The potential of global coastal flood risk reduction using various DRR measures

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10   **Abstract.** Coastal flood risk is a serious global challenge facing current and future generations. Several disaster risk reduction (DRR) measures have been posited as ways to reduce the deleterious impacts of coastal flooding. On the global scale, however, efforts to model the effects of DRR measures (beyond structural) in the future are limited. In this paper, we use a global-scale flood risk model to estimate the risk of coastal flooding, and to assess and compare the effectiveness and economic performance of various DRR measures, namely: dykes and coastal levees, dry-proofing of urban assets, zoning restrictions in flood-prone

15   areas, and management of foreshore vegetation. To assess the effectiveness of each DRR measure, we determine the extent to which they can limit future flood risk as a percentage of regional GDP to the same value as today (the so-called *relative-risk constant* objective). To assess their economic performance, we estimate the economic benefits and costs. If no DRR measures are taken in the future, we estimate expected annual damages to exceed $2 trillion USD by 2080, directly affecting an estimated 15 million people. Over 90% of sub-national regions in the world can achieve their *relative-risk constant* targets if at least one

20   of the investigated DRR measures is employed. At the global scale, we find the effectiveness of dykes and coastal levees in achieving the *relative-risk constant* objective to be 98%, dry-proofing to be 49%, zoning restrictions to be 11%, and foreshore vegetation to be 6%. In terms of direct costs, the overall figure is largest for dry-proofing ($151 billion) and dykes and coastal levees ($86 billion), much more than those of zoning restrictions ($27 million) and foreshore vegetation ($366 million). While zoning restrictions and foreshore vegetation achieve the highest global benefit-cost ratios, they also provide the least benefits

25   overall. We show that there are large regional patterns in both the effectiveness and economic performance of modelled DRR measures. Future research could assess the indirect costs and benefits of these four and other DRR measures as well as their subsequent hybridisation.

1 Introduction

30 Coastal floods have historically been, and currently are, one of the deadliest and most damaging natural hazards in the world (Idier et al., 2020; Guha-Sapir et al., 2015). Sea-level rise will cause this hazard and subsequent impacts to increase in severity and affect society more frequently in future decades (Nicholls & Cazenave, 2010; Jevrejeva et al., 2018; Vitousek et al., 2017; Muis et al., 2020). Numerous studies have been conducted using global-scale models to assess coastal flood risk, its components – i.e. hazard, exposure, and vulnerability (Kron, 2005; UNDRR, 2015a), and the magnitude of impacts that are

35 possible if this changing risk is left unaddressed (e.g., Hoozemans et al., 1993; Hinkel & Klein, 2009; Hinkel et al., 2010; Jongman et al.; 2012; Hallegatte et al., 2013; Hinkel et al., 2014; Neumann et al., 2015; Schuerch et al., 2018; Vafeidis et al., 2019; Tiggeloven et al., 2020; Menéndez et al. 2020). The aforementioned studies project increases in global figures for people affected by coastal flooding and the associated expected damages are projected to increase through the end of the 21st century according to all the aforementioned studies. Projected increases to Expected Annual Damages (EAD) range from tens-of-

40 billions to trillions, while increases in Expected Annual Affected Population (EAAP) are projected into the tens-of-millions.

These projected changes in risk illustrate that the need for disaster risk reduction (DRR) measures is increasingly urgent (Griggs & Reguero, 2021; UNDRR, 2019). There have been numerous global calls for meaningful action towards reducing coastal flood risk, including the Warsaw International Mechanism for Loss and Damage Associated with Climate Change Impacts (UNFCCC, 2013) and the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015b). The United Nations'

45 most recent Adaptation Gap Report concluded that more ambition is needed to avert future disasters (Neufeldt et al., 2021).

Several DRR measures, such as structural measures (dykes, coastal levees, etc.), individual measures (floodproofing, flood insurance, etc.), community-wide measures (land use policy, early warning systems, etc.), and nature-based solutions (mangroves, wetlands, beach and dune nourishment, etc.), have been posited to reduce the deleterious impacts of coastal flooding. Some of these measures have subsequently been assessed using global models. For example, Hinkel and Klein

50 (2019), Lincke and Hinkel (2018), Tamura et al. (2019), Tiggeloven et al. (2020), and Schinko et al. (2020), all improve the understanding of structural DRR measures now and in the future, demonstrating that large benefits can be achieved by raising flood protection levels.

Other DRR measures, such as building-level protection, nature-based solutions, or zoning restrictions, meanwhile, have received much less attention in the global-scale literature. Regarding building-level protection, several studies have assessed

55 floodproofing of buildings against river flooding up to the national or continental level (e.g., Kreibich et al. (2005) and Haer et al. (2019)), but such studies are so far missing for coastal flooding at the global scale. In terms of nature-based solutions, some studies have quantified the current flood risk reduction benefits of conserving existing natural areas (Tiggeloven et al., 2022; Menéndez et al. 2020; Beck et al. 2018), but only Beck et al. (2022) do so regarding the future benefit of expanding these ecosystems, and only for the Caribbean. Hinkel and Klein (2009) assessed the effect of beach nourishment and wetland

60   nourishment on coastal flood risk. To date, no studies have assessed the global-scale potential of zoning restrictions, although local case studies such as Muis et al. (2015) for Java and Koks et al. (2014) for Belgium point towards the potential of expanding the modelling of this DRR measure to the global scale. Furthermore, there is a distinct lack of studies that have compared the effectiveness and/or economic performance of different DRR measures on the global scale.

