large increase in the protection standards of upper-middle-income countries due to rising living standards crossing a threshold value (especially in Brazil and China). This raises protection standards along large lengths of coast in 2015, following Table 4. Under the Risk Intolerance strategy, this is reinforced by the response to the adaptation deficit, which is discussed in more detail below. In all cases, this spike is the highest investment requirement, but if this strategy was followed, these costs would probably be distributed over a longer period, spreading the additional investment demand over time (see aggregated costs in Figure 8). Under RCP2.6, after 2015, annual costs are approximately constant, reflecting a near constant and slow rate of sea-level rise. Hence capital costs are linear and maintenance costs only rise slowly. In contrast, under RCP8.5 costs approximately double from 2020 to 2100, reflecting accelerating sea-level rise and a large increase in maintenance costs. Under Strategy 5 (Cost-benefit analysis) the broad costs are similar although often slightly lower than the Risk Intolerance strategy.

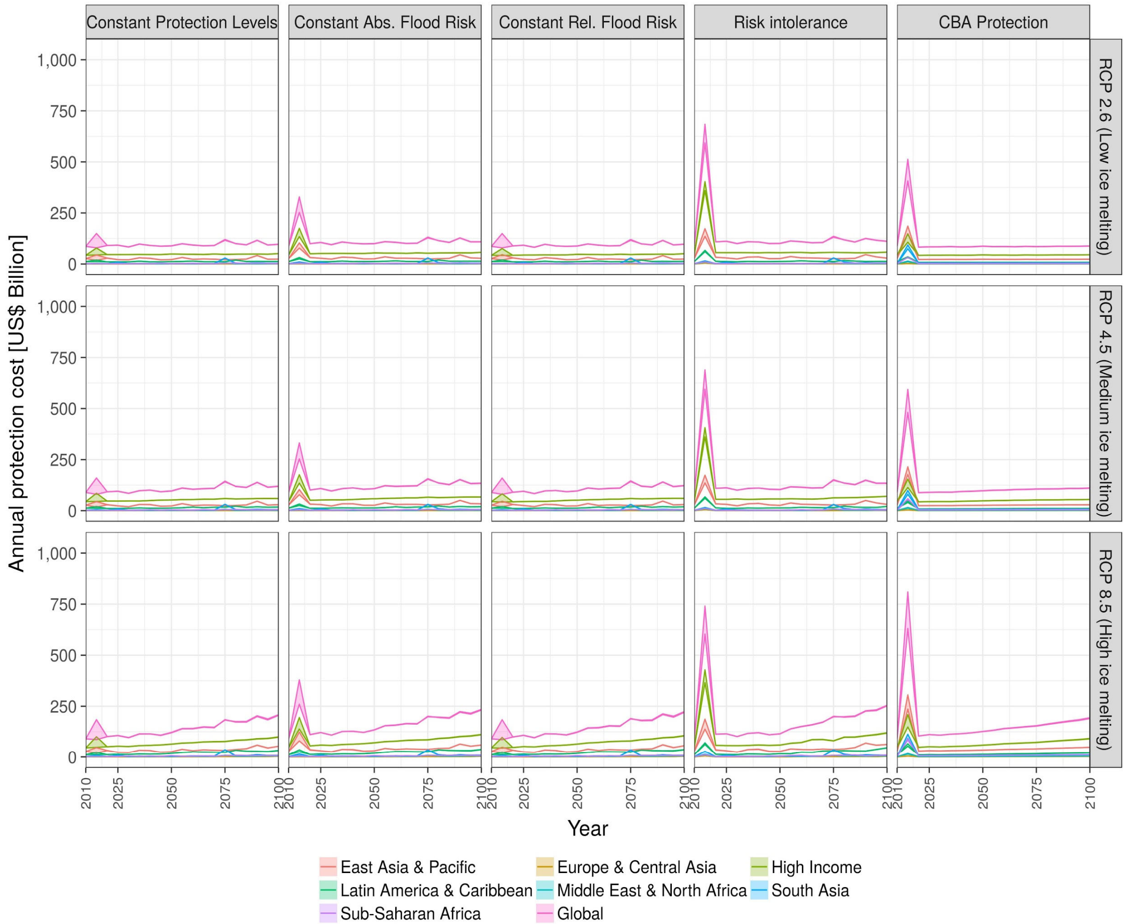

Figure 7. Annual protection costs (for dike and barrier protection) for the seven regions and the total global costs over time for SSP2, high adaptation unit cost, the five adaptation strategies and three sea-level rise scenarios. Includes maintenance and capital costs. The spike in 2015 is discussed in the text. Results for other scenarios are shown in Appendix A.1.1.

Tables 10 and 11 show the range of undiscounted protection costs (capital and maintenance) across all the different scenarios. Table 10 shows the total costs from 2015 to 2100, while Table 11 focuses on the near-term costs from 2015 to 2030. Across the five strategies these total US$0.6 trillion to US$2.5 trillion, US$1.0 trillion to US$3.7 trillion, US$0.6 trillion to US$2.6 trillion, US$1.7 trillion to US$5.5 trillion, and US$1.4 trillion to US$6.7 trillion from 2015 to 2030 and US$2.9 trillion to US$14 trillion, US$3.5 trillion to US$16.6 trillion, US$2.8 trillion to US$14.6 trillion, US$4.3 trillion to US$18.3 trillion, and US$3.8 trillion to US$18.2 trillion from 2015 to 2100, respectively. The biggest uncertainty in these ranges is the unit cost. The highest costs are found with the Risk Intolerant and CBA strategies. With the CBA strategy, the residual risks are much lower than the other strategies (Section 4.3) and overall it has the lowest cost.

Table 10. The range of total undiscounted protection costs from 2015 to 2100 across all uncertainties under the five protection strategies (US dollars 10^3 billion). The main uncertainty is the unit cost.

		Adaptation strategy cost (capital and maintenance)				
Scenarios		1. CP	2. CAFR	3. CRFR	4. RI	5.CBA
	SSP2	4.6-13.2	5.5-15.6	4.8-13.5	6.1-17.3	6.8-16.0
	SSP3	4.4-12.5	5.2-14.8	4.5-12.7	5.7-16.3	6.2-13.6
RCP8.5	SSP5	4.9-14.0	5.8-16.6	5.2-14.6	6.4-18.3	7.9-18.2
	SSP2	3.5-10.0	4.2-11.9	3.5-10.0	4.8-13.6	5.0-11.4
	SSP3	3.3-9.4	4.0-11.2	3.2-9.2	4.5-12.8	4.4-10.0
RCP4.5	SSP5	3.7-10.5	4.5-12.6	3.8-10.8	5.1-14.4	5.7-13.2
	SSP2	3.1-8.8	3.8-10.7	3.1-8.8	4.5-12.8	4.3-9.8
	SSP3	2.9-8.3	3.5-10.1	2.8-8.0	4.3-12.1	3.8-8.8
RCP2.6	SSP5	3.3-9.3	4.0-11.4	3.3-9.5	4.7-13.4	5.8-11.5

Table 11. The range of total undiscounted protection costs from 2015 to 2030 across all uncertainties under the five protection strategies (US dollars 10^3 billion). The main uncertainty is the unit cost.

		Adaptation strategy cost (capital and maintenance)				
Scenarios		1. CP	2. CAFR	3. CRFR	4. RI	5.CBA
	SSP2	0.7-2.4	1.1-3.6	0.7-2.4	1.7-5.3	2.3-5.7
	SSP3	0.7-2.4	1.1-3.6	0.7-2.4	1.7-5.3	2.0-4.6
RCP8.5	SSP5	0.8-2.5	1.1-3.7	0.8-2.6	1.7-5.5	2.8-6.7

	SSP2	**0.6-2.2**	**1.0-3.2**	**0.6-2.1**	**1.7-5.0**	**1.9-4.3**
	SSP3	**0.6-2.2**	**1.0-3.2**	**0.6-2.1**	**1.7-5.0**	**1.6-3.6**
RCP4.5	**SSP5**	**0.7-2.2**	**1.0-3.3**	**0.7-2.3**	**1.7-5.2**	**2.3-5.2**
	SSP2	**0.6-2.1**	**1.0-3.1**	**0.6-2.1**	**1.7-5.0**	**1.7-3.8**
	SSP3	**0.6-2.1**	**1.0-3.1**	**0.6-2.0**	**1.7-5.0**	**1.4-3.3**
RCP2.6	**SSP5**	**0.7-2.2**	**1.0-3.4**	**0.7-2.2**	**1.7-5.1**	**2.0-4.7**

Figure 8. Cumulative protection costs (for dike and barrier protection) for the all RCP sea-level rise scenarios across the adaptation strategies. SSP2 and high adaptation unit costs are assumed. Results for other scenarios are shown in Appendix A.1.2

Figures 8 shows the cumulative costs for the same assumptions as in Figure 7 for three time periods: (1) 2015 to 2030, (2) 2031 to 2050 and (3) 2051 to 2100. Over the period 2015 to

2100, the total costs are about US$2,800 billion to US$11,500 billion for RCP2.6 and US$4,400 billion to US$18,300 billion for RCP8.5. In regional terms, most investment is in the High Income Countries followed by East Pacific and Asia.

The costs considered here are composed of both capital and maintenance costs. As the stock of defenses increases with time, the absolute maintenance costs grow substantially. It is important to consider these cost requirements and make sure that the flood management governance institutions have sufficient funding available to support them. Maintenance is an area which can easily be underfunded or ignored, and if this occurs this leads to an increased chance of defense failure.

Figure 9 shows the global capital and maintenance costs in relative terms for the sea-level rise scenarios across the adaptation strategies. Under RCP2.6, maintenance costs are substantial and constitute about 75% of costs per year throughout the century and are even higher under Strategy 5 (Cost-benefit analysis). Under RCP8.5, the relative investment cost rises towards the end of the century as sea-level rise accelerates and there are larger investment costs to keep pace. However, maintenance remain more than half the annual costs. It should be noted that the spike in protection costs in 2015 that is apparent in Figures 7 and 8 is also apparent here as a spike in relative investment cost.

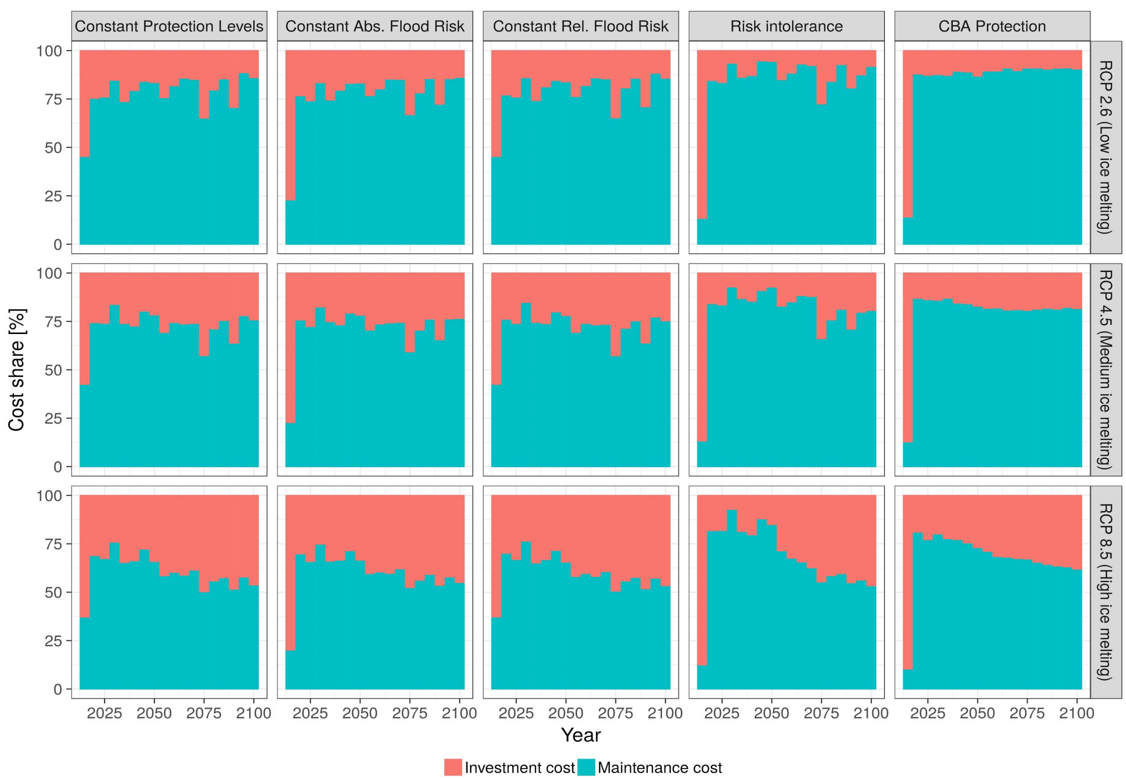

Figure 9. The share of capital versus maintenance costs (for dike and barrier protection) for SSP2, all SLR and all adaptation strategies from 2015 to 2100. Results for other scenarios are shown in Appendix A1.1.3.

