Global Investment Costs for Coastal Defence Through the 21st Century

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Executive Summary

Sea-level rise threatens low-lying areas around the world's coasts with increased coastal flooding during extreme sea level events during storms. One response to this challenge is to build or upgrade coastal flood defences as exemplified by the Netherlands, New Orleans or much of the Chinese coast. In this paper we examine the potential investment costs of such an adaptation strategy applied globally over the 21st Century for sea-level rise scenarios consistent with the RCP2.6 and RCP8.5 emissions and the SSP2 socio-economic scenarios. Results are reported at the scale of World Bank Regions and the globe. This considers several contrasting scenarios of protection strategies as defined below. The DIVA model framework for coastal analysis is used to perform the analysis. This represents the world's open coast as 12,148 linear segments and also considers 245 coastal rivers, comprising 434 distributaries in total. These rivers are focussed on the world's large coastal cities where coastal flood risk and defence needs are concentrated. Defence assumptions follow earlier global analyses. For population density below 30 people/km^2, there are no defences. Above this threshold, defence standards increase with population density and wealth levels. Information from Hallegatte et al (2013) on protection standards is used where appropriate. Unit capital defence costs are developed based on the best data available. Maintenance costs are also considered and grow with the stock of defences over time. Three defence technologies are considered: (1) sea dikes for the open coast; (2) river dikes for the coastal reaches of rivers which are influenced by sea level; and (3) storm surge barriers. This is the first time that surge barriers have been considered in such an analysis. Two adaptation approaches are followed using these technologies: (1) *dike only protection* which is based on sea dikes and river dikes; and (2) *dike and barrier protection* which is based on sea dikes, surge barriers and limited river dikes as required seaward of the surge barriers. These adaptation approaches are employed following four adaptation strategies (or scenarios) on how protection might be implemented across the world. Note that these are not economic optimization approaches and rather ask what would the costs be if we followed a defined defence strategy everywhere. These strategies are as follows: (1) Constant Protection Levels -- maintain current protection levels (raising defences with sea level); (2) Constant Absolute Flood Risk -- maintain average annual losses for protected areas (considering sea-level rise and socio-economic developments) in absolute terms; (3) Constant Relative Flood Risk -- maintain relative average annual losses for protected areas (considering sea-level rise and socio-economic developments) in relative terms; (4) Risk Intolerance -- keep

relative average annual losses below 0.01% percent of local GDP. Adaptation Strategy 4 takes a normative approach and assumes the world protects like the Netherlands. This allows us to consider the scale of the adaptation deficit compared to the other adaptation strategies if such an approach was followed.

These results provide improved estimates of the protection costs given sea-level rise compared to earlier estimates. Considering the Constant Protection Level Strategy from 2015 to 2100, the total accumulated defence costs are US$2.7 to US$7.6 trillion and US$3.4 to US$9.6 trillion for the RCP2.6 and RCP8.5 scenarios, respectively. These new defence costs are higher than earlier estimates, reflecting several improvements. These include the higher and more realistic range of unit defence costs that are used compared to earlier studies. Further we consider the costs of maintenance of all the existing dike stock, which is a substantial cost and was ignored or not fully considered in earlier analyses. Maintenance is the largest component of the protection costs. Lastly, earlier studies focussed on sea dikes, while this study also includes river dikes and surge barriers where appropriate. We also evaluate an estimate of the adaptation deficit comparing Risk Intolerant Protection to Constant Level Protection and find it to be to about US$ 260 to 660 billion in 2015, or an increase of about 15% of the costs of the Constant protection Level Strategy. This is one of the first estimates of this type and it depends on a number of assumptions: more effort to estimate actual protection is recommended. Regionally most investment is High Income OECD countries and Upper Middle Income Countries, especially before 2050. After 2050, investment in Lower Middle Income Countries becomes more significant, but the relative ranking remains the same.

Future analyses could useful focus on benefit-cost analysis and benefit cost analysis as well as more investigation of protection costs, including empirical data collection. Linking these types of analyses to more detailed datasets and also a wider range of adaptation types would be useful. Benefit-cost analyses might be insightful.

1 Introduction

This paper evaluates plausible cost estimates for coastal defence 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 defence investment strategies. Hence, this analysis recognises that there is not a single protection cost estimate and actual protection costs will depend on multiple factors, including the aims of the defence investment. The analysis is reported at the scale of World Bank Regions and the globe.

The analysis considers three distinct defence technologies (1) sea dikes, (2) river dikes and (3) surge barriers. These are combined into two defence 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 defences are estimated based on assumptions applied in earlier global estimates of global flood risk. The defence approaches are applied using adaptation strategies (or scenarios) rather than economic optimization approaches and ask what would the protection costs 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 defence infrastructure for coastal flooding that provides a set of protection services for a range of realistic demands/conditions.

All costs are reported in 2014 US dollars.

The paper 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 some illustrative results, including the length of defences 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.

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 defence in places such as north-west 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.

The available protection cost estimates are summarised 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 defence types have often been shared between studies with the original Dronkers et al (1990) costs being influential.

While the costs reported in Table 1 are large in absolute terms, in relative terms they are more 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 illustrates 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 defences. 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.

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	$50-$131 billion/year (for RCP8.5) (costs for the year 2100) Accumulated costs: $3.0-$6.1 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 2005. (For RCP2.6 corresponding costs are $22-$58 billion/year in the year 2100 and accumulated costs US$2.2 trillion - US$ 4.4 trillion). Protects about 500,000 km (about 50%) of the world's estimated open coasts. Considers both capital and maintenance costs, but only for dikes built after 2000 as the study quantifies the cost of sea-level rise and not the cost of coastal protection against current sea-level variability.

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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 1 and 2). The analysis is conducted within the framework of the Dynamic Interactive Vulnerability Assessment (DIVA) Model 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 firstly consider the DIVA flood module. We then need to consider the adaptation measures and costs that are considered in the analysis. Then the methods to estimate the current (2015) protection levels are considered: these define the baseline against which future defence 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. Lastly we consider the climate and socio-economic scenarios that are utilised.