The overarching aim of this paper is therefore to assess and compare the effectiveness and economic performance (in terms of
65   economic benefits and costs) of various DRR measures on coastal flooding at the global scale. We assess four different DRR measures, namely: 1) dykes and coastal levees; 2) foreshore vegetation; 3) zoning restrictions; and 4) dry-proofing of buildings. To assess the effectiveness of each DRR measure, a baseline of desired risk reduction must be established. Different criteria have been considered to establish what level of risk reduction should be aimed for and compared in terms of performance (e.g., Tiggeloven et al., 2020). As outlined by the Sendai Framework, an equitable target of risk reduction needs to be established to
70   ensure a realistic pathway forward for all regions of the world, regardless of development state or socioeconomic status. Here, we use a target in which future flood risk as a percentage of regional GDP remains constant in the future at the same level as today, also known as the *relative-risk constant* objective, as described in Ward et al. (2017) and Tiggeloven et al. (2020).

Two main research questions guide this work: 1) what level of risk reduction is needed to achieve the targets set by a *relative-risk constant* objective; and 2) to what extent can various DRR measures achieve this level of risk reduction? To answer these
75   questions, we expand the GLOFRIS, a global flood risk estimation methodology developed for coastal flooding (Ward et al., 2013; Tiggeloven et al., 2020), by implementing several DRR measures and assessing their effectiveness against a pre-defined risk target.

2 Methodology

The methodological components of this paper can be summarised in three steps (Figure 1): (1) risk estimation (section 2.1);
80   (2) simulating risk reduction (section 2.2); and (3) measure evaluation (section 2.3). In the first step we estimate the current and future risk by combining data on hazard, exposure, and vulnerability, and taking the integral of the resulting risk curve to calculate EAD and EAAP. We also set a risk reduction target per sub-national region using the *relative-risk constant* objective. In the second step, we estimate the risk reduction that could be achieved by each of the DRR measures studied as well as the residual risk remaining after taking these measures. The colours displayed in Figure 1 relate to the individual components of
85   coastal flood risk that we model and assess: blue for hazard (reduction), green for exposure (reduction), and purple for vulnerability (reduction). In the third step, we determine the effectiveness of each measure in terms of the extent to which they can achieve the *relative-risk constant* risk reduction target and perform a benefit-cost analysis.
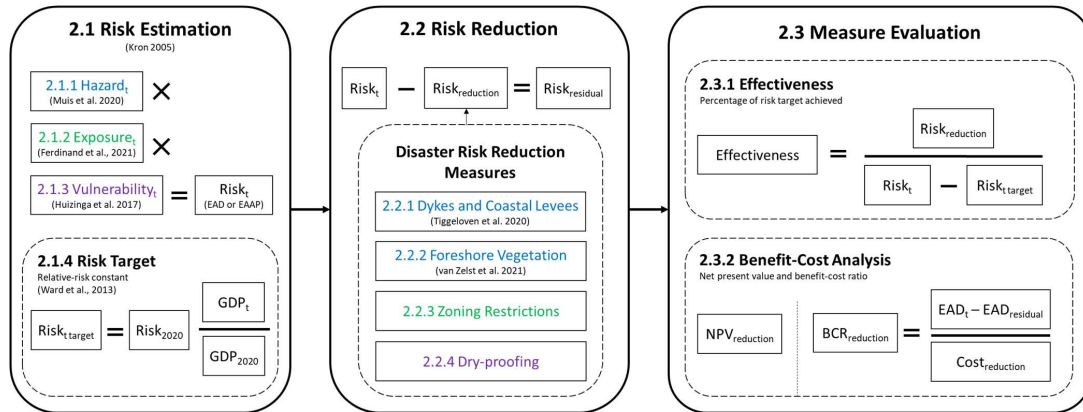
Figure 1: Our study's analysis follows three main methodological steps.

2.1 Risk estimation

We extend the GLOFRIS framework to estimate risk in our study, which was originally developed for global riverine flood risk modelling (Ward et al., 2013; Winsemius et al., 2013) and recently modified for global coastal flood risk modelling (Tiggeloven et al., 2020). We expand the framework by adding several DRR measures and a module for assessing their effectiveness against a pre-defined risk reduction target. GLOFRIS simulates flood risk by combining information on hazard, exposure, and vulnerability. Hazard is represented by inundation maps showing the flood extent and depth for different return periods at a horizontal resolution of 30" x 30" under various climate scenarios. Exposure is represented by population maps and land use maps that show urban areas and estimate their economic value (also 30" x 30"). Vulnerability is represented by so-called vulnerability curves, or depth-damage functions, which show the percentage of the economic value per grid cell that would be damaged at different flood depths. The datasets to be used for hazard, exposure, and vulnerability in this paper are discussed in sections 2.1.1 to 2.1.3.