Figure 10 (and Appendix A.1.4) shows the adaptation deficit in 2015. It compares the cost of Strategy 1 Constant Protection to Strategy 4 Risk Intolerant and Strategy 5 CBA Protection.

Globally, it amounts to as much as US$4 trillion. Regionally, the largest adaptation deficits are in the High Income countries, following East Pacific and Asia. While these costs are large, the capital costs are one-off investments -- once made, the defense standards can be maintained with similar maintenance costs to the other adaptation strategies -- global annual maintenance costs are increased by roughly US$10 billion to US$25 billion/year.

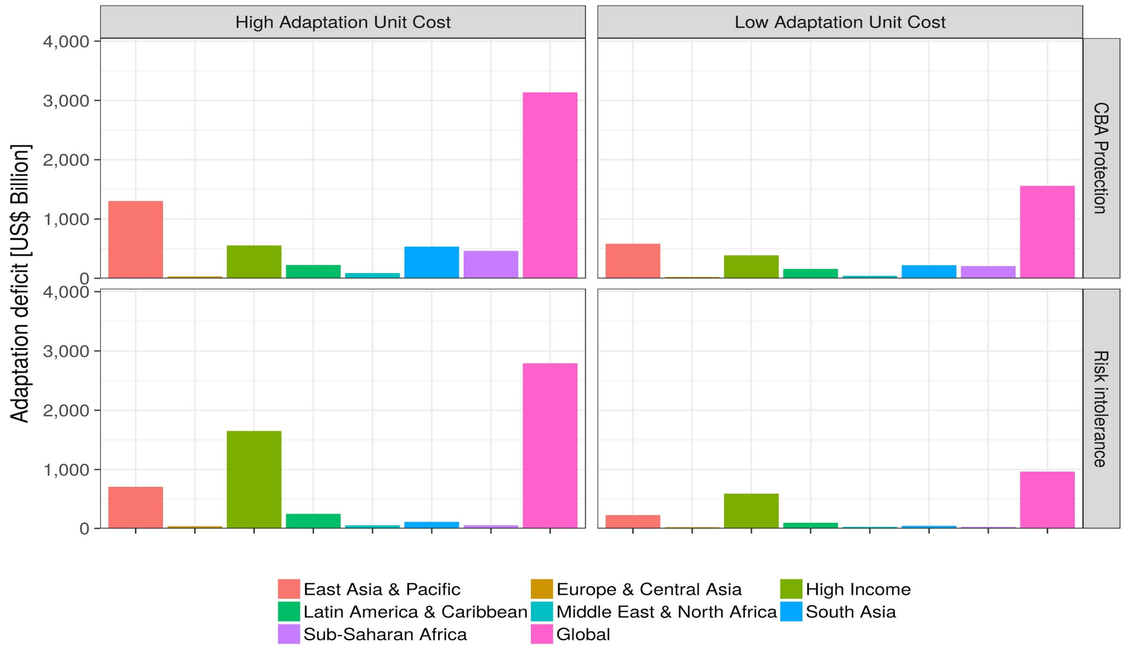

Figure 10. Estimate of the adaptation deficit in 2015 for the Risk Intolerance and CBA Protection Strategies (for dike and barrier protection). The cost is derived from the difference between Constant Protection and the two stated strategies. Results for other scenarios are shown in Appendix A1.1.4.

4.3 Flood plain exposure and residual damage

Figure 11 shows the flood plain population over the 21st century under all SSPs and RCPs. Flood plain population does not depend on the adaptation scenario. Note that these calculations assume uniform population change across each nation. At the end of the century it is highest under SSP3 and RCP8.5 sea-level rise (300 million people). Und SSP2 and SSP5 global population is falling towards the end of the century and thus global floodplain population is also declining (except for SSP2 and RCP 8.5).

Annual residual damage costs are shown in Figures 12 and 13, and also in Appendix A.1.5. Residual damages grow with time in all cases, mainly reflecting both economic growth so asset values grow and sea-level rise which influences the flood depth and hence damage during flood events. Strategy 5 gives the lowest damages by far, reflecting the goal of the approach. The largest damages are estimated at less than US$400 million per year in 2100 (Figure 13), while with the other strategies, losses can be up to US$3,000 billion per year in 2100 under RCP8.5. Hence the CBA Protection approach would seem to deliver the overall lowest costs.

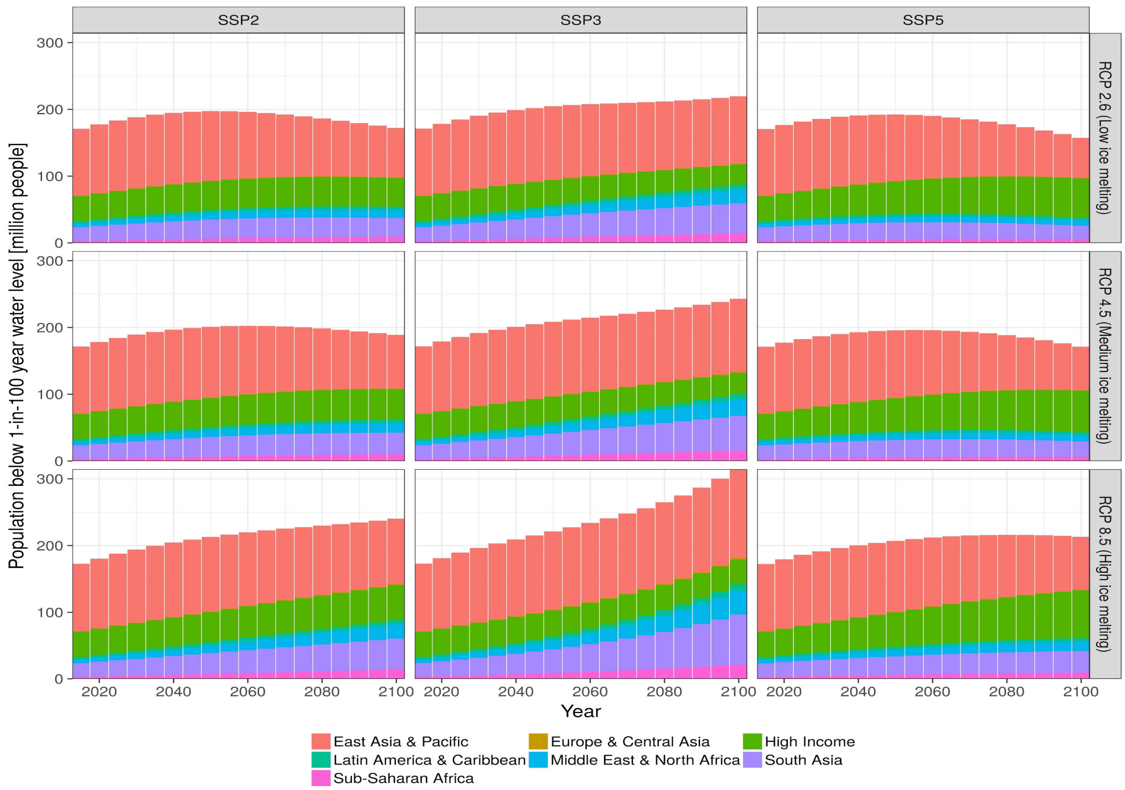

Figure 11. Population living below the 1-in-100-year flood event per region over time (for all scenarios). These results neither depend on the adaptation strategy nor on the adaptation unit cost.

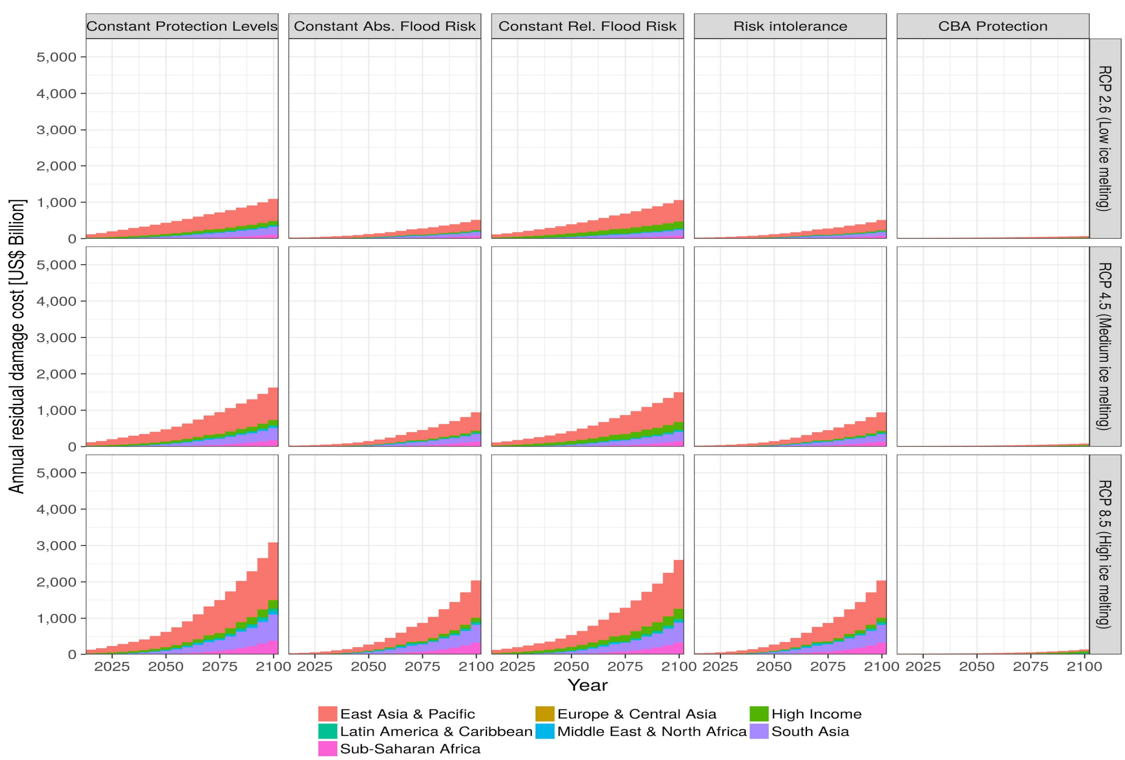

Figure 12. Annual residual damage cost during 21st century per region for all adaptation strategies, sea-level rise scenarios and the SSP2 scenario. Unit costs only influence the results for CBA Protection (see Figure 13). Results for other scenarios are shown in Appendix A1.1.5.

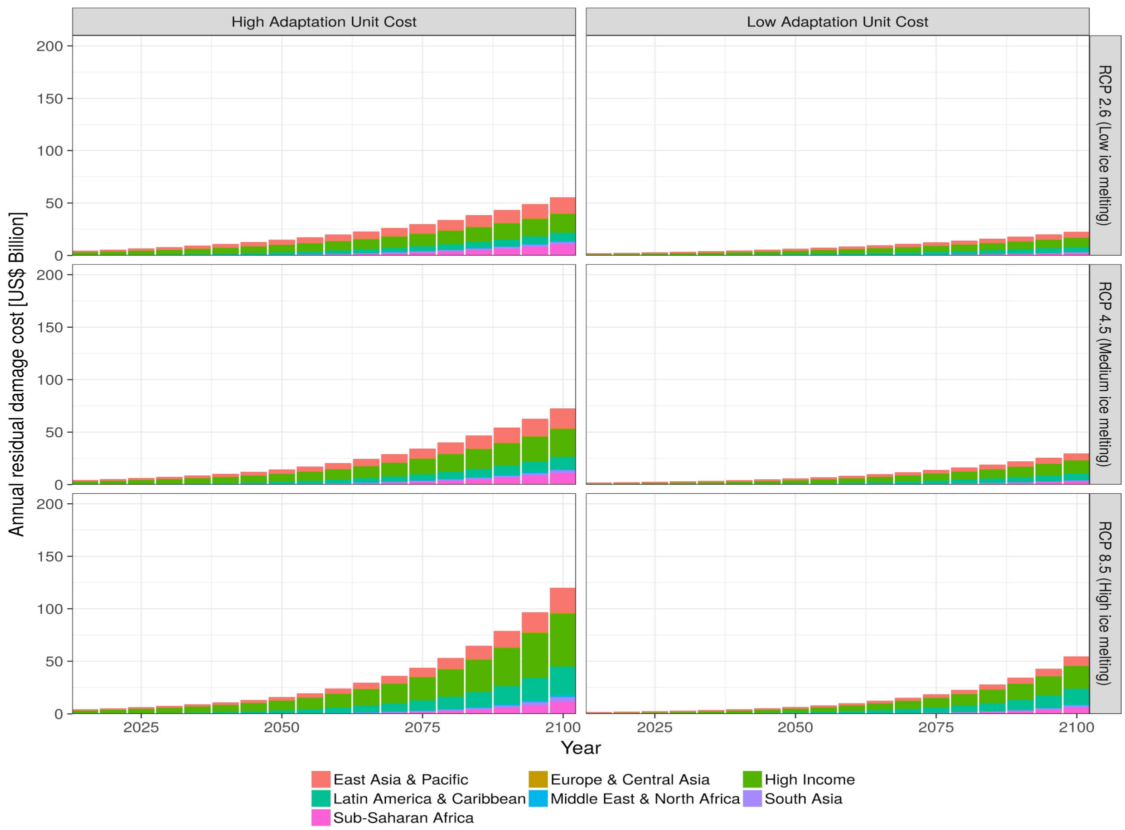

Figure 13. The annual residual damage cost for Strategy 5 (Cost-benefit analysis protection) for the SSP2 scenario and the low and high unit defense costs. Results for other scenarios are shown in Appendix A1.1.5.