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

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

Defence Technologies	(1) Sea dikes
	(2) River dikes
	(2) Surge barriers
Defence 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

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 datasets 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 coast 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 include 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.

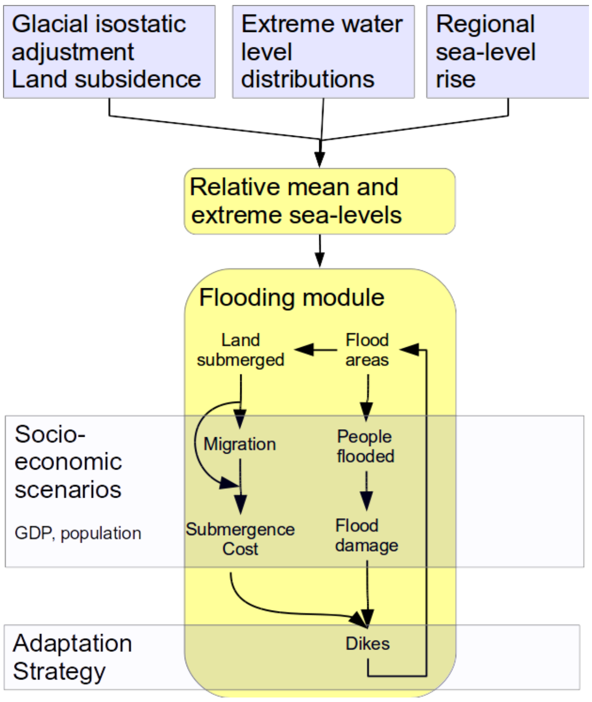

Figure 1. The DIVA Flood Module (following the approach of Hinkel et al., 2014).

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 paper 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 North-West 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 defence 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 paper we

analyse two different defence 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 cost (construction and maintenance cost) through the 21st century are considered versus the accumulated river dike cost (construction and maintenance cost) through 21st century.

Of the 434 river distributaries considered, 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. The dike only protection leads to longer lengths of defences (Figure 2).

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

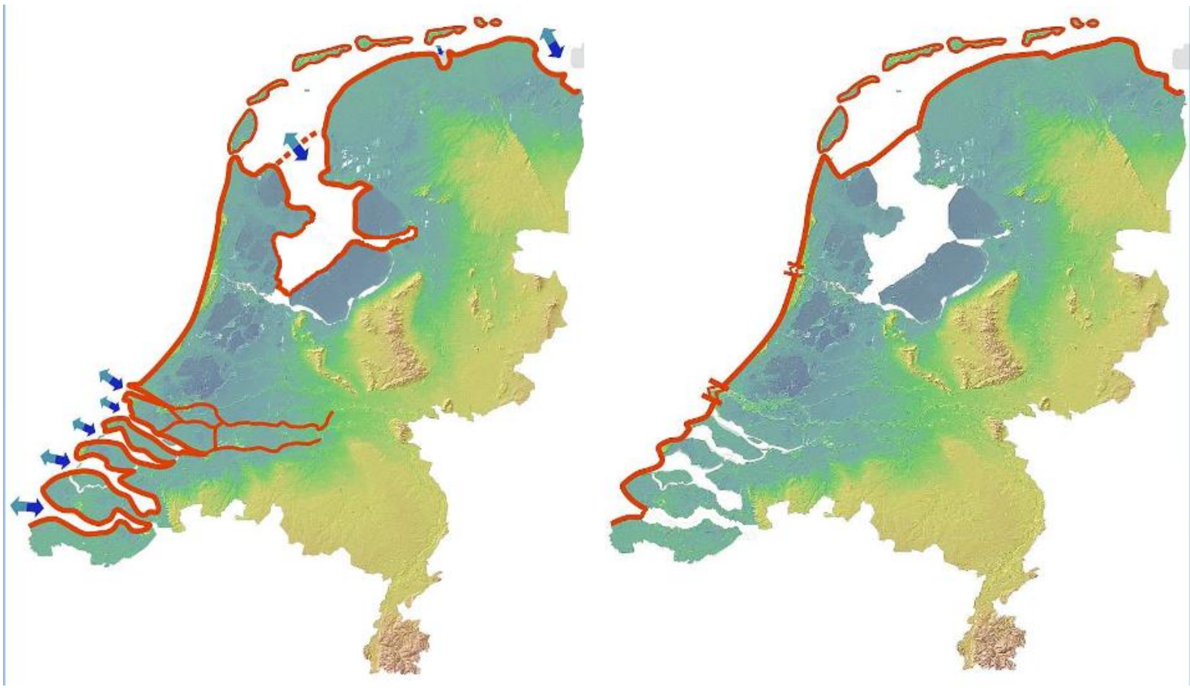

Figure 2: A comparison of open protection (left) versus closed protection (right), illustrated in the case of the Netherlands.

3.3 River and river distributary dataset

For this paper 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 dataset 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., 2008a; Hallegatte et al., 2013). The dataset was based on the original DIVA river dataset (Vafeidis et al., 2008), which was extended to a 245 river dataset. For each river we identified the main distributaries using Google Earth, defining a total of 434 distributaries (Figure 3).