EAAP and EAD values can be calculated for current conditions as well as future conditions for each DRR measure under various Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs). Current levels refer to those in 2020, while a future timestep consists of the window of 20 years on either side of a given year. For this analysis, we examine future results under RCP6.0/SSP2 in 2080.

2.1.1 Hazard

This analysis uses hazard maps that show floods for the following return periods: 2, 5, 10, 25, 50, 100, 250, 500, and 1000 years. The hazard maps show the extent and depth of flooding per grid cell (30" x 30") for each return period under current

conditions and under sea-level rise projections (Garner et al., 2022) for RCP 6.0. The coastal hazard maps were developed using data from CODEC (Muis et al., 2020), which is based on the hydrodynamic Global Tide and Surge Model (GTSM)

110 forced with wind and pressure fields derived from ERA5 (Hersbach et al., 2020) and enriched with simulated tropical cyclones using the IBTrACS (International Best Track Archive for Climate Stewardship) archive.

From GTSM, extreme values are estimated for the required return periods by fitting a Gumbel distribution. These extreme sea levels are then used as input for a GIS-based inundation model using the MERIT DEM (Yamazaki et al., 2018), as described in Tiggeloven et al. (2020), to simulate the inundation. This is a static flood model that simplifies all dynamic processes into

115 a single attenuation factor of the water levels over land (Vafeidis et al., 2019) and does not include future changes in waves and storminess. Results of RCP6.0, an intermediate climate change scenario, are explored here in the main text.

2.1.2 Exposure

Exposure input includes current and future population and urban areas, current and future GDP, and maximum economic damage per urban grid cell. Gridded data for population and urban areas and GDP are taken from the 2UP model (Andree &

120 Koomen, 2017). The 2UP model uses the Global Human Settlement (GHSL) framework (Corbane et al., 2019) as a starting point for current exposure and then independently simulates future expansion and development. GHSL provides a built-up area grid derived from Sentinel-2 global image composite for reference year 2018 using Convolutional Neural Networks (GHS-S2Net) at a resolution of 10'x10', which is resampled to 30"x30" (Ferdinand et al., 2021). Future simulations of built-up area include five narrative descriptions of future societal development associated with SSPs, which vary from sustainable global

125 development to regional conflict (O'Neill et al., 2017). We present our results using SSP2, or the "Middle of the road" scenario.

Maximum economic damages are estimated using the methodology of Huizinga et al. (2017), where a root function is used to link GDP per capita to construction costs for each country. To convert construction costs to maximum damages, several adjustments are carried out using the suggested factors by Huizinga et al. (2017) for the different occupancy types. The urban grid cells of the layers from the 2UP database are assumed globally to be 75 % residential, 15 % commercial, and 10 %

130 industrial, based on a European-scale study by Economidou et al. (2011) and a comparison of European cities' share of occupancy type of CORINE Land Cover data (EEA, 2016). Following Huizinga et al. (2017), the density of buildings per occupancy type are set to 20 % for residential and 30 % for commercial or industrial.

To estimate future maximum damages, the current values are scaled with the GDP per capita per country from the SSP database. Boundaries of countries are derived from version 3.6 of the Global Administrative Areas dataset (GADM, 2020).

135 Future gridded GDP values are taken from Van Huijstee et al. (2018), which uses the national GDP per capita from the SSP database as input.

2.1.3 Vulnerability

Vulnerability is represented using different global flood depth–damage functions (Nasiri et al., 2016) for each occupancy type mentioned in the previous section. The curves used here are taken from Tiggeloven et al. (2020) and are based on the empirical

140 curves described in Huizinga et al. (2017). The resulting damages are represented as a percentage of the maximum damage, or the total assumed economic value of the given cell. This maximum damage is reached at a water level depth of 6m.

2.1.4 Risk target

To assess the effectiveness of the DRR measures, we establish a baseline risk reduction target against which each measure is benchmarked. While this target could be set in terms of financial or human impact using many indicators, in this analysis, the

145 target risk reduction is set by the so-called *relative-risk constant* objective as defined by Ward et al. (2017) and applied by Tiggeloven et al. (2020). Specifically, we define the *relative-risk constant* target as the level of future risk in which the percentage of future impacted GDP to future total GDP is held constant to the percentage of current GDP impacted to current total GDP. The *relative-risk constant* target is calculated for each sub-national region individually, and for this study is presented at the time-step of 2080.

150 An estimate of the current flood protection standard for each sub-national region is required to calculate the current risk. We use estimates of the current protection level by applying the FLOPROS modelling approach as originally described in Scussolini et al. (2016) and applied for coastal flooding by Tiggeloven et al. (2020). In the absence of information regarding the protection standards of certain sub-national regions, a 2-yr protection standard in 2020 is assumed. Meanwhile, a maximum of 1000-yr protection standard assumed in only some special cases (e.g., the Netherlands and Singapore). Due to sea-level rise

155 and subsidence, the protection standard of current flood protection infrastructure will decrease in the future if no improvements are made (e.g., a DRR measure that provides protection against a 100-yr event today may only protect against a 75-yr event in the future).