5 Discussion

These results provide a comprehensive set of estimates of the protection costs and related parameters given sea-level rise from 2015 to 2100 for a range of defense strategies. The differences in costs between most of the defense strategies are smaller than might be expected and the choice of using surge barriers or not similarly has a small effect on estimates of protection costs. Hence, we focus on Strategy 1 (Constant Protection) and Strategy 5 (Cost-benefit analysis) which is more distinctive from Strategies 1 to 4. For Strategy 1, the total defense costs from 2015 to 2100 are US$2.9 trillion to US$9.3 trillion and US$4.4 trillion to US$14.0 trillion for RCP2.6 and RCP8.5, respectively. For Strategy 5, the same costs are up to US$11.4 trillion and US$18.2 trillion for RCP2.6 and RCP8.5, respectively. These costs are higher than any earlier estimates in Table 1, reflecting the higher unit costs, the inclusion of river protection due to sea-level rise and more realistic maintenance costs. Here we include all defenses that need to be maintained, including the legacy defenses built before 2015 which have often been ignored in earlier analyses. While these costs are high, the cost-benefit analysis finds that such investment makes economic sense, at least over the next 80 years.

The cost-benefit calculations suggest that protection is the optimum response along about 22% to 32% of the world's coast, depending on the scenarios. Hence, it is uncertain for 10% of the world's coast if protect or retreat is the best option. The remaining 68% of the coast might be expected to be allowed to evolve more naturally, and low-cost ecosystem-based or nature-based approaches to coastal defense might be appropriate (e.g., Temmerman et al., 2013).

This analysis shows that following a protection strategy commits the adapters to a long-term maintenance strategy with maintenance costs exceeding the capital costs under all the scenarios considered here. The Netherlands and London provide good examples of major flood defense systems that have a long history based on historic floods and are now being actively maintained and upgraded including allowance for sea-level rise as needed (Lavery and Donovan, 2005; Tarrant and Sayers, 2012; Ranger et al., 2013; Stive et al., 2011; van Alphen 2015). These efforts are linked to strengthening of flood management institutions, long-term planning that looks many decades into the future and securing the commitment to funding. For protection to be successful elsewhere, similar arrangements will be required, including the committed funding streams required for maintenance and the governance institutions to deliver the maintenance. Based on historic precedent, complacency in this regard can lead to disaster, with New Orleans and Hurricane Katrina being a recent example. Recognition of residual risk is also critical as defenses will sometimes fail even if they are well maintained. For example, Hallegatte et al. (2013) identified that if we protect the world's large coastal cities, we should expect to see fewer, but bigger and more damaging coastal floods. Hence, protection does not avoid the need for other pillars of risk management such as flood warnings and disaster preparedness. Any coastal society following a protection approach needs to recognize these long-term commitments which will go on for centuries (Nicholls et al., 2018). If this commitment cannot be delivered, then alternative approaches to coastal adaptation are recommended.

The construction of defenses under rising sea levels also has secondary impacts which include the removal of accommodation space for the migration of coastal wetlands (Schuerch et al., 2018). This degrades coastal wetlands as sea levels rise (termed coastal squeeze) and this effect should be considered when selecting adaptation options.

In this analysis, we have considered relative sea-level rise due to the sum of climate-induced sea-level rise, glacial-isostatic adjustment and deltaic subsidence. Human-induced subsidence in coastal cities can also be significant, with multiple meters of subsidence observed in some coastal cities over the last few decades or longer (e.g., Nicholls, 1995; Kaneko and Toyota, 2011; Nicholls, 2018). In Asia, the World Bank (2010) saw subsidence as an equal threat for coastal megacities as climate-induced sea-level rise. While not analyzed here, city subsidence will not change the fundamental results, but it will enhance the costs of protection, including the maintenance costs, and it will increase the impacts if protection fails (Hallegatte et al., 2013). Mitigation of human-induced subsidence should be considered wherever possible as an immediate preventative response available to cities.

6 Conclusion

This represents the most comprehensive analysis of building coastal protection to sea-level rise completed to date. For all the protection models considered, one-third or less of the world's coast is protected. Under Cost-benefit analysis (Strategy 5), the coastal length protected over the 21st century is 22 to 32 percent of the globe, depending on the scenarios. For Strategies 1 to 4, the protected length increases over time to about 30 percent of the globe by 2100. The population in the coastal flood plain responds to demographic change -- despite a rise in sea level, the coastal population falls under the SSP2 and SSP5 demographic scenarios, reflecting stabilizing and then falling global population. The residual risk grows with time under all scenarios and is substantially lower under cost-benefit assumptions, as the investments are optimized to reduce the sum of the residual damage and investment costs.

The total defense costs are much higher than the earlier estimates summarized in Table 1. Under the highest cost estimates and the highest sea-level rise (RCP8.5) they are as much as US$18.3 trillion (Risk Intolerant Protection, RCP8.5 and high unit defense costs) from 2015 to 2100. This is about 10 times higher than most earlier cost estimates and up to three times higher than the last protection analysis by Hinkel et al (2014). The higher costs here reflect a higher range of unit costs and the inclusion of realistic maintenance costs, including for the defenses that existed in 2015, and that must be maintained to provide protection to 2100. The consideration of river defenses due to sea-level rise also raise costs. Cost-benefit analysis–based protection has high end costs from about US$8.8 trillion up to US$18.2 trillion (depending on the sea-level rise scenario) from 2015 to 2100. This demonstrates that while these investments in coastal protection are large, they are economically rational as the benefits outweigh the costs. Given the lower residual damage, CBA Protection is the lowest cost option, as might be expected. The differences in costs in employing surge barriers versus river dikes are not large at the global and regional scale presented here.

While cost-benefit analysis offers lower costs over the century, early investment is larger as the defenses are not of an optimum standard in 2015. This might be interpreted as one estimate of the adaptation deficit -- this additional early investment is up to about US$4 trillion. However, there are large uncertainties and empirical observations of protection standards are limited. Hence, these should be considered as an indicative estimate and the size of the adaptation deficit remains an important topic for future research.

Importantly, building defenses is not a one-off capital investment. Over the 21st century, the cost of a comprehensive protection strategy is dominated by maintenance costs in all the cases considered in this report (Figure 9; Appendix A1.3). This indicates that the development of appropriate institutions and governance mechanisms to deliver maintenance, as well as the necessary funding streams, are essential for such a protection-based adaptation strategy to be effective. The Netherlands and the Thames Estuary (London) are good examples of major flood defense systems that have been built and are now being actively maintained and upgraded as needed. They are linked to strong flood management institutions and long-term planning looking many decades into the future. For protection to be successful elsewhere, similar arrangements will be required, including guaranteeing the funding streams for maintenance (see Hinkel et al., 2018). Any coastal society following a protection approach needs to recognize this long-term commitment. The danger of focusing on defense without this support is that society is lulled into a false sense of security, leading to bigger coastal disasters. If this commitment cannot be delivered, then alternative coastal adaptation approaches are recommended, such as accommodation or retreat. Further, even if well-maintained, defenses are always associated with residual risk and appropriate measures need to be put in place for its management, especially in coastal cities (Hallegatte et al., 2013). Hence appropriate flood warnings and disaster preparedness mechanisms remain essential even if a good protection and maintenance regime is in place. Defenses also degrade coastal wetlands as sea levels rise (termed coastal squeeze).

Lastly, the world does not end in 2100 and protection is forever. Sea levels can be expected to continue to rise for centuries even if we fully follow the Paris Agreement and stabilize global temperature (Nicholls et al., 2018). Hence, protection upgrade and maintenance will need to continue into the 22nd century and beyond.

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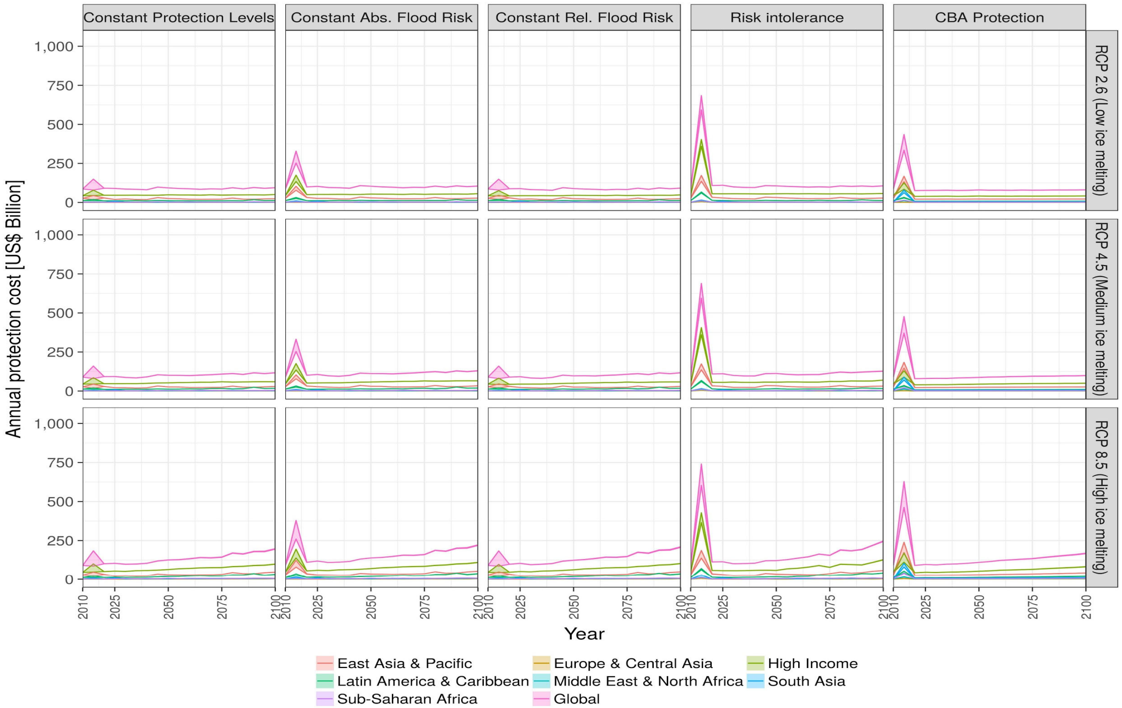
Appendix 1. Additional Results