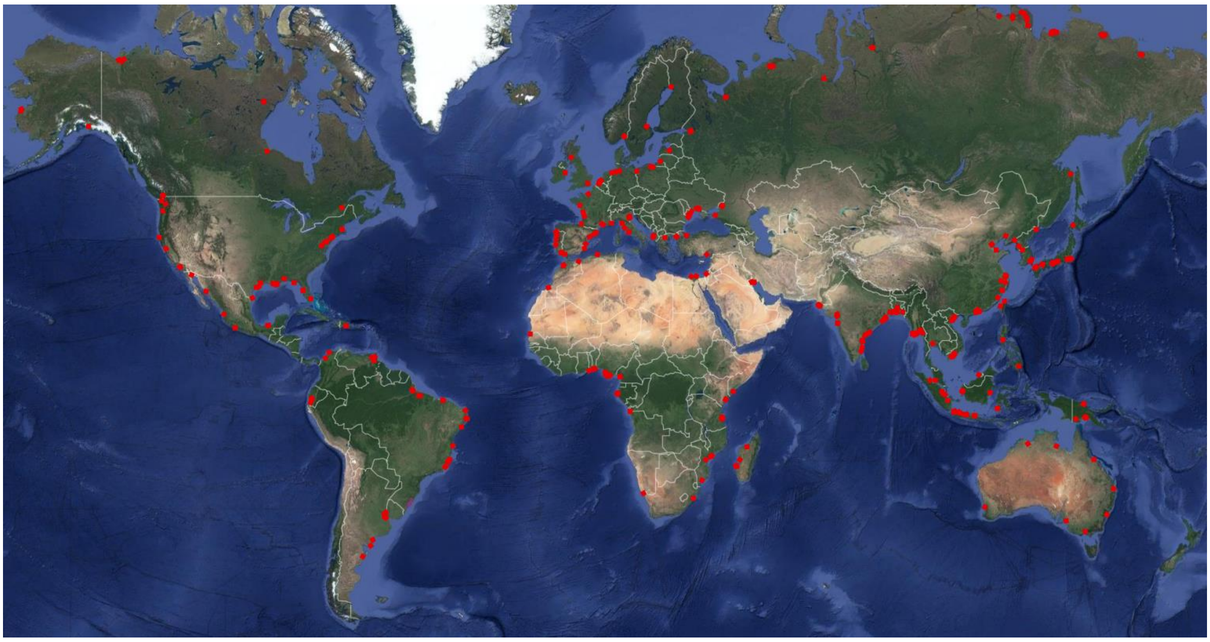

Figure 3: The river mouths (red dots) considered in this study.

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.

3.3 Sea and river dike costs

3.3.1 Sea dikes

Sea dikes are built along the open coast where required using the length of the coastal segments in DIVA. We estimate capital costs and also maintenance costs (1.0% of the capital cost per year) (Nicholls et al., 2010). 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 dikes 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 defence 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 produces a new range of costs represented by low and high estimates of dike unit costs. 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 costs and make sure they are considered, rather than forgotten or ignored.

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

3.3.2 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-1000 year extreme sea level event could penetrate inland along the river. This is done by dividing the water level of the 1-in-1000 year event by the river slope. Hence, the impact length of the 1-in-1000 year event increases with sea-level rise. For distributaries for which the length from to mouth to the main river is smaller then the impact length, only the former is considered. River dikes are increased in height (with SLR) and in length (with increased impact length). 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. 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.

3.4 Surge barriers 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 the open coast requirement.

The unit costs for surge barriers are taken from Table 3 of Jonkman et al., (2013). We use the minimal (US$ 97,000per m height and meter width) and maximal (US$ 374,000 per m 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.

3.5 Current protection levels

There are no global datasets on current levels of protection and protection levels 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)		

3.6 Adaptation strategies

In this paper, we assess the costs for the following four adaptation strategies (which are essentially scenarios of how protection might be applied globally):

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, defences 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 am Rotterdam in 2005 as calculated by Hallegatte et al. (2013) and applies this Dutch standard as a risk intolerant world.

Under Strategy 1, the defences are raised with relative sea-level rise, while under the other strategies, the defences 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. 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. Note that in any time step, the protected length is the same for all adaptation strategies.

3.7 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 summarised in Table 5.

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

Two global mean sea-level rise scenarios are taken assuming relatively low and high emissions, respectively. These are the 50th percentile of RCP2.6 (using the HadGEM-ES2 model), and the 50th percentile of RCP8.5 (using the HadGEM-ES2 model) (taken from Hinkel et al., 2014).

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)	7.4	8.4	9.4	9.7	9.2
GDP per capita (US$, global average)	14,400	20,800	30,000	46,700	72,600
Sea-level rise, RCP 2.6 (global coastal average, m)	0.03	0.08	0.14	0.21	0.28
Sea-level rise, RCP 8.5 (global coastal average, m)	0.03	0.09	0.19	0.39	0.65

4 Results

Here illustrative results from the approach described 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) Low income countries; (2) Lower middle income countries; (3) Upper middle income countries; (4) High income OECD countries; and (5) High income non-OECD countries. 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. Only the dike and barrier defence approach is considered.

4.1 Required Length/Quantity of Protection

Based on the assumptions described in Table 4, we find that 23.1 % of the world's coastline require protection by dikes in 2015 (Figure 5). These comprise (1) low income countries: 7.9% of the coast, (2) lower middle income countries: 20.4% of the coast, (3) upper middle income countries: 22.3% of the coast, (4) high income OECD countries: 27.9% of the coast, and (5) high income non-OECD countries: 13.9% of the coast. Table 6 summarises the actual length of protection required over time. From 2015 to 2100, the length of protection increases in all cases. The global increase is 16% in length, while in Lower Middle Income countries it is a 67% increase in length. Note that the length of protection estimated here is substantially less than that reported by Tol (2002) and Hinkel et al (2014) in Table 1.

Similarly, protection is required for 229 out of 434 (52.8%) river distributaries in 2015. Globally, a total length of 11,000 km river dikes are required. Under the Constant Protection Levels Strategy, dike only protection and the high sea-level rise scenario, by 2100 the number of protected river distributaries increases to 238 and the global length of river dikes increases to 12,500 km . This reflects that in some regions additional river dikes become necessary due to rising living standards (following Table 4) and that in general the dikes need to extend further inland as sea levels rise.