2.2 Risk reduction

The DRR measures modelled in this analysis can be roughly divided into three categories; measures that either reduce hazard

160 (i.e., dykes and coastal levees and foreshore vegetation), exposure (i.e., zoning restrictions), or vulnerability (i.e., dry-proofing). Of course, these four DRR measures could arguably influence and alter another component of risk – additional development occurring behind a dyke thus increasing potential exposure in the event of a failure (Haer et al., 2020), for example. For the purpose of simplifying the study, though, we do not explore these unintended effects or consequences of DRR measures. In the following subsections, we describe each of the four DRR measures assessed in this study.

2.2.1 Dykes and coastal levees

The modelling of dykes and coastal levees largely follows the methodology detailed in Tiggeloven et al. (2020), in which inundation depth is used as a proxy for dyke height and thereafter translated into a protection standard. Similar to the flood hazard modelling methodology, water levels for dyke heights are derived from GTSM (Muis et al., 2020) and corresponding current wave conditions at different return periods from the ERA-Interim reanalysis (Dee et al., 2011).

Assuming that the incoming wave direction is perpendicular to the coast, the wave attenuation over the foreshore is determined via a lookup table consisting of numerical modelling results (Tiggeloven et al., 2022; van Zelst et al., 2021). Current dyke heights with respect to local hydrological conditions, wave attenuation, and extreme sea level are calculated with the empirical EuroTop formulations (Pullen et al., 2007) and are based on a standard 1:3 dyke profile without berms. This is representative of a low-cost dyke. To calculate future dyke heights, sea-level rise is added directly to the crest height (Jackson & Jevrejeva, 2016). Subsidence levels, taken from Kooi et al. (2018), are also considered when calculating dyke height. Subsidence is assumed to take place directly on the dyke and therefore computed on the crest height, which is similar for sea-level rise calculations.

The difference between current and future dyke (and coastal levee) heights, multiplied by the length required and the unit costs, represents the cost associated with this DRR measure. This cost methodology is also described in Tiggeloven et al. (2020). The costs of raising dykes are estimated by calculating the total length of dyke heightening per grid cell and multiplying by a unit cost set to \$7 million km m−1 based on reported costs in New Orleans (Bos, 2008). This unit cost is multiplied by a construction index multiplier, based on civil-engineering constructions costs, to adjust the construction costs to account for differences between countries (Ward et al., 2010). The unit cost value used is within a reasonable range when compared to various studies (Aerts et al., 2013; Jonkman et al., 2013; Lenk et al., 2017; Tiggeloven et al., 2020). The costs are discounted with a discount rate of 5 % until 2100 (lifespan of investment) and with operation and maintenance costs of 1 %. We assume that initial investments are made in 2020, with construction complete after 20 years (Tiggeloven et al., 2020). We also assume that the dykes as modelled do not fail for water levels below the crest level and fail completely for water levels that are higher.

2.2.2 Foreshore vegetation

The enhanced effect of foreshore vegetation (i.e., salt marsh conservation and mangrove restoration) on wave attenuation is modelled based on the methodology of Tiggeloven et al. (2022), which largely builds on van Zelst et al. (2021) regarding the quantification of wave attenuation and energy dissipation provided by foreshore vegetation. This vegetation can assist in wave attenuation and lower extreme sea level estimates, which in turn can reduce the inundation extent and depth otherwise experienced along coastal areas. Specifically in this research, current extents of salt marshes are conserved (Tiggeloven et al.,

2022) and mangrove extents are expanded based on the Mangrove Restoration Potential Mapping Tool as developed by
195   Worthington & Spalding (2018).

Critically, as there is no existing database of potentially restorable salt marshes, we assume a constant extent of this specific type of foreshore vegetation from now into the future. The type of vegetation is determined by maps of global salt marshes (Mcowen et al., 2017) and mangroves (Giri et al., 2011). Vegetation data from maps of the Corine Land Cover for Europe only and GlobCover v2.2 for the rest of the world are derived to complement areas of missing data.

200   No direct costs are considered to be incurred with preservation of existing salt marshes (Tiggeloven et al., 2022). We therefore assume that the direct costs of the foreshore vegetation measure stem from mangrove restoration. The total area of new mangroves that are capable of being restored is just under one million hectares, as identified by the Mangrove Restoration Potential Mapping Tool (Worthington & Spalding, 2018). We set initial investment costs to ~$42,800 per hectare of new mangroves in high and upper-middle income countries and ~$1,410 in lower-middle- and low-income countries, with
205   maintenance costs set to 2.5% of the initial investment per year (Aerts, 2018; Bayraktarov et al., 2016; Marchand, 2008; Siddharth Narayan et al., 2016). We assume that all mangrove restoration, if supported and funded properly, can occur rather quickly (Ellison et al., 2020; Kaly & Jones, 1998) and is therefore complete by 2030. Throughout the remainder of the simulation, restored mangrove areas are held spatially constant.