Contents

A.1.1 Protection cost over time



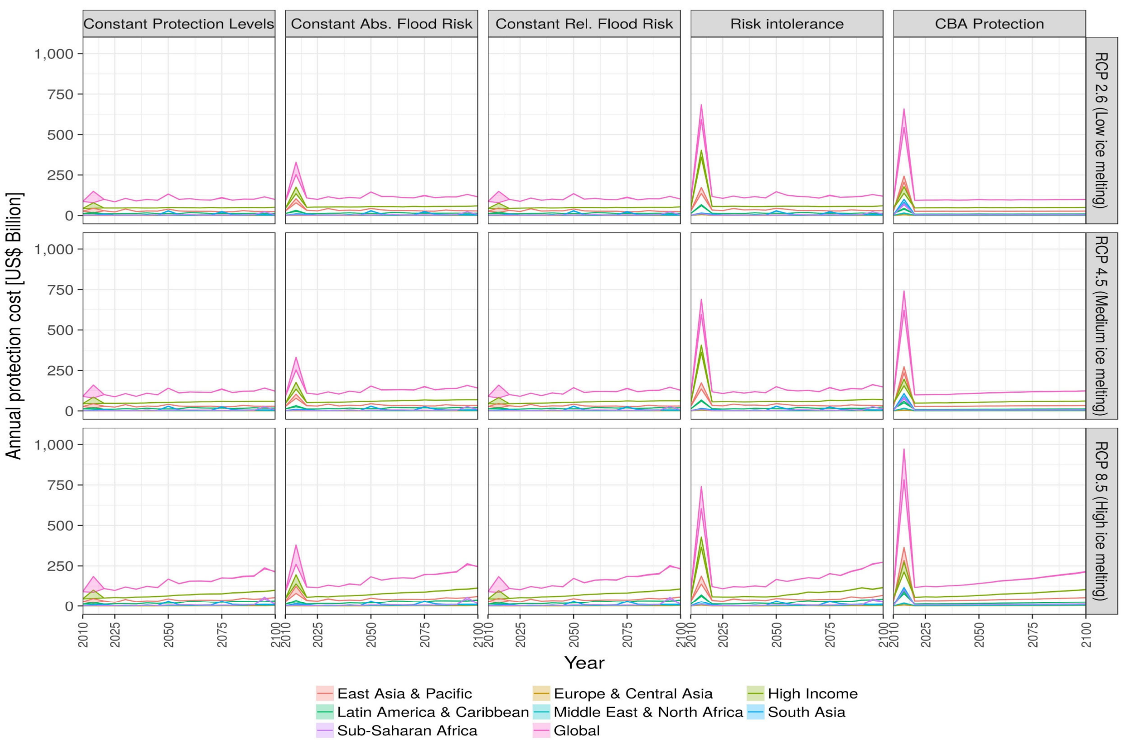
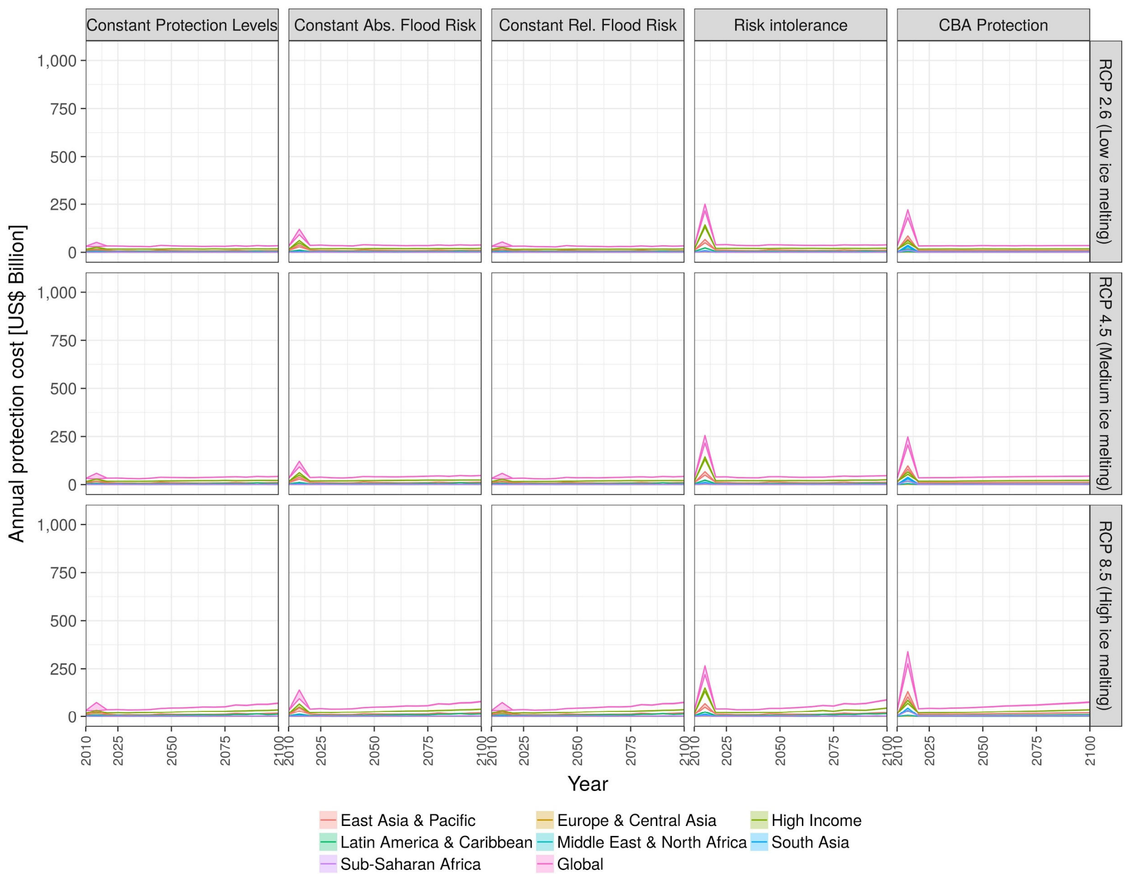


Figure A1: Protection costs per region over time as in Figure 7 for SSP3 (upper figure) and SSP5 (lower figure) and high adaptation unit cost.



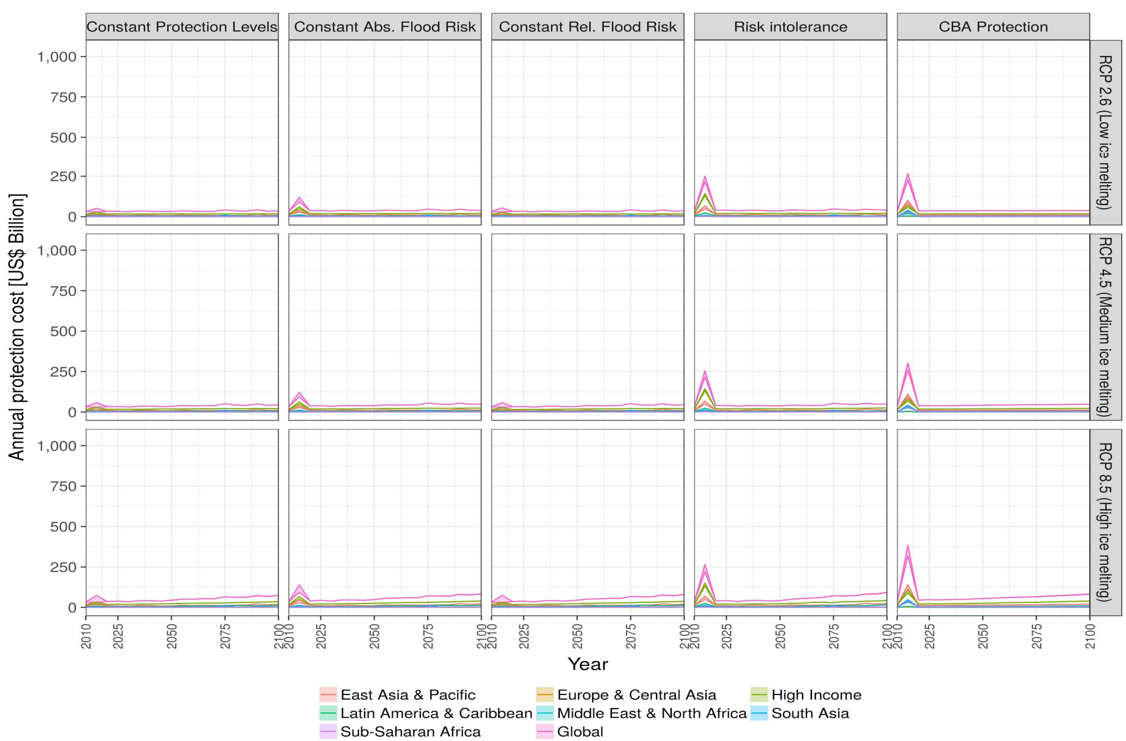


Figure A2: Protection costs per region over time as in Figure 7 for SSP3 (upper figure) and SSP2 (lower figure) and low adaptation unit cost.

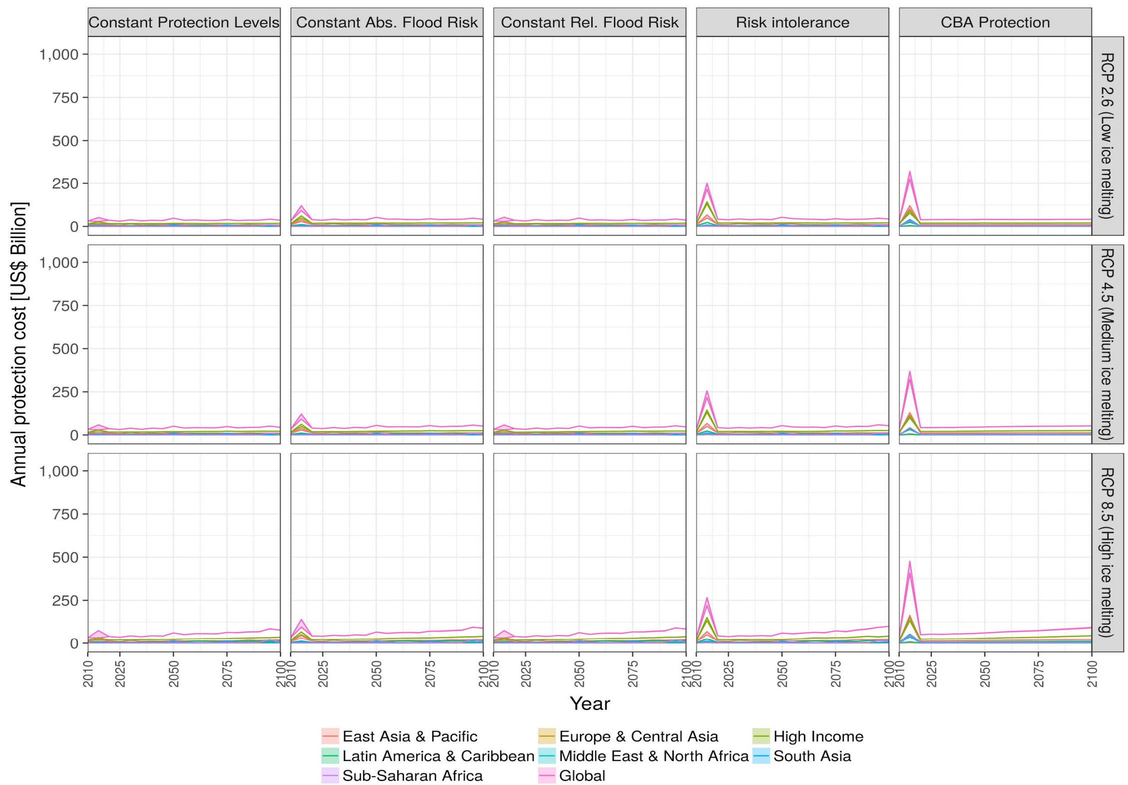


Figure A3: Protection costs per region over time as in Figure 7 for SSP5 and low adaptation unit cost.

A.1.2 Cumulative protection costs

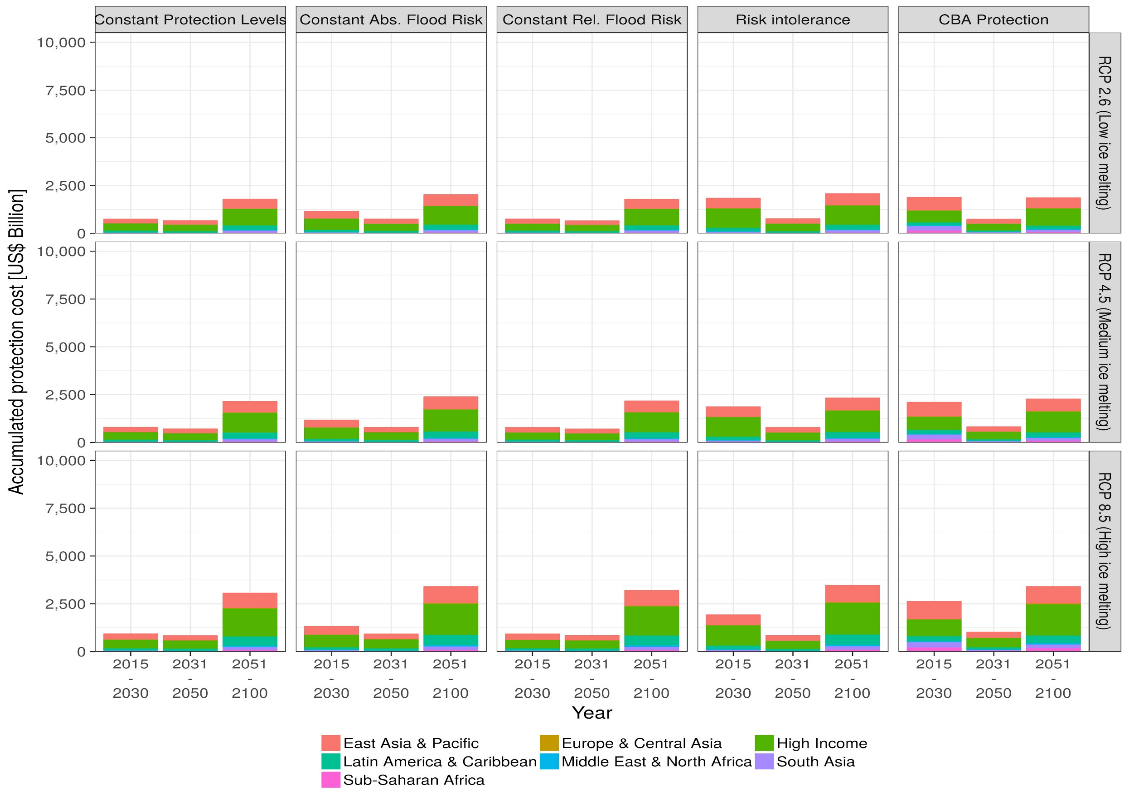


Figure A4: The cumulative protection (capital and maintenance) costs as in Figure 9 for SSP2 and low adaptation unit cost.