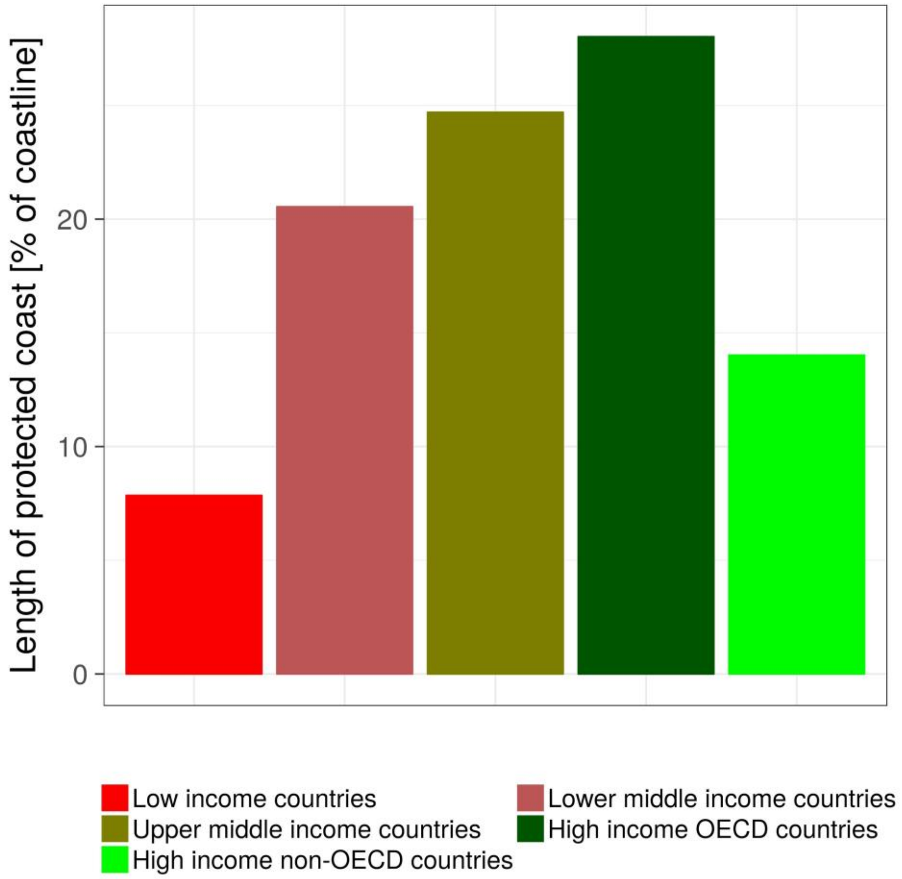

Figure 5: Percentage of protected open coast in 2015 in the five regions used in the study, following the assumptions in Table 4. Absolute values can be found in Table 6.

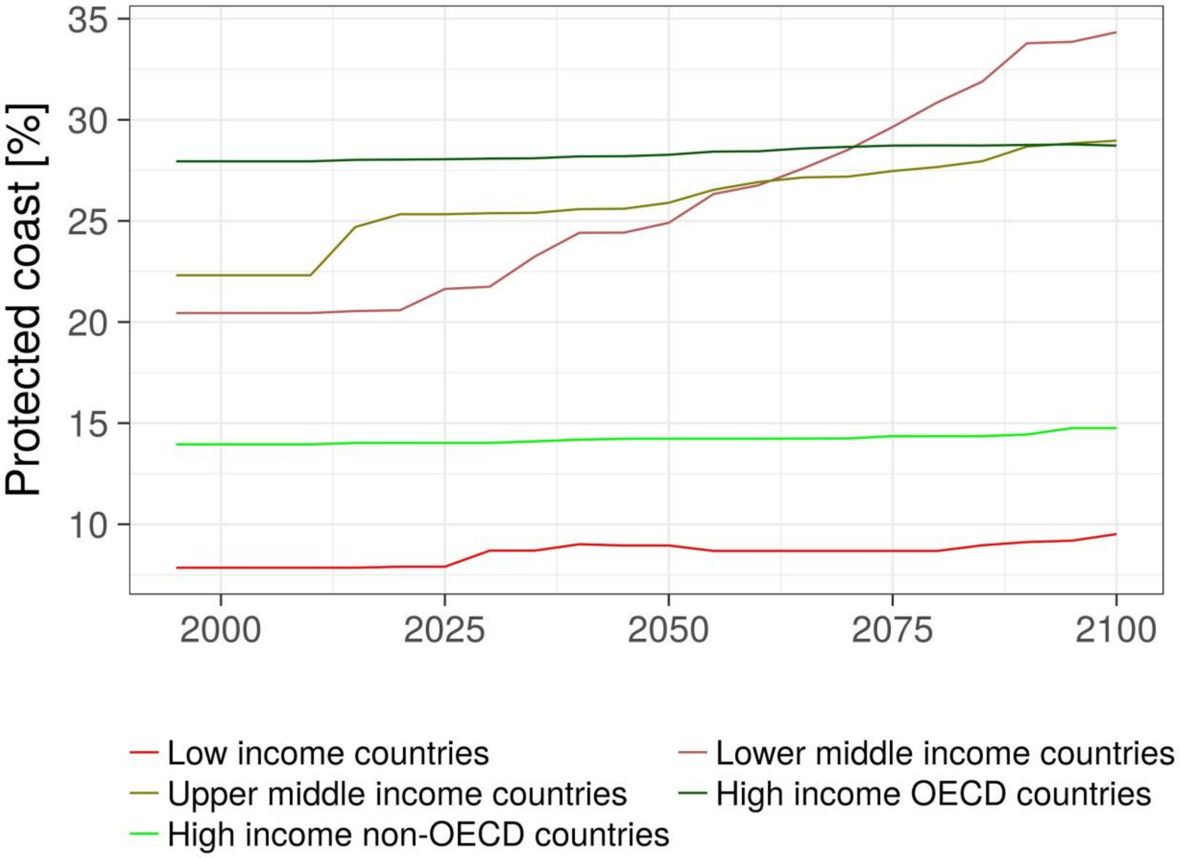

Figure 6. Percentage of protected open coast in the five regions used in the study over time. Absolute values can be found in Table 6.

Table 6. The length of protected open coast (in km) globally and by region over time (for selected years). 2010 is included to illustrate the large increase in protected length in Upper middle income countries in 2015. For reference, the global length of open coast is 690,000 km.

Year	**2010**	**2015**	**2030**	**2050**	**2100**
Low income countries	1,800	1,800	2,000	2,000	2,100
Lower middle income countries	24,400	24,500	26,000	29,700	41,000
Upper middle income countries	37,900	42,000	43,100	44,000	49,200
High income OECD countries	85,000	85,200	85,400	86,000	87,300
High income non-OECD countries	10,500	10,500	10,500	10,700	11,100
Total (global)	160,000	164,000	167,000	172,000	191,000

4.2 Protection Costs

All protection costs consider the costs of the dike and barrier protection strategies.