2.2.3 Zoning restrictions

210   With zoning restrictions, we assess the potential reduction in flood risk that could be achieved by restricting future urban development in flood-prone regions. This is achieved by performing a simulation of future urban expansion using the 2UP model (PBL, 2022) in which no expansion of urban areas is allowed in cells that are inundated by the 1000-yr return period flood in 2080, according to the flood hazard maps described in section 2.1.1. Cells that are classed as urban in the current time period remain urban in the future. In 2UP, this means that the future urban cells that would otherwise develop over time in the
215   1000-yr flood zone are instead reassigned to another likely non-flood-prone location within the same country, based on simple suitability functions (Ferdinand et al., 2021).

Although it does not eliminate existing risk, this DRR measure results in fewer people and assets being exposed to flood risk under future scenarios, and therefore results in benefits as we define them in this study. The main direct cost of exposure reduction through zoning restrictions is the administrative cost associated with implementing such a policy, which varies
220   significantly on local scales and in styles of implementation (Dunham, 1959; Porse, 2014). When compared to the costs of other measures such as dykes and coastal levees, though, the direct costs associated with zoning restriction are marginal. Here, a nominal total cost per sub-national region of $2,000,000 (for high and upper-middle income regions) or $500,000 (for lower-middle- and low-income regions) is applied evenly over all years of simulation (Meng, 2021; Ran & Nedovic-Budic, 2016; de

Bruin et al., 2014). While having minimal direct cost in its implementation, altering development with zoning restrictions also

225 produces an opportunity cost, which is the difference of economic value of land that would have been developed within a flood-prone area as opposed to leaving that land in a less developed state (Parsons & Wu, 1991). These opportunity costs may be significant on the local scale. For our analysis, though, we assume that any potential GDP growth still occurs in-country but is only displaced away from the flood zone.

2.2.4 Dry-proofing

230 For vulnerability reduction, the analysis focuses on dry-proofing for individual buildings. Dry-proofing makes a structure and its contents less likely to face damage from a flood event (i.e., waterproofed) up to a certain water level (Zevenbergen et al. 2007). Dry-proofing, for example, has been shown to be (cost-) effective in certain regions around the world (Kreibich et al., 2005; Haer et al., 2019). The uptake of such measures can be reinforced by building codes. Recent studies have investigated this vulnerability reduction measure on a European scale by Haer et al. (2019), but a global analysis is lacking. For this global

235 analysis, we assume that assets cannot be dry-proofed safely above 1m as water pressure above these levels would reduce the structural integrity of a building (FEMA, 2021).

We also assume that all assets – residential, commercial, and industrial – receive this treatment within urbanised cells only. Based on previously mentioned assumptions of land-use type and density in section 2.1.2, this amounts to a total dry-proofing area of 22.5% of any given urban cell. Considering the default protection standard of a 2-yr return period, areas of potential

240 application are defined as all inundated urban cells within the 2-yr flood zone that have an inundation depth of less than 1m. In all remaining return periods, dry-proofing is assumed to be applied in inundated areas not excluded by the above delineation. Because this measure is used to protect physical assets within exposed areas (thus reducing monetary damage) but does nothing to alleviate human safety concerns, EAAP will not be altered.

We apply the costs of dry-proofing on a per area basis of buildings within urban cells (m^2). The costs, and therefore

245 affordability, are dependent on the income-level of different regions (Hudson, 2020; Aerts, 2018). Thus, we assume a cost of ~$1,300 per square meter for high and upper-middle income countries and ~$580 per square meter for lower-middle- and low-income countries. Most existing literature describes in detail the costs posed by dry-proofing within the United States and other developed nations (FEMA, 2021, de Ruig et al., 2020, de Graaf et al., 2013).

2.3 Measure evaluation

250 #### 2.3.1 Effectiveness

We assess the effectiveness of the examined DRR measures by evaluating their ability to reduce (monetary) risk to maintain the relative-risk *constant* target per sub-national region. This effectiveness is expressed as the risk reduction achieved by the

DRR measure divided by the amount of risk reduction that was required to reach the *relative-risk constant* target. For example, if a measure can achieve the entire amount of required risk reduction to lower future risk levels to the exact level of the risk

255 target, the effectiveness of the measure is 1. While it is possible to exceed 1 if a measure reduces risk further than the *relative-risk constant* target, in this study we only report values up to 1. The minimum effectiveness is assumed to be 0, where a measure is unable to reduce any future risk when compared to the scenario in which no action is taken. The effectiveness of each measure is calculated for each sub-national region.

2.3.2 Benefit-cost analysis

260 A benefit-cost analysis (BCA) is performed to demonstrate the economic feasibility of a DRR measure, using two indicators, namely Net Present Value (NPV) which is the net return on investment discounted to present value, and the Benefit-Cost ratio (BCR), which is the ratio between discounted benefits and discounted costs. For NPV, the benefits and costs are discounted with a discount rate of 5%. This discount rate is within the range of financial-equivalent rates for adaptation efforts in the face of increasing flood risk (Ward et al., 2017).