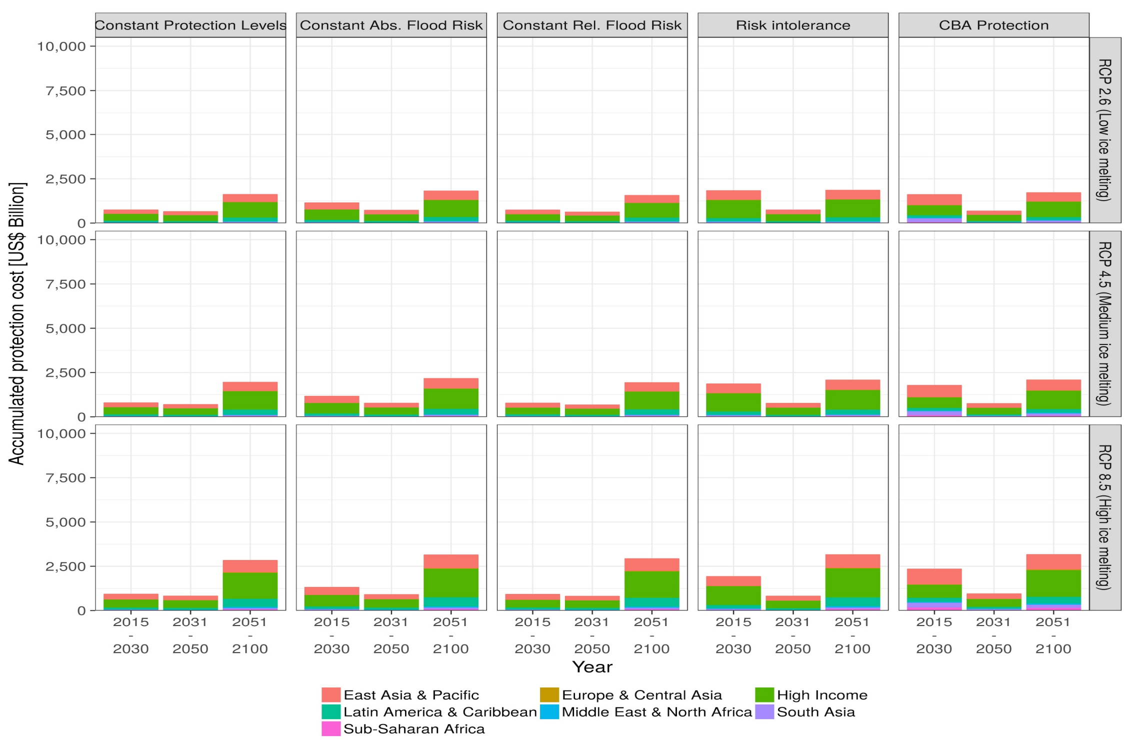
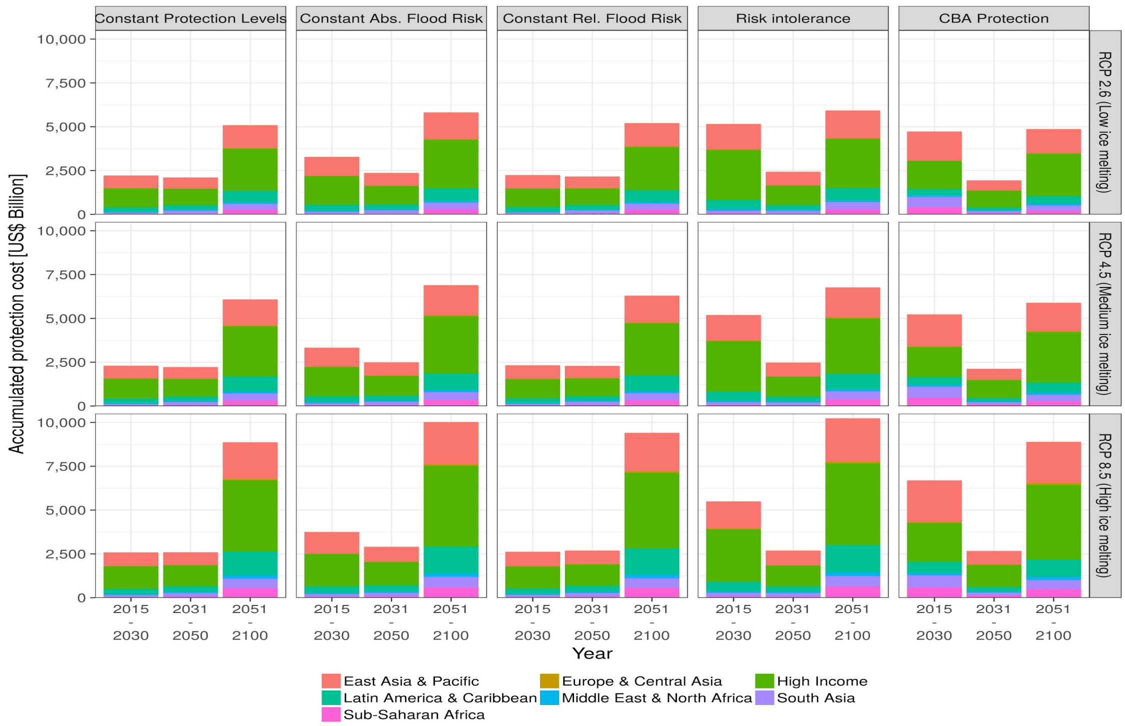


Figure A5: The cumulative protection (capital and maintenance) costs as before for SSP3 (high Adaptation unit costs in the upper figure) (low Adaptation unit costs in the lower figure)



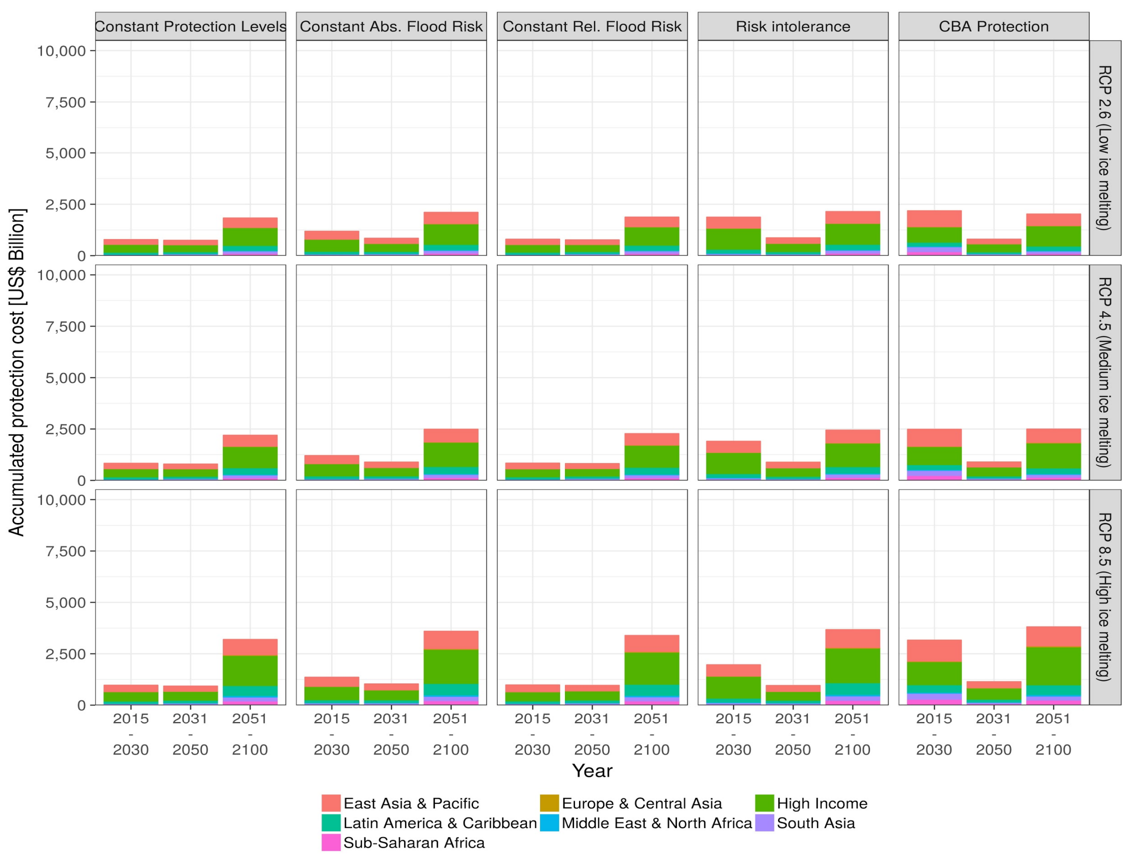


Figure A6: The cumulative protection (capital and maintenance) costs as before for SSP5 (high Adaptation unit costs in the upper figure) (low Adaptation unit costs in the lower figure)

A.1.3 Share of protection and maintenance cost

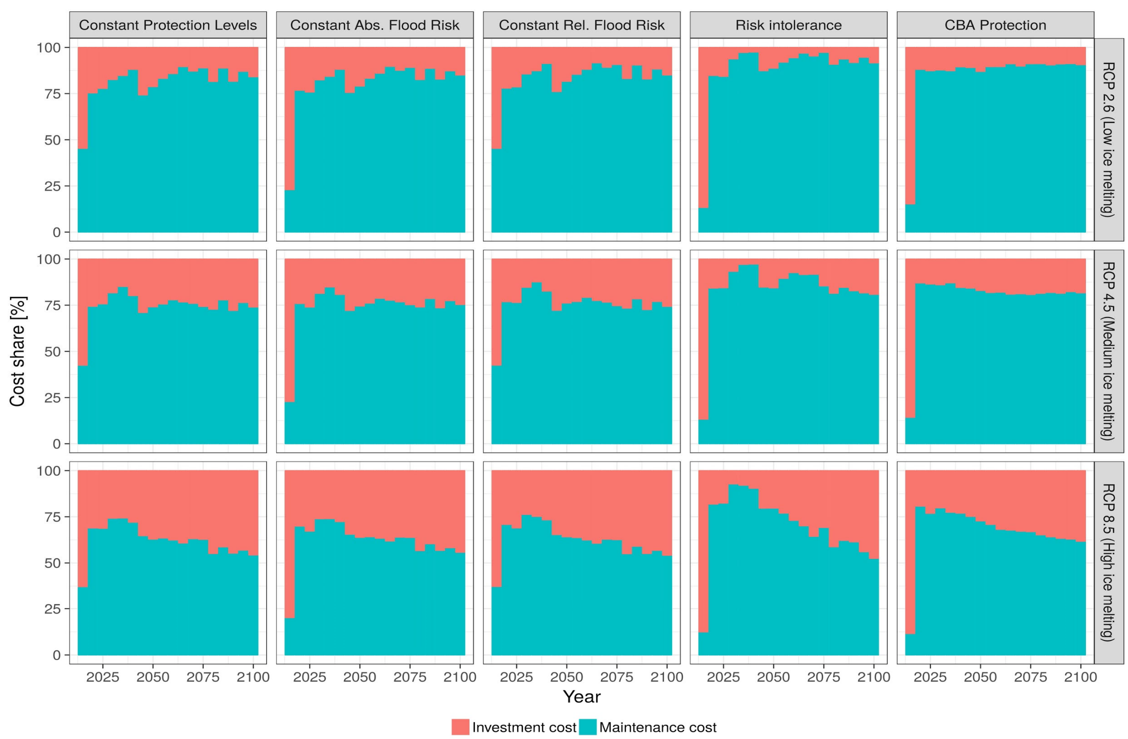
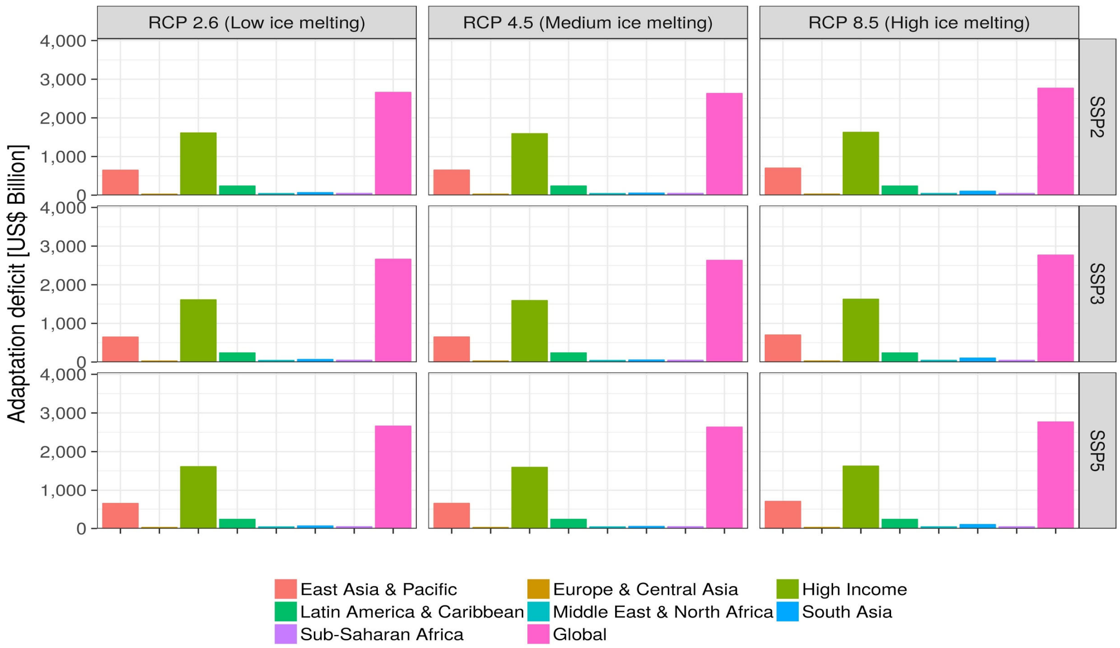