Figures 7 and 8 show the annual protection costs including the sum of capital and maintenance costs for the four Adaptation Strategies and the two RCP sea-level rise scenarios and the range of 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 Defence Approaches produce similar estimates of annual protection costs rising through the 21st Century. In 2100, global costs are about US$ 30 to US$ 90 billion per year under RCP2.6 and about US $50 to more than US $150 billion per year under RCP8.5.

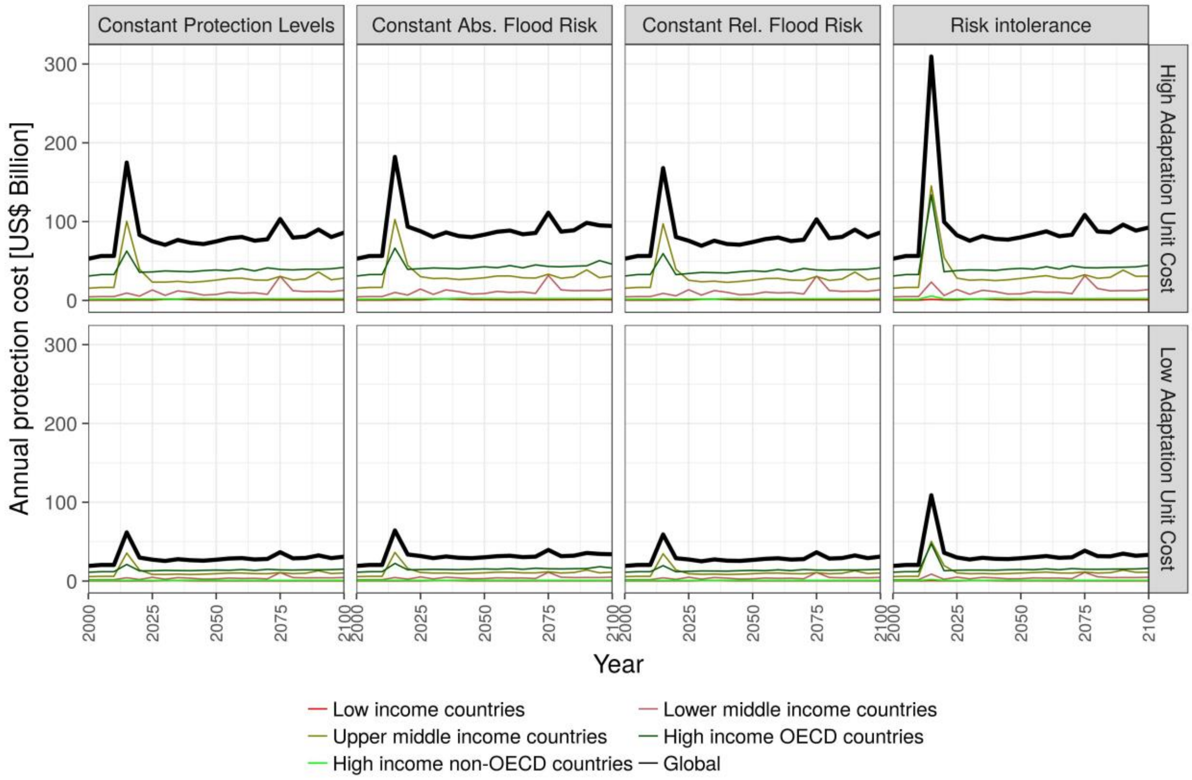

Figure 7. Annual protection costs (for dike and barrier protection) for the five regions and the total global costs over time for the four Adaptation Strategies and the RCP2.6 sea-level rise scenario. Includes maintenance and capital costs. The spike in 2015 is discussed in the text.

A spike in the costs occurs in 2015 occurs in all cases and is the biggest of several spikes in time. It reflects a large increase in the protection standards of upper middle income countries due to rising living standards (especially in Brazil and China) which raise protection standards on large lengths of coast in 2015, following the protection rules in Table 4. Under the Risk Intolerance Strategy, assuming this implemented in 2015, this is strongly 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 in the real world these costs could be distributed over a much longer period spreading the additional investment requirement over time. Note that in Figures 7 and 8, it is assumed that these additional costs occur over 5 years (which is the DIVA time step).