265 Yearly discounted benefits are divided by initial and yearly discounted costs. To calculate the benefits of each DRR measure, EAD is calculated for every year of the lifetime of each measure and subtracted from the EAD for every year without the measure. The results of each yearly calculation are summed to determine the total benefits. Costs are calculated by summing investment and capitalized maintenance costs. The costs reported in this paper are in US$2005 at Purchasing Power Parity (PPP) and were adjusted using GDP deflators from the World Bank. As mentioned, indirect benefits such as nature

270 contributions to people (Barbier et al., 2011; Jakovac et al., 2019), are not included in this benefit-cost analysis.

3 Results

The results of this analysis are presented on several spatial scales, including on the global, regional (i.e., World Bank analytical regions), national, and sub-national level. The results of RCP6.0/SSP2 in 2080 are examined and visualised in this section, with full sub-national-level results available in the supplement.

275 3.1 Risk estimation assuming no DRR action

Future global flood risk values will eclipse those of the present if no action is taken. Without any DRR action (i.e., only maintaining the height of current protection structures), EAD is projected to increase by nearly a factor of 300 and global EAAP is projected to roughly quadruple by 2080 (Table 1). By the year 2080, global EAD will be over $2 trillion, while global EAAP will exceed 15 million people. Generally, EAD exhibits an exponential growth pattern while EAAP increases linearly

280 through the examined time-steps of this study. The impacts of current and future coastal flood risk are also shown at the regional scale in Table 1.

Table 1: Current and future EAD (Billion USD) and EAAP (Millions) per World Bank analytical region, with percentage of total regional GDP and population impacted provided in parentheses.

World Bank Analytical Region	2020 EAD B USD	2080 EAD B USD	2020 EAAP M ppl.	2080 EAAP M ppl.
East Asia & Pacific	2.815 (0.008%)	1082 (1.04%)	2.140 (0.09%)	6.354 (0.34%)
Europe & Central Asia	0.552 (0.002%)	14.27 (0.02%)	0.155 (0.02%)	0.167 (0.02%)
Latin America & Caribbean	0.319 (0.004%)	75.79 (0.22%)	0.070 (0.01%)	0.200 (0.03%)
Middle East & North Africa	0.130 (0.002%)	17.30 (0.06%)	0.089 (0.02%)	0.316 (0.05%)
North America	0.128 (0.001%)	35.35 (0.09%)	0.036 (0.01%)	0.110 (0.02%)
South Asia	0.187 (0.002%)	388.7 (0.51%)	1.130 (0.06%)	6.070 (0.25%)
Sub-Saharan Africa	3.277 (0.114%)	527.2 (1.00%)	0.439 (0.04%)	2.359 (0.10%)
GLOBAL TOTAL	7.407 (0.007%)	2186 (0.55%)	3.705 (0.05%)	15.58 (0.17%)

Between 2020 and 2080, all regions are projected to experience substantial percentage increases in both EAD and EAAP. Due to relatively low existing levels of risk and protection standards, the largest percentage increase to EAD is in South Asia, while the largest percentage increase to EAAP is in Sub-Saharan Africa. The largest share of future risk in absolute monetary terms is found in three regions: East Asia and the Pacific, Sub-Saharan Africa, and South Asia. These regions are projected to experience increases to EAD of roughly $1.08 trillion, $524 million, and $389 million, respectively, reflecting the large-scale urbanisation and population growth projected to occur in these regions throughout the remainder of the century. Beyond economic development, South Asia is projected to see nearly five million more people affected by coastal flooding annually by 2080 than currently. The relative risk values (i.e., EAAP relative to total regional population, and EAD relative to total GDP of the region) are also shown in Table 1 in parentheses. These results show that while spatially localised, coastal flooding has a major economic and human impact on entire global regions.

Similar patterns can also be seen on the (sub-)national scale. The largest percentage increases to EAD are projected in Bangladesh, Senegal, and Madagascar (three countries with low current levels of risk), while the largest absolute changes are projected in China, India, and Indonesia. The ten countries with the highest future EAAP all belong to the three World Bank

regions with highest future EAAP mentioned previously. While certain high-income countries, such as The Netherlands, United States of America, and United Kingdom, are also projected to have high future EAAP, lower-middle income countries represent the largest portion – roughly two-thirds – of future EAAP. Changes in both absolute and relative EAD and EAPP