Figure A7: The relative share of capital versus maintenance costs as in Figure 11 for the SSP3 (upper figure) and SSP5 (lower figure) socio-economic scenarios

A.1.4 Adaptation deficit



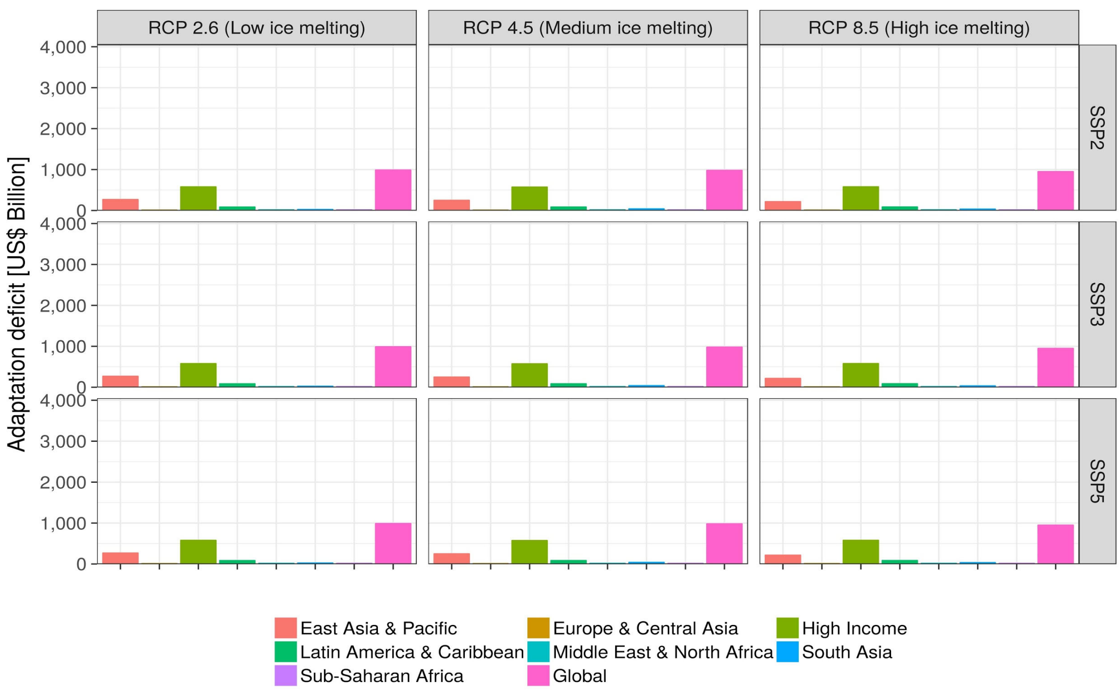


Figure A8: The adaptation deficit for each RCP/SSP under the risk intolerance strategy assuming high (upper figure) and low adaptation unit cost (lower figure).

Figure A9: The adaptation deficit for each RCP/SSP under the CBA adaptation strategy assuming high (upper figure) and low adaptation unit cost (lower figure).

A.1.5 Residual damage cost

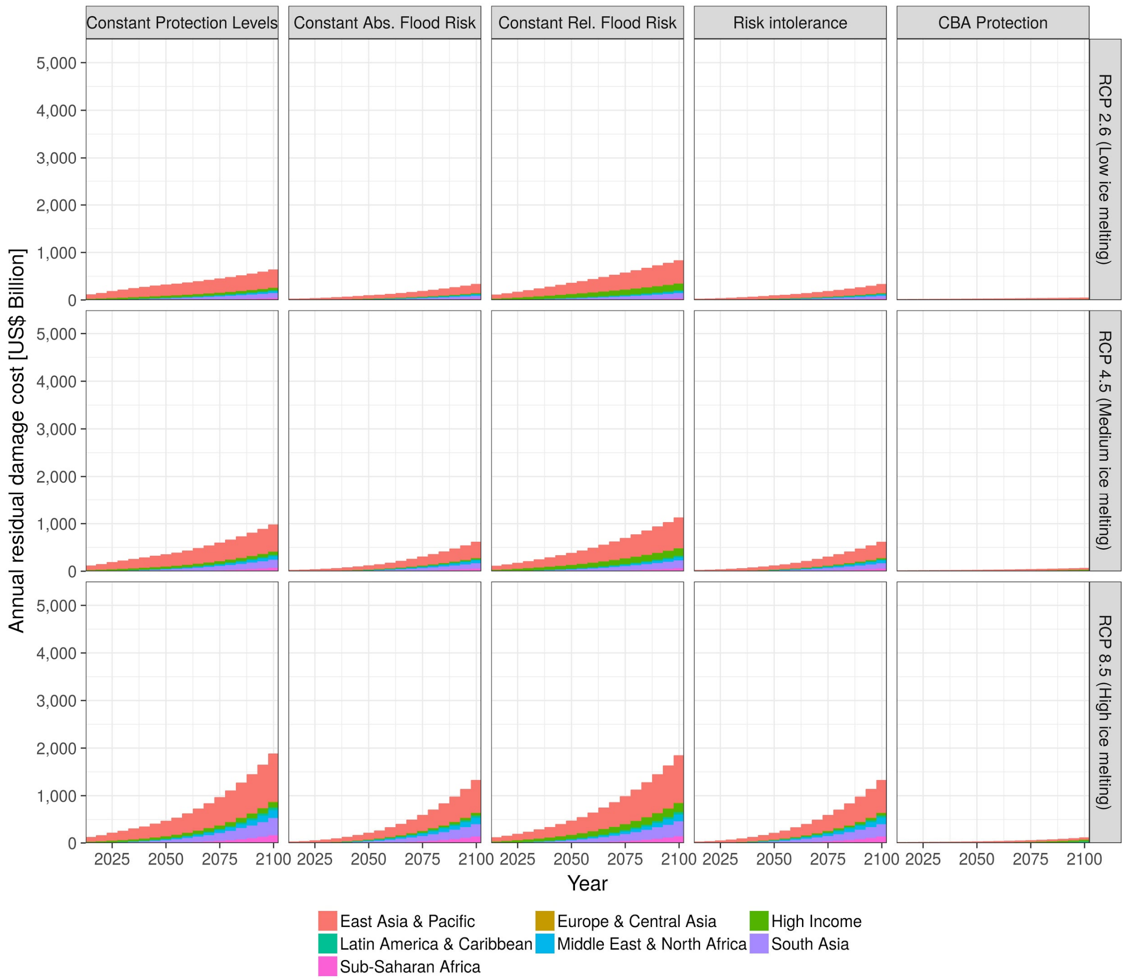


Figure A10. Annual residual damage cost during 21st century per region for SSP3.

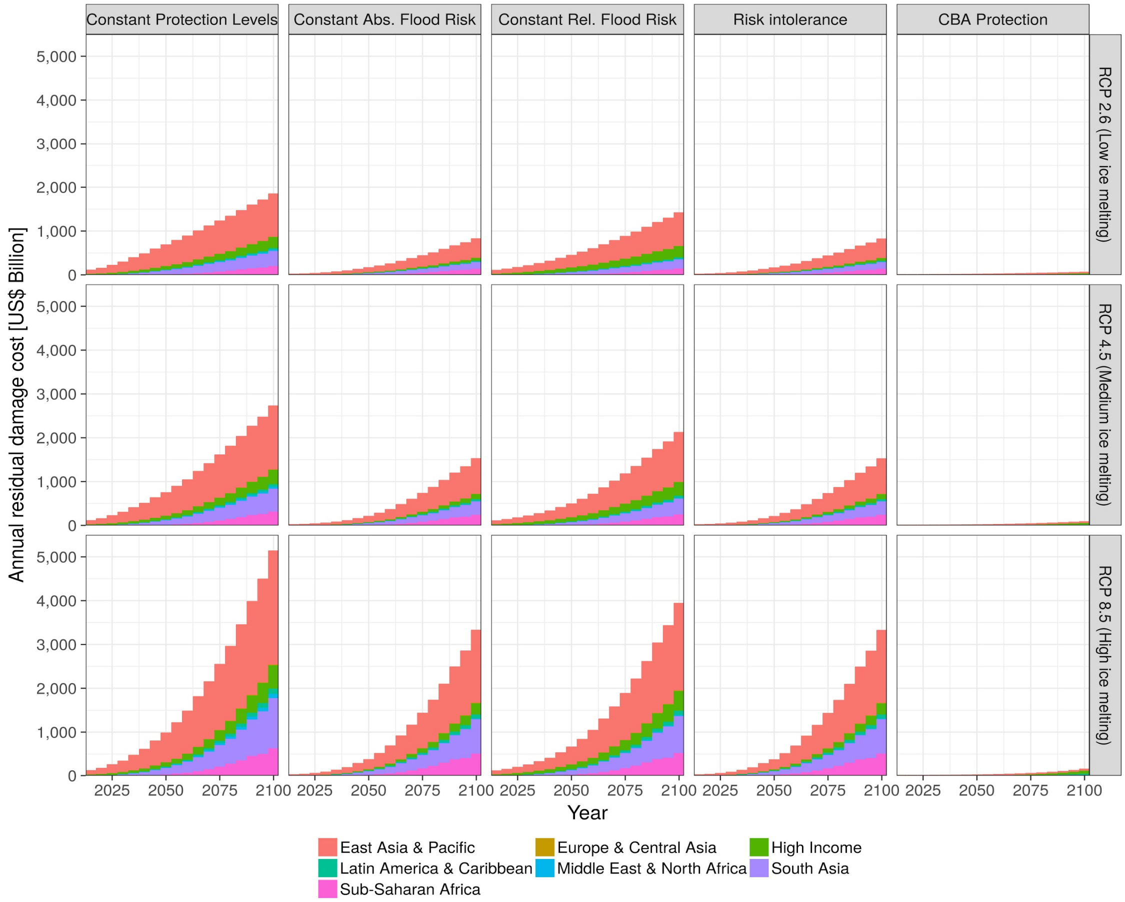


Figure A11. Annual residual damage cost during 21st century per region for SSP5.

Appendix 2. Improved estimates of unit costs of sea dikes

A.2.1 Introduction

This section introduces determinants of unit costs of sea dikes, and approaches and limitations to improve global unit cost estimates. Current DIVA estimates are based on Dronkers et al. (1990) and Hoozemans et al. (1993). In recent years, several new unit cost estimates have been reported for case studies. Jonkman et al. (2013) and Lenk et al. (2016) provide unit cost overviews for several countries; these and other (meta) sources are summarized in Table A1.

Table A1: Sources reporting unit costs for coastal defense measures.

Source	Analysis	Country	Spatial scale or location
Dronkers et al. 1990	Global adaptation analysis. Unit costs are based on measures as applied in The Netherlands and assumed standard dimensions. Country cost factors are derived from expert judgment and applied to other countries	Any	Country level estimates
Hoozemans et al. 1993	Global vulnerability assessment. As in Dronkers et al. (1990), improved by continuous cost functions of dikes and dunes, and inclusion of extreme sea levels	Any	Country level estimates
Environment Agency 2008	Technical feasibility and cost analysis for upgrading protection standards of fixed defenses in the Thames Estuary	United Kingdom	Thames Estuary
Linham, Green, and Nicholls 2010	Adaptation cost analysis of the world's largest port cities	Australia, France, Germany, Italy, New Zealand, South Africa, Spain, United Kingdom, United States - California, Mozambique	Country or state level estimates
Jonkman et al. 2013	Case study comparison. Collection of project-based information and conversion in comparable units	The Netherlands	Country level estimates for urban and rural areas
		United States	New Orleans
		Vietnam	Hai Phong / Nam Dinh
Lenk et al. 2016	Regression analysis. Comparison with results of other meta studies	Netherlands	Country level estimates

	Canada	Vancouver, estimates for urban and rural areas

A.2.2 Determinants of unit costs of sea dikes

Unit costs of coastal protection measures are defined as costs per kilometer length per meter height increment of a flood protection measure. Jonkman et al. (2013) identify material and labor costs, design choices related to the alignment of the system, and the types of measures in an urban or rural environment as the main determinants of unit costs of coastal protection on the basis of three case studies. Moreover, land acquisition costs for dike construction will tend to be higher in urban areas than in rural areas (Delcan Corporation 2012), or involve structural solutions without increasing dike width in urban areas (Kok et al. 2008).