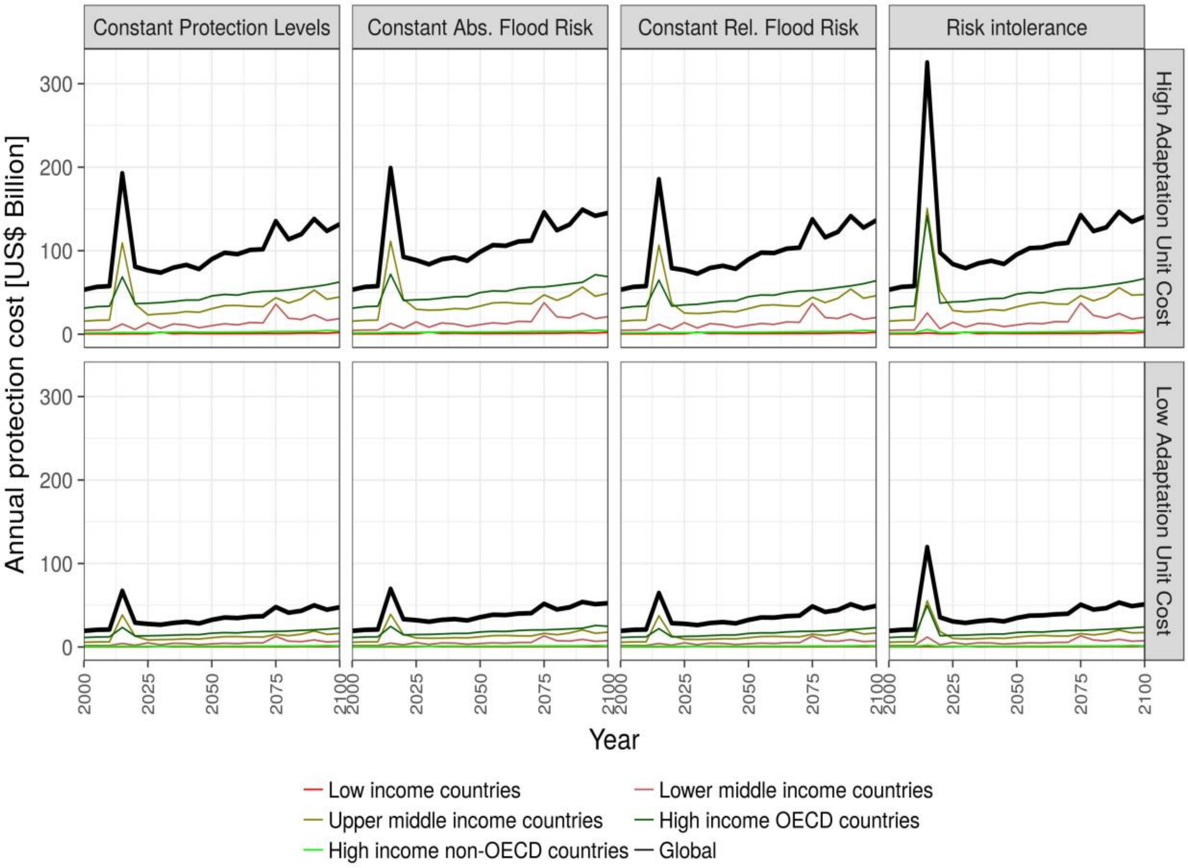

Figure 8. Annual protection costs (for dike and barrier protection) for the five regions and the total global costs over time for the four Adaptation Strategies and the RCP8.5 sea-level rise scenario. Includes maintenance and capital costs. The spike in 2015 is discussed in the text.

Figure 9.Cumulative protection costs (for dike and barrier protection) for the RCP2.6 sea-level rise scenario across the adaptation strategies.

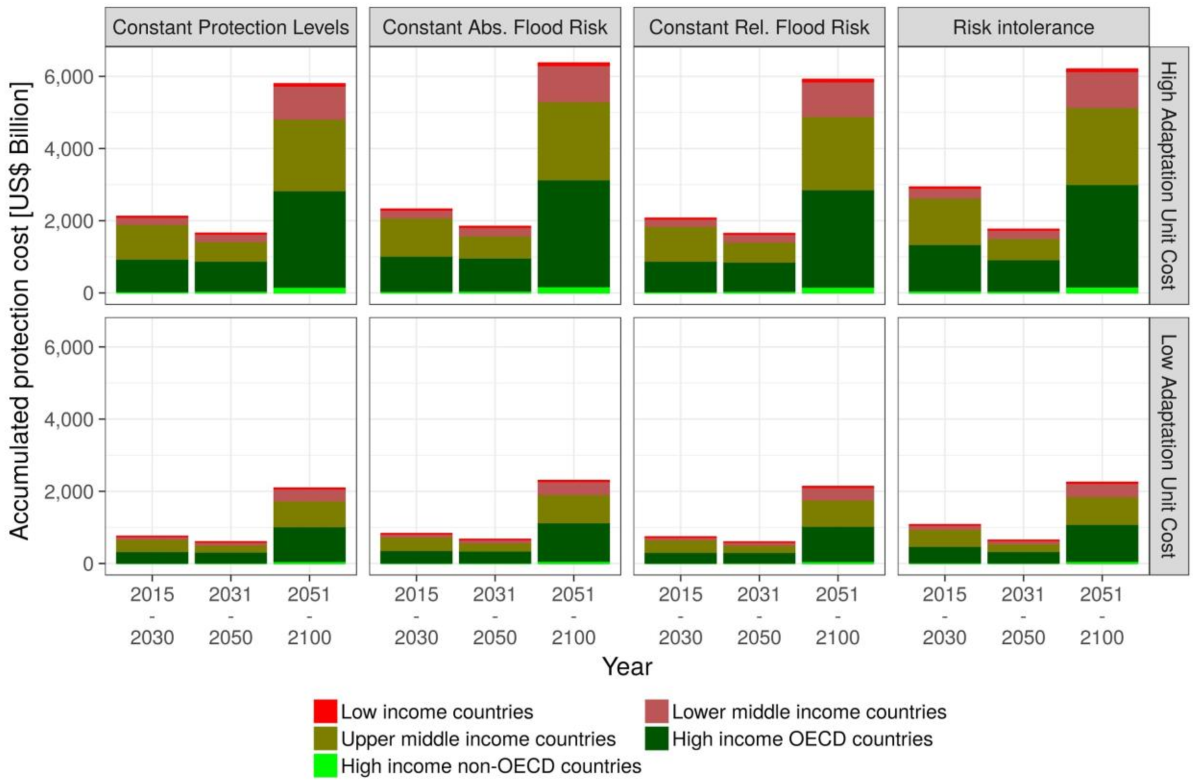

Figure 10. Cumulative protection costs(for dike and barrier protection) for the RCP8.5 sea-level rise scenario across the adaptation strategies.

Figures 9 and 10 shows the cumulative costs for the same assumptions as Figures 7 and 8 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$ 2.7 to 8.9 trillion for RCP2.6 and US$ 3.4 to 10.9 trillion for RCP8.5. In regional terms, most investment is in the High Income OECD countries, followed by Upper Middle Income countries.

The costs considered here are composed of both capital and maintenance costs. As the stock of defences increases with time, so 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 defence failure.

Figure 11 shows the global capital and maintenance costs in relative terms for the RCP2.6 and RCP8.5 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. 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.