300   are shown per sub-national region between from current conditions and future conditions in Figure 2.
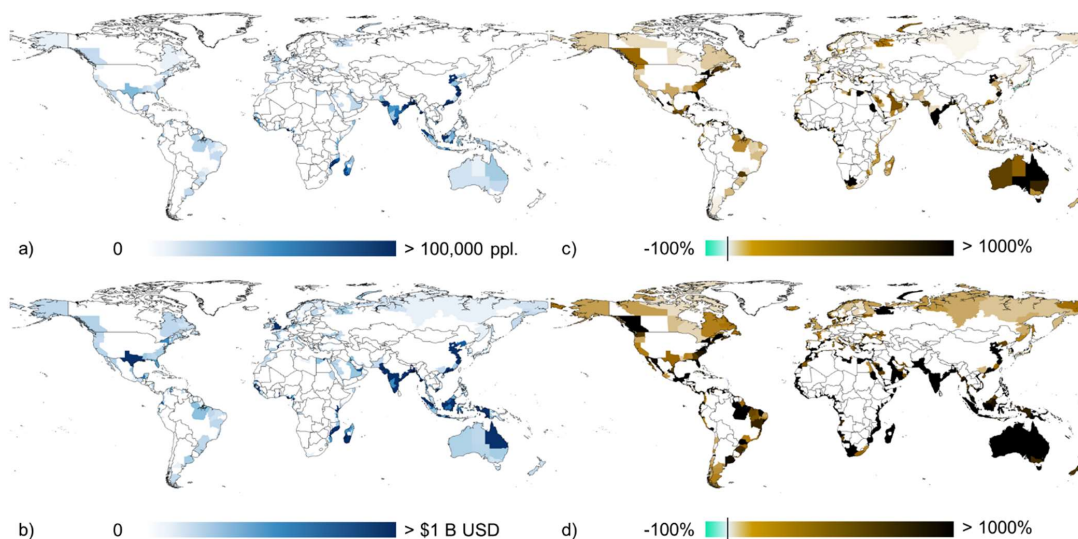
Figure 2: Global maps depicting simulated sub-national regional changes between 2020 and 2080 in: a) absolute EAAP, b) absolute EAD, c) relative EAAP, and d) relative EAD, assuming there are no increases to current protection standards.

The differences in simulated risk between regions, countries, and sub-national regions result from differences in (changes) in

305   hazard and exposure, as well as the assumed current protection standard per sub-national region. Within our modelling framework, many sub-national regions in South Asia, East Asia and the Pacific, and Sub-Saharan Africa are assigned low current levels of protection from flooding. Meanwhile, the highest estimated current protection standards are found in high income countries. For example, Singapore and the Netherlands are evaluated to have current protection standards equivalent to a 1000-yr return period event. The assumed current flood protection standards have a major influence on the calculated risk,

310   as demonstrated by Ward et al. (2013), which indicates that the level of risk is to a large part influenced by actions taken to prepare for and mitigate flood risk.

3.2 Future risk target

We estimate that increases in current protection standards are required in most sub-national regions to achieve respective *relative-risk constant* targets. Sub-national protection standards in 2080 if no changes are made to current protection standards are shown in Figure 3, while sub-national future protection standards required to counteract the downgrading of current protection standards are shown in Figure 4.
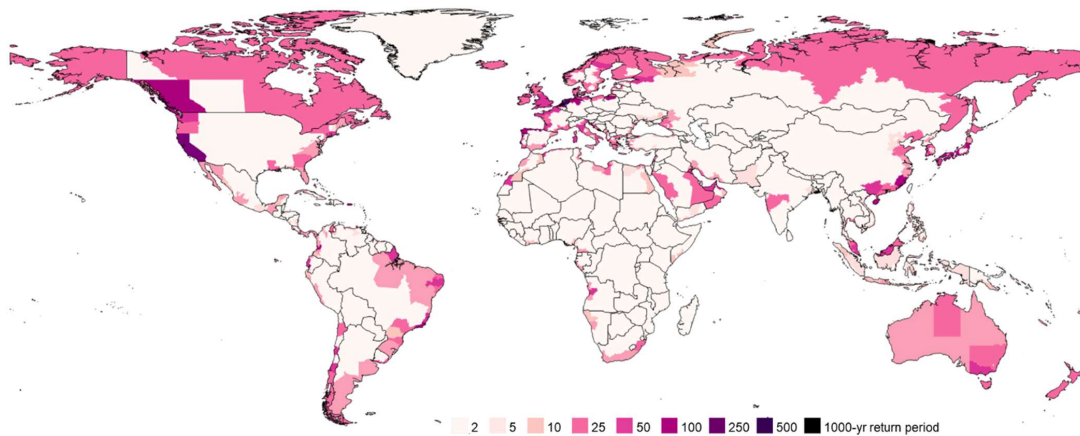
Figure 3: Sub-national protection standards estimated for the year 2080 assuming no changes to current protection standards are made in response to sea-level rise or subsidence.
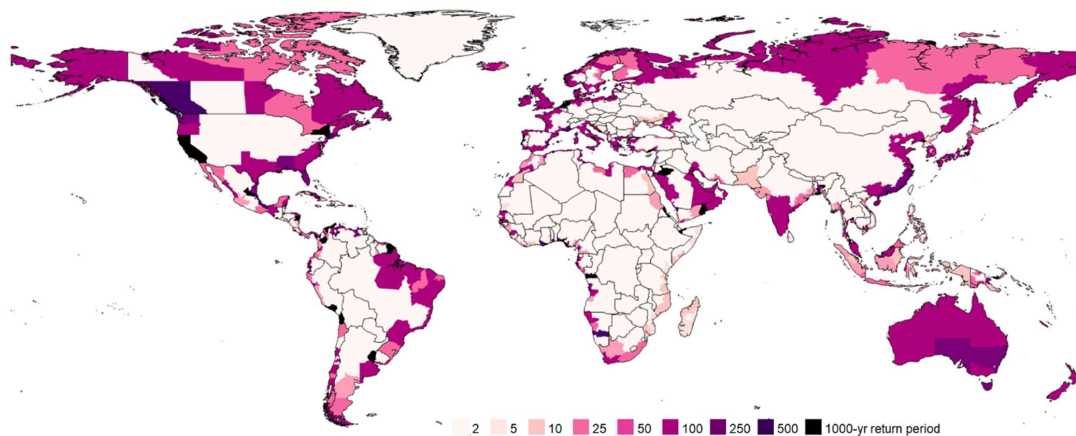
Figure 4: Estimated protection standards required for sub-national regions to achieve their *relative-risk constant* risk reduction targets in 2080.