In Dronkers et al. (1990) country cost factors ( ) have been applied to derive unit cost ( ) estimates of coastal protection measures at the country level:

$$C_i = CCF_i \cdot C_{NLD} \text{ , Eq. 1}$$

where C_{NLD} are Dutch unit costs of a standard one-meter dike increment of a dike of variable height, which comprises standard dimensions, construction materials and construction methods. The country cost factor of the Netherlands is normalized to one. The country cost factor is a correction for local conditions in material and labor inputs, mobilization of equipment, economies of scale and land acquisition costs. Differences in costs of financial capital are not included (Dronkers et al., 1990). Country cost factors have been informed by expert judgment of the (then) Delft Hydraulics. Hoozemans et al. (1993) improved these unit cost estimates by the development of continuous cost functions for stone protected and clay covered sea dikes, and sand dunes. They also included an allowance for extreme sea levels which influences initial dike heights, and roughly doubled global costs compared to Dronkers et al. (1990) (see Table 1).

To set the stage, we analyzed possible determinants of unit costs of sea dikes with a country-level cross-sectional data set from the DIVA database. The total sample contains 248 observations. We removed 47 observations without low-lying land below 10 meters A.D., as these do not have sea dikes. Furthermore, eight outliers with very high asset densities (e.g. Monaco, Gibraltar, Bahrain) were excluded from the econometric analysis.

A least squares regression analysis was performed to investigate how experts appear to have evaluated the importance of local differences in determinants of unit costs, as revealed by the differences in country cost factors. A linear specification with initial dike height and no intercept was considered, as suggested by the results of Lenk et al. (2016) and some robustness checks. Country characteristics were also included: GDP per capita, log-transformed country averages of population densities and asset densities in low-lying areas, corruption and democracy variables, and a population-asset density interaction.

Table A2: Unit cost results (OLS, no intercept).

	Estimate	Std. Error	t value	Pr(>|t|)
Initial dike height	7.79E-01	1.74E-01	4.48	0.00 (***)
GDP per capita	4.64E-05	1.72E-05	2.69	0.01 (***)
Log Population density	6.12E-01	1.06E-01	5.78	0.00 (***)
Log Asset density	-3.17E-01	2.70E-01	-1.17	0.24
Corruption	-5.94E-01	3.36E-01	-1.77	0.08 (*)
Democracy	2.28E-01	6.44E-02	3.54	0.00 (***)
Log Pop. dens.*Log Asset dens.	-6.71E-02	4.41E-02	-1.52	0.13

Table A2 reports the results; the adjusted-R^2 is 0.77 and the F-test is 92.57 on 7 and 186 degrees of freedom, P-value is 0.00. Higher initial dike heights, higher GDP per capita and higher population densities are associated with higher unit costs. The results suggest that more expensive local labor costs and more expensive land inputs may increase unit costs of sea dikes. Asset density, in contrast, is insignificant. Democracy and corruption are associated with higher unit costs. The latter is only significant at α=0.1. The corruption variable has been scaled inversely, i.e. a higher score means less corruption, which explains the negative sign.

A.2.3 Pragmatic approaches for improving the global unit cost estimates of sea dikes

This section discusses a pragmatic approach to improve global unit cost estimates of sea dikes, and the current data limitations to achieve this goal. Dronkers et al. (1990) and Hoozemans et al. (1993) multiplied unit cost estimates of the Netherlands by country unit cost factors to derive unit costs for all countries. More recent unit cost estimates of sea dikes are now available for the Netherlands. Jonkman et al. (2013) report that unit cost estimates of sea dikes range from 4.9 M to 13.5 M euros (2014) for rural areas in the Netherlands, and from 16.9 M to 24.4 M euros for urban areas.[1]

One pragmatic approach to derive new rural and urban unit cost estimates at the global level would be to multiply the recent rural and urban unit cost ranges of the Netherlands with the original country unit cost factors. However, we hypothesize that applying the Dutch urban unit cost ranges would lead to an upward bias of unit cost estimates at the global level due to a set of specific circumstances in the Netherlands that have not been reflected in the country cost factors. These include the large national budget available for defense works, the large share of land below sea level, high protection standards, high protected value in rural areas, a strong solidarity which favors protection of rural areas more than in other countries, and the polycentric urban structure. Unfortunately, we cannot statistically test this hypothesis due to the low number of case studies reporting urban unit costs at the country level.

Alternatively, we apply the rural ranges of the Netherlands to the rest of the world by multiplying them with the DIVA country factors and compare the results with unit costs found in available case studies. Table A3 shows this comparison for the United States, Canada, the United Kingdom and Vietnam. Appendix 2 contains a complete overview of DIVA country cost factors, previous DIVA estimates of unit costs and the newly estimated unit cost ranges. The case studies suggest that country unit cost factors are accurate for some countries, and inaccurate for others. The unit cost estimates reported for New Orleans, USA from the US Army Corps of Engineers in Jonkman et al. (2013), range from 4.0 M to 12.8 M euros (reference year 2014). These estimates resemble the unit cost estimate range in Table A3. Similarly, Canada's dike unit cost may be in the range of 2 M to 12 M euros based on Lenk et al. (2015). However, the rural estimates of dike unit cost for Hai Phong and Nam Dinh, Vietnam reported in Jonkman et al. (2013) are 10 times lower than those reported in Table A3 for rural areas.

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[1] Converted to 2014 price levels.

Table A3: Comparison between sea-dike unit cost derived from recent Dutch rural estimates. multiplied by DIVA country unit cost factors (left) and taken from available case studies (right). Unit costs are in M Euro km^{-1} m^{-1}, reference year 2014

DIVA			Case study results		
Country	**Current estimate**	**New estimate**	**Case study estimate**	**Location or area type**	**Meta source**
Netherlands	4.2	[4.9-13.5]	[4.9-13.5]	Rural	Jonkman et al. (2013)
			[16.9-24.4]	Urban	Jonkman et al. (2013)
USA	3.8	[4.3-11.9]	[4.0-12.8]	New Orleans	Jonkman et al. (2013)
Canada	3.6	[4.2-11.4]	[2-12]	Any	Lenk et al. (2016)
UK	4.7	[5.5-15.1]	[16-20]	Thames	Environment Agency (2008)
Vietnam	4.6	[5.3-14.6]	[0.8-1.3]	Rural	Jonkman et al. (2013)

Overall, the replacement of DIVA point estimates by ranges based on recent Dutch estimates has some appealing features. It clarifies that unit cost estimates of countries are highly uncertain, and it may improve unit cost estimates if country cost factors are correctly specified. However, the external validity of the method remains limited due to inaccurate country cost factors. Replacing the Dutch unit costs with recent estimates without updating country cost factors does not resolve systematic biases.

A.2.4 Suggestions for further research on dike costs

The case study results suggest that some country cost factors may be inaccurate. These may be improved by more empirical research on unit costs.

A.2.4.1 Production factors of dike construction

Case studies on dike unit costs indicate that the production factors labor (wages), land and physical capital (materials, machinery) are among the key determinants of the unit costs of sea dikes. Unit cost estimates may be improved by estimation of a production function of sea dikes:

$$X_i = f(Labour_i, Land_i, Capital_i \quad)$$

For this, data on local input and output levels and input prices are needed. However, international surveys on factor use or costs, such as material surveys, for dike construction are currently absent (Jonkman et al. 2013). In some cases, such information is seen as commercially sensitive and hence even if collected it is not in the public domain. Some case studies are nonetheless available that provide illustrations of factor use for construction of coastal protection measures (e.g. Dijkman 2007). However, case study information cannot be generalized across countries, as this is largely explaining the variation in unit costs, and input data are largely lacking for sea dikes.

A.2.4.2 Meta-analysis of case studies

A meta-analysis as in Lenk et al. (2016), may be improved by more case studies, as well as by inclusion of country characteristics that have been omitted. However, this is a large effort, as available case studies are based on grey literature. Currently, the number of case studies remains insufficient for out-of-sample predictions of unit costs, and the sample of case studies needs to be increased.

A.2.5. Other cost issues for further research

A.2.5.1 Total costs

Dronkers et al. (1990) apply dike length multipliers to coastline length "as the crow flies", to estimate total costs. This method is obsolete, and the applied dike length multipliers are likely to be inaccurate. Total cost estimates may not only be improved by updating unit cost estimates, but also by replacing previous dike length approximations by country totals of segment lengths as is already done in DIVA. However, the base coastline could be reviewed to test coastal lengths, especially where there are large populations and hence potential demands for defenses.

A2.5.2 Other measures for unit costs

Investment flexibility under sea level rise uncertainty is not addressed in the concept of unit costs, as gradual implementation of the work is not considered (Dronkers et al., 1990). However, the fixed cost component of structural flood protection investments is essential for economic decision-making, and it motivates anticipatory adaptation for the case of flood prevention by dike construction (van Dantzig 1956; Eijgenraam et al. 2016). It may therefore be useful to distinguish between the cost components of unit costs of sea dikes that are constant independent of the size of a dike increment, and the cost components that are not. Without this distinction, unit cost estimates may be of less use to inform coastal adaptation decisions, and they may reduce the accuracy of cost estimates at the global (or smaller) level.

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Appendix 3. Unit costs of sea dikes in M euros km^{-1} m^{-1}, reference year 2014

Country	DIVA unit cost	Country unit cost factor	New unit cost estimate - Low	New unit cost estimate - High
Aruba	1.6	0.4	1.8	5.0
Afghanistan	0.0	0.0	0.0	0.0
Angola	2.6	0.6	3.0	8.3
Anguilla	4.7	1.1	5.5	15.1
Aaland	2.1	0.5	2.5	6.8
Albania	2.0	0.5	2.3	6.2
Andorra	0.0	0.0	0.0	0.0
United Arab Emirates	3.3	0.8	3.8	10.4
Argentina	8.3	2.0	9.6	26.5
Armenia	4.2	1.0	4.9	13.5
American Samoa	3.8	0.9	4.3	11.9
French Southern Territories	2.8	0.7	3.2	8.8
Antigua and Barbuda	2.6	0.6	3.0	8.3
Australia	3.8	0.9	4.3	11.9
Austria	0.0	0.0	0.0	0.0
Azerbaijan	4.2	1.0	4.9	13.5
Burundi	0.0	0.0	0.0	0.0
Belgium	4.2	1.0	4.9	13.5
Benin	2.8	0.7	3.2	8.8
Bonaire, Saba and Saint Eustatius	1.6	0.4	1.8	5.0
Burkina Faso	0.0	0.0	0.0	0.0
Bangladesh	1.3	0.3	1.5	4.1
Bulgaria	2.0	0.5	2.3	6.2
Bahrain	3.3	0.8	3.8	10.4
Bahamas	2.8	0.7	3.2	8.8
Bosnia and Herzegovina	1.4	0.3	1.6	4.4
Saint Barthelemy	2.8	0.7	3.2	8.8
Belarus	4.2	1.0	4.9	13.5
Belize	2.9	0.7	3.4	9.4
Bermuda	1.6	0.4	1.8	5.0
Bolivia	0.0	0.0	0.0	0.0

Brazil	8.7	2.0	10.0	27.6
Barbados	2.6	0.6	3.0	8.3
Brunei Darussalam	2.8	0.7	3.2	8.8
Bhutan	0.0	0.0	0.0	0.0
Bouvetisland	2.6	0.6	3.0	8.3
Botswana	0.0	0.0	0.0	0.0
Central African Republic	0.0	0.0	0.0	0.0
Canada	3.6	0.8	4.2	11.4
Cocos Islands	3.8	0.9	4.3	11.9
Switzerland	0.0	0.0	0.0	0.0
Chile	2.6	0.6	3.0	8.3
China	6.4	1.5	7.4	20.3
Côte d'Ivoire	2.8	0.7	3.2	8.8
Cameroon	3.4	0.8	4.0	10.9
Congo, Dem. Rep.	3.4	0.8	4.0	10.9
Congo, Rep.	7.0	1.7	8.1	22.4
Cook Islands	2.0	0.5	2.3	6.2
Colombia	3.9	0.9	4.5	12.5
Comoros	3.1	0.7	3.6	9.9
Cabo Verde	2.9	0.7	3.4	9.4
Costa Rica	2.8	0.7	3.2	8.8
Cuba	2.0	0.5	2.3	6.2
Curacao	1.6	0.4	1.8	5.0
Christmas Island	3.8	0.9	4.3	11.9
Cayman Islands	4.7	1.1	5.5	15.1
Cyprus	2.1	0.5	2.5	6.8
Czech Republic	0.0	0.0	0.0	0.0
Germany	4.4	1.0	5.1	14.0
Djibouti	2.3	0.5	2.6	7.3
Dominica	3.3	0.8	3.8	10.4
Denmark	4.1	1.0	4.7	13.0
Dominican Republic	2.6	0.6	3.0	8.3
Algeria	2.1	0.5	2.5	6.8
Ecuador	2.3	0.5	2.6	7.3
Egypt, Arab Rep.	1.5	0.3	1.7	4.7
Eritrea	1.7	0.4	1.9	5.3
Western Sahara	2.2	0.5	2.5	6.9
Spain	2.1	0.5	2.5	6.8