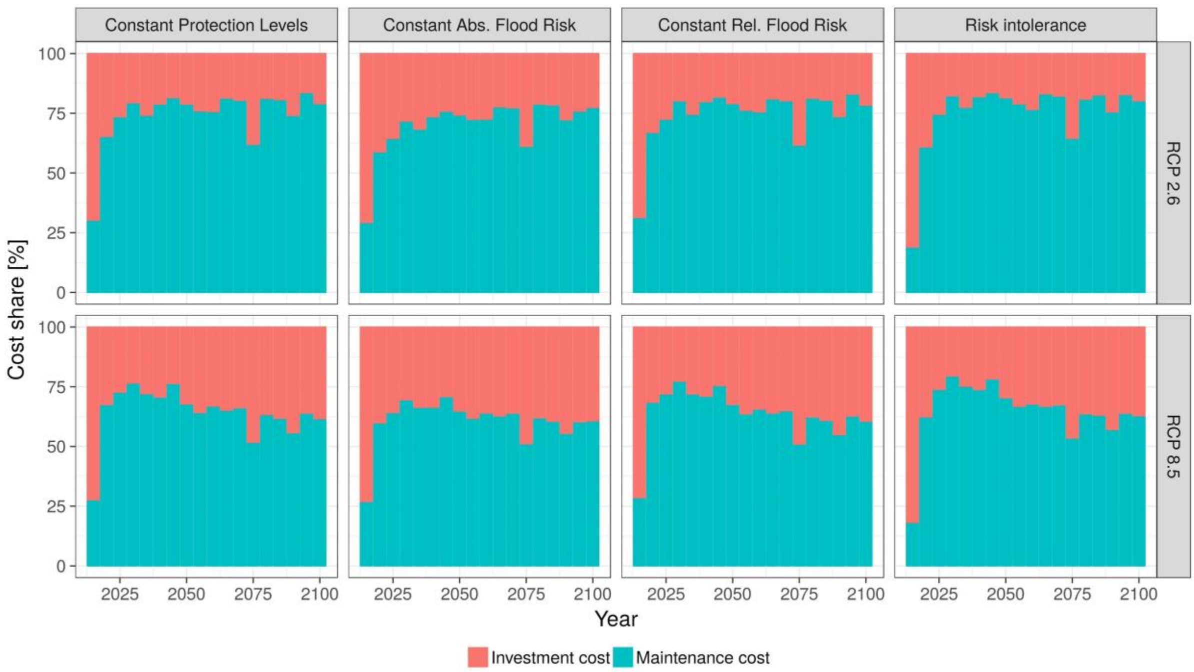

Figure 11. The share of capital versus maintenance costs (for dike and barrier protection) for RCP2.6 and RCP8.5 from 2015 to 2100.

Figure 12 shows the absolute adaptation deficit in 2015. Globally, it amounts to about US$ 260 to 660 billion. The largest adaptation deficits are in the high income OECD countries, followed by the upper middle income countries. While these costs are large, the capital costs are one-off investments -- once made the defence standards can be maintained with similar

costs to the other adaptation strategies. As noted earlier, these additional costs can be distributed over time. In Figures 7 and 8, they are dealt with over 5 years from 2015 to 2020. This could be spread over longer time spans and if the adaptation deficit was addressed in practise, it is likely this is how increased protection would be provided.

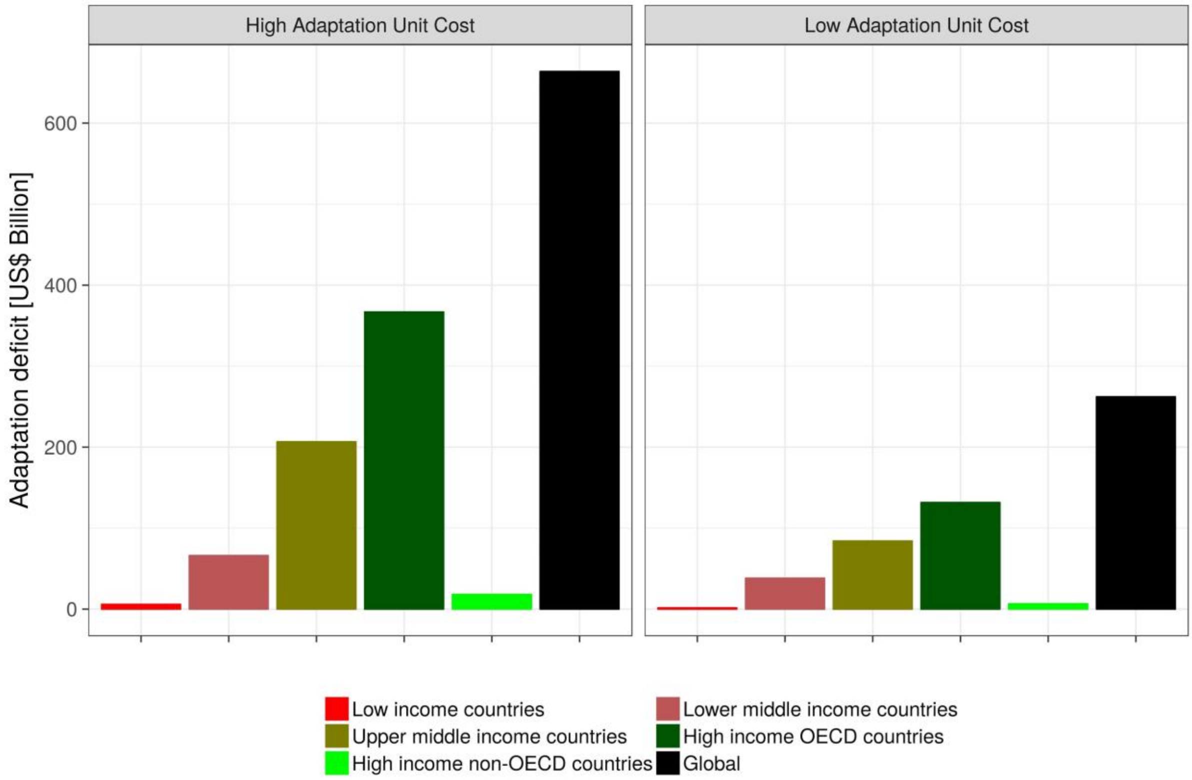

Figure 12. The absolute adaptation deficit in 2015, following the Risk Intolerance Strategy (for dike and barrier protection).

5 Discussion/Conclusions

These results provide estimates of the protection costs given sea-level rise from 2015 to 2100 for a range of defence strategies. The differences in costs between Constant Protection Levels , Constant Absolute Flood Risk and Constant Relative Flood Risk Strategies are quite small, and hence we focus on the Constant Protection Level Strategy. The total accumulated defence costs from 2015 to 2100 are US$2.8 to US$7.7 trillion and US$3.4 to US$9.6 trillion for the RCP2.6 and RCP8.5 scenarios, respectively.

These new defence costs are an improvement on earlier estimates and they are also higher than any earlier estimates in Table 1. This reflects several factors, including the higher range of unit defence costs that are used compared to earlier studies such as Hinkel et al (2014). Further in this analysis we consider the costs of maintenance of the existing dike stock (in 2015), which is substantial and was not considered in earlier studies, including Hinkel et al (2014). If this maintenance component was not considered, the costs in this study would be reduced to US $1.9 to $6.6 trillion for RCP8.5 and US $1.2 to $4.6 trillion for RCP2.6, respectively. Hinkel et al (2014) only consider sea dikes, while this study also includes river dikes and surge barriers. If we ignore river dikes and surge barriers we reduce the costs in

this study to US $1.7 to $5.9 trillion for RCP8.5 and US $1.0 to $4.1 trillion to RCP2.6, respectively.

Table 7 summarises the different components of the global protection results from Hinkel et al (2014) and this study. This shows that open coast defences dominants adaptation costs compared to river defences. Maintenance costs are much larger than the capital costs, reflecting that under the assumptions used here. These are a large stock of dikes built before 2015 to adapt to current coastal flood problems. These are costly to maintain.

Table 7. A comparison between the global defence costs of Hinkel et al (2014) and this study for the Constant Protection Level Strategy from 2015 to 2100, and consideration of the adaptation deficit (additional costs) implied by the Risk Intolerant Protection Strategy. The maintenance costs used by Hinkel et al (2014) are labelled B, while the maintenance costs used by this study are labelled A. For this study the relevant contributions of the different costs relative to Constant Level Protection Strategy are also presented. All costs are US$ 2014. n/c – not considered.

Components	Hinkel et al (2014)		This Study			
	RCP2.6	RCP8.5	RCP2.6		RCP8.5	
Capital Costs Sea Dikes	1.22-2.85	1.93-4.49	0.67-1.85	24%	1.17-3.21	34%
Maintenance Costs of All Sea Dikes (A)	n/c (7.11-8.07)	n/c (7.22-8.50)	1.93-5.32	70%	2.07-5.70	60%
Maintenance Costs of Sea Dikes built since 2015 (B)	0.98-1.59	1.03-1.61	(0.39-1.08)	14%	(0.53-1.47)	15%
Maintenance Costs of Sea Dikes built before 2015 (C)	n/c (6.13-6.48)	n/c (6.19-6.89)	(1.54-4.24)	56%	(1.54-4.23)	45%
Capital Costs River Dikes/Barriers	n/c	n/c	0.11-0.36	4%/5%	0.16-0.50	5%
Maintenance Costs River Dikes/Barriers	n/c	n/c	0.04-0.14	1%/2%	0.05-0.15	1%/2%
TOTAL COSTS Constant Level Protection	2.20-4.44	2.96-6.10	2.76-7.67		3.44-9.56	
Adaptation Deficit in 2015	n/c	n/c	0.23-0.67	8%/9%	0.26-0.66	7%/8%
Additional Costs from 2020 to 2100	n/c	n/c	0.44-1.24	16%	0.52-1.33	14%/15%
TOTAL COSTS Risk Intolerant Protection	n/c	n/c	3.20-8.90	16%	3.96-10.90	14%/15%

The Risk Intolerant Protection Strategy is also shown in Table 7 and this raises costs by about 15% over the century compared to the Constant Protection Level Strategy.

Regionally, most investment is High Income OECD countries and Upper Middle Income Countries, especially before 2050. After 2050, investment in Lower Middle Income Countries becomes more significant, but the relative ranking remains the same.

While the absolute costs are high, when compared to the assets at risk they are generally affordable. Analyses such as Fankhauser (1995) and Tol (2002) based on a benefit-cost analysis suggest that it is worth protecting large lengths of shoreline against a 1-m rise in sea level. Tol (2002) suggested that it was optimum to protect 348,000 km of the world's coastline. Using the same method as Tol (2002), Nicholls et al (2008b) showed that even if unit protection costs increased by 100 times, more than 100,000 km of the world's coastline would be worth protecting under cost-benefit analysis assumptions. The increased costs presented here are unlikely to change the conclusion that these defences are economically justifiable in many locations. Equally this analysis supports the view that most of the world's coast will be allowed to evolve naturally and hence we are likely to have a bifurcation of coastal evolution: coastal protection of valuable coastal areas and retreat where human assets are limited, representing most of the world's coastline.

The downsides of defences should be noted. If we do follow a widespread defence strategy, then the world's developed coast will increasingly start to resemble the Netherlands, with growing flood plains and potential damage and threat to life if defences fail (Hallegatte et al., 2013). If we follow a protection strategy, this residual risk must be considered and managed which implies ongoing investment in flood simulation, forecasting and warning. These costs are not considered here, but are modest compared to the defence costs considered. While maintenance costs have been considered here, it is more challenging to deliver maintenance than capital investment for defence upgrade. This implies significant efforts to enhance flood management and governance institutions. Plans like the new Bangladesh Delta Plan 2100 show efforts to establish the necessary institutions. In terms of the defences that might be used, there are more choices than just sea dikes and for example beach and dune nourishment is a viable option that might be widely applied (Linham and Nicholls, 2010).

Future analyses could useful focus on benefit-cost analysis and benefit cost analysis as well as more investigation of protection costs, including empirical data collection. Linking these types of analyses to more detailed datasets and also a wider range of adaptation types would be useful. Benefit-cost analyses might be insightful.

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