Estonia	4.2	1.0	4.9	13.5
Ethiopia	2.8	0.7	3.2	8.8
Finland	2.1	0.5	2.5	6.8
Fiji	3.1	0.7	3.6	9.9
Falkland Islands	4.7	1.1	5.5	15.1
France	2.8	0.7	3.2	8.8
Faroe Islands	4.1	1.0	4.7	13.0
Micronesia, Federal State of	1.6	0.4	1.8	5.0
Gabon	5.7	1.3	6.6	18.2
United Kingdom	4.7	1.1	5.5	15.1
Georgia	4.2	1.0	4.9	13.5
Guernsey	4.7	1.1	5.5	15.1
Ghana	4.2	1.0	4.9	13.5
Gibraltar	4.7	1.1	5.5	15.1
Guinea	5.6	1.3	6.4	17.7
Guadeloupe	1.6	0.4	1.8	5.0
Gambia	4.1	1.0	4.7	13.0
Guinea-Bissau	5.6	1.3	6.4	17.7
Equatorial Guinea	2.9	0.7	3.4	9.4
Greece	1.8	0.4	2.1	5.7
Grenada	3.3	0.8	3.8	10.4
Greenland	4.1	1.0	4.7	13.0
Guatemala	4.1	1.0	4.7	13.0
French Guiana	2.6	0.6	3.1	8.4
Guam	3.8	0.9	4.3	11.9
Guyana	5.6	1.3	6.4	17.7
Hong Kong SAR, China	2.8	0.7	3.3	9.0
Heard Island and McDonald Islands	3.8	0.9	4.3	11.9
Honduras	4.4	1.0	5.1	14.0
Croatia	1.4	0.3	1.6	4.4
Haiti	2.6	0.6	3.0	8.3
Hungary	0.0	0.0	0.0	0.0
Indonesia	1.6	0.4	1.9	5.2
Isle of Man	4.7	1.1	5.5	15.1
India	5.7	1.3	6.6	18.2
British Indian Ocean Territory	4.7	1.1	5.5	15.1
Ireland	4.7	1.1	5.5	15.1
Iran, Islamic Republic	2.9	0.7	3.4	9.4

Iraq	4.9	1.2	5.7	15.6
Iceland	3.9	0.9	4.5	12.5
Israel	2.0	0.5	2.3	6.2
Italy	2.8	0.7	3.2	8.8
Jamaica	3.1	0.7	3.6	9.9
Jersey	4.7	1.1	5.5	15.1
Jordan	2.1	0.5	2.5	6.8
Japan	6.0	1.4	7.0	19.2
Kazakhstan	4.2	1.0	4.9	13.5
Kenya	6.2	1.5	7.2	19.7
Kyrgyzstan	4.2	1.0	4.9	13.5
Cambodia	5.6	1.3	6.4	17.8
Kiribati	2.5	0.6	2.8	7.8
Saint Kitts and Nevis	1.9	0.4	2.1	5.9
Kosovo	2.3	0.5	2.6	7.3
Korea, Rep.	18.5	4.3	21.3	58.7
Kuwait	3.3	0.8	3.8	10.4
Lao PDR	0.0	0.0	0.0	0.0
Lebanon	1.4	0.3	1.6	4.4
Liberia	2.8	0.7	3.2	8.8
Libya	3.4	0.8	4.0	10.9
Saint Lucia	3.3	0.8	3.8	10.4
Liechtenstein	0.0	0.0	0.0	0.0
Sri Lanka	1.1	0.3	1.3	3.6
Lesotho	0.0	0.0	0.0	0.0
Lithuania	4.2	1.0	4.9	13.5
Luxembourg	0.0	0.0	0.0	0.0
Latvia	4.2	1.0	4.9	13.5
Macau	3.4	0.8	4.0	10.9
Saint Martin	2.8	0.7	3.2	8.8
Morocco	3.6	0.8	4.2	11.4
Monaco	0.8	0.2	0.9	2.5
Moldova	4.2	1.0	4.9	13.5
Madagascar	2.8	0.7	3.2	8.8
Maldives	2.8	0.7	3.2	8.8
Mexico	5.2	1.2	6.0	16.6
Marshall Islands	1.9	0.4	2.1	5.9
Macedonia, FYR	0.0	0.0	0.0	0.0

Mali	0.0	0.0	0.0	0.0
Malta	2.0	0.5	2.3	6.2
Myanmar	8.7	2.0	10.0	27.6
Montenegro	2.3	0.5	2.6	7.3
Mongolia	0.0	0.0	0.0	0.0
Northern Mariana Islands	3.8	0.9	4.3	11.9
Mozambique	5.2	1.2	6.0	16.6
Mauritania	6.7	1.6	7.7	21.3
Montserrat	4.7	1.1	5.5	15.1
Martinique	1.7	0.4	1.9	5.3
Mauritius	2.8	0.7	3.2	8.8
Malawi	0.0	0.0	0.0	0.0
Malaysia	3.8	0.9	4.3	11.9
Mayotte	2.8	0.7	3.2	8.8
Namibia	6.2	1.5	7.2	19.7
New Caledonia	1.8	0.4	2.0	5.6
Niger	0.0	0.0	0.0	0.0
Norfolk Island	3.8	0.9	4.3	11.9
Nigeria	4.9	1.2	5.7	15.6
Nicaragua	6.0	1.4	7.0	19.2
Niue	2.0	0.5	2.3	6.2
Netherlands	4.2	1.0	4.9	13.5
Norway	2.6	0.6	3.0	8.3
Nepal	0.0	0.0	0.0	0.0
Nauru	3.7	0.9	4.3	11.8
New Zealand	2.0	0.5	2.3	6.2
Oman	2.9	0.7	3.4	9.4
Pakistan	4.4	1.0	5.1	14.0
Panama	4.4	1.0	5.1	14.0
Pitcairn Islands	4.7	1.1	5.5	15.1
Peru	2.1	0.5	2.5	6.8
Philippines	1.5	0.3	1.7	4.7
Palau	1.6	0.4	1.8	5.0
Papua New Guinea	2.5	0.6	2.8	7.8
Poland	4.2	1.0	4.9	13.5
Puerto Rico	2.5	0.6	2.8	7.8
Korea, Dem. People’s Rep.	2.8	0.7	3.2	8.8
Portugal	1.6	0.4	1.9	5.2

Paraguay	0.0	0.0	0.0	0.0
West Bank and Gaza	1.2	0.3	1.4	3.7
French Polynesia	1.7	0.4	1.9	5.3
Qatar	2.0	0.5	2.3	6.2
Reunion	1.5	0.3	1.7	4.7
Romania	4.1	1.0	4.7	13.0
Russian Federation	4.2	1.0	4.9	13.5
Rwanda	0.0	0.0	0.0	0.0
Saudi Arabia	2.9	0.7	3.4	9.4
Sudan	2.8	0.7	3.2	8.8
Senegal	4.2	1.0	4.9	13.5
Singapore	4.1	1.0	4.7	13.0
South Georgia and the South Sandwich Islands	4.7	1.1	5.5	15.1
Saint Helena	4.7	1.1	5.5	15.1
Svalbard and Jan Mayen	2.6	0.6	3.0	8.3
Solomon Islands	2.6	0.6	3.0	8.3
Sierra Leone	4.1	1.0	4.7	13.0
El Salvador	3.8	0.9	4.3	11.9
San Marino	0.0	0.0	0.0	0.0
Somalia	6.4	1.5	7.4	20.3
Saint Pierre and Miquelon	2.8	0.7	3.2	8.8
Serbia	2.3	0.5	2.6	7.3
South Sudan	2.8	0.7	3.2	8.8
São Tomé and Príncipe	1.8	0.4	2.0	5.6
Suriname	4.4	1.0	5.1	14.0
Slovak Republic	0.0	0.0	0.0	0.0
Slovenia	1.4	0.3	1.6	4.4
Sweden	2.1	0.5	2.5	6.8
Swaziland	0.0	0.0	0.0	0.0
Seychelles	2.9	0.7	3.4	9.4
Syrian Arab Republic	2.1	0.5	2.5	6.8
Turks and Caicos Islands	4.7	1.1	5.5	15.1
Chad	0.0	0.0	0.0	0.0
Togo	2.8	0.7	3.2	8.8
Thailand	5.6	1.3	6.4	17.7
Tajikistan	4.2	1.0	4.9	13.5
Tokelau	2.0	0.5	2.3	6.2

Turkmenistan	4.2	1.0	4.9	13.5
East Timor	1.0	0.2	1.1	3.1
Tonga	3.1	0.7	3.6	9.9
Trinidad and Tobago	3.8	0.9	4.3	11.9
Tunisia	6.2	1.5	7.2	19.7
Turkey	2.1	0.5	2.5	6.8
Tuvalu	1.5	0.3	1.7	4.7
Taiwan, China	0.9	0.2	1.0	2.8
Tanzania	2.8	0.7	3.2	8.8
Uganda	0.0	0.0	0.0	0.0
Ukraine	4.2	1.0	4.9	13.5
United States Minor Outlying Islands	3.8	0.9	4.3	11.9
Uruguay	6.4	1.5	7.4	20.3
United States	3.8	0.9	4.3	11.9
Uzbekistan	4.2	1.0	4.9	13.5
Vatikan	2.8	0.7	3.2	8.8
Saint Vincent and Grenadine	1.8	0.4	2.0	5.6
Venezuela, RB	5.9	1.4	6.8	18.7
British Virgin Islands	4.7	1.1	5.5	15.1
Virgin Islands, U.S.	2.5	0.6	2.9	8.1
Vietnam	4.6	1.1	5.3	14.6
Vanuatu	2.9	0.7	3.4	9.4
Wallis and Futuna	2.8	0.7	3.2	8.8
Samoa	2.5	0.6	2.8	7.8
Yemen, Rep.	1.2	0.3	1.4	3.7
South Africa	7.2	1.7	8.3	22.9
Zambia	0.0	0.0	0.0	0.0
Zimbabwe	0.0	0.0	0.0	0.0

Appendix 4. The Dynamic Interactive Vulnerability Assessment (DIVA) Model

The Dynamic Interactive Vulnerability Assessment (DIVA) model (Hinkel et al., 2009) currently offers, to our knowledge, both the most detailed global scale representation of the coastal zone and the implications of sea-level rise and the most comprehensive and advanced representation of relevant processes at the global scale, including adaptation. It includes a global database which represents the world's coasts (excluding Antarctica), using more than 12,000 linear segments with more than 100 parameters per segment. The DIVA model focuses on various aspects including coastal erosion impacts and adaptation (Hinkel et al., 2013), coastal wetland change (Spencer et al., 2016) and coastal flood impacts and adaptation (Hinkel et al., 2014). Here we will focus on flooding and use the same model as Hinkel et al (2014). The flood module can assess the impacts of increased coastal flooding on the population and coastal assets by comparing results obtained using various available data sources and adaptation strategies under a comprehensive sample of state-of-the art socioeconomic and sea-level rise scenarios. Flood risk is considered in terms of expected annual damage to assets, expected annual number of people flooded, and adaptation costs in terms of the dike and other defense investments and the additional maintenance costs to maintain the new defenses. The maintenance costs can be significant and are important to consider as it is important that such maintenance is included in long-term plans.

For adaptation, Hinkel et al. (2014) follow earlier studies, such as Hoozemans et al. (1983) and Nicholls (2004), and consider a common protection approach using dikes contrasting various adaptation strategies. One initial DIVA approach to adaptation was based on a demand for safety function (Yohe and Tol, 2002) which attempts to model human behavior based on empirical observation. However, the DIVA framework is flexible, and a wide range of alternative adaptation strategies can be formulated and explored (e.g. Sadoff et al., 2015). In each case, as sea levels rise, the capital and maintenance costs, as well as residual damages can be estimated.

DIVA has been used to investigate the implications of sea-level rise in earlier assessments by the World Bank and the Asian Development Bank, including the global analysis of Nicholls et al. (2010), the East Asia analysis of Nicholls et al. (2013) and the national analysis of Kebede et al. (2010).

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