As discussed in section 2.1.4, 2080 protection standards are in most cases lower than 2020 protection standards due to sea-level rise and subsidence. The largest decreases to current protection standards occur in sub-national regions within Portugal, Japan, Brunei, the United States of America, and the Netherlands. All these sub-national regions have current simulated protection standards to protect from an inundation event well above that of the 100-yr return period. By 2080, with increasing hazard, over 230 sub-national regions around the world will have their protection standards minimized to a 2-yr protection standard – the lowest possible level in our analysis.

In some cases, areas with minimal or no existing protection standards against coastal flooding would require significant increases to protection standards, for example by doubling or tripling the order of magnitude of protection provided (e.g., from a 5-yr protection standard to a 500-yr). Many of these instances are found in Sub-Saharan Africa, where many regions have low current protection standards in the modelling framework. Other areas begin with low current flood protection standards, but only require minor increases to reach their target (e.g., from a 3-yr protection standard to a 5-yr). Many of these cases are found in Latin and Central America, where there is topographic relief from the coasts towards the inland. In other regions, relatively small changes in flood protection standards are required because the current protection standards are already high, meaning that actions have already been taken to mitigate flood risk in the past. Existing high protection standards that still require large increases are found in sub-national regions worldwide, with many of these cases located in North America, Europe and Central Asia, and East Asia and the Pacific.

340   Fifty-two sub-national regions do not require an increase in their respective protection standard in 2080 to reach the *relative-risk constant* target. This can occur for several reasons. Firstly, in some regions future EAD does not increase considerably in the face of changing hazard, due to limited existing exposure or limited simulated change in future exposure, such as along parts of the steep Chilean and Peruvian coasts. Secondly, in some regions localised sea-level rise is marginal, such as in Scandinavia and Russia where post-glacial rebound is present. Thirdly, where large changes in hazard and exposure are

345   projected to occur, the projected overall growth in regional GDP may be higher than the overall growth in EAD, such as in several coastal provinces of China.

3.3 Risk reduction provided by DRR measures

In this section, we assess to what extent the *relative-risk constant* targets can be achieved by taking one of the four DRR measures introduced in section 2.2 and applying them individually on the global scale. The globally aggregated findings of the

350   benefit-cost analysis as well as effectiveness of each individual measure are summarised in Table 2. While it is assumed that dykes and coastal levees can be built anywhere in the world, the other DRR measures are restricted in terms of suitability. Based on our assessment, foreshore vegetation, zoning restrictions, and dry-proofing are only applicable in 23%, 84%, 45% of sub-national regions evaluated with (future) coastal flood risk. The metrics for each DRR measure in Table 2 are calculated only for the applicable regions.

355   **Table 2: The globally aggregated benefits and costs (Billion USD), BCR, NPV (Billion USD), and effectiveness of each individual DRR measure in 2080. Included in parentheses are the total number of applicable sub-national regions where each DRR measure is assessed.**

	Benefits B USD	Costs B USD	BCR	NPV B USD	Effectiveness in applicable regions
Dykes and coastal levees (927 regions)	493	86.01	7.44	14.03	98%
Foreshore vegetation (227 regions)	17.2	0.366	59.8	0.556	6%
Zoning restrictions (784 regions)	46.5	0.027	598	0.401	11%
Dry-proofing (417 regions)	242	151.5	2.10	4.165	49%

The largest overall benefit as well as overall cost of the evaluated DRR measure is for dykes and coastal levees. The benefits of foreshore vegetation and zoning restrictions are smallest in magnitude while the least costly measure overall is zoning

360   restrictions. The lowest BCR is achieved by dry-proofing, due to the high costs. Because of the low costs, zoning restrictions

achieve the highest simulated BCR of any of the evaluated measures. Still, all four DRR measures achieve globally aggregated BCRs > 1, meaning the long-term benefits of each DRR measure outweigh the costs on the global scale. All globally aggregated NPVs are also positive, with the highest exhibited by dykes and coastal levees, followed by dry-proofing.

365 In all World Bank analytical regions, dykes and coastal levees have the highest effectiveness in terms of the percentage of the *relative-risk constant* target that they can achieve. Still, considerable reductions are also possible within certain (sub-national) regions by employing foreshore vegetation, zoning restrictions, or dry-proofing. North America exhibits the highest effectiveness in achieving its risk target when using dry-proofing (98%), while the Middle East and North Africa achieves high effectiveness scores for foreshore vegetation (23%) and for zoning restrictions (34%). South Asia achieves the highest simulated BCRs for all DRR measures of all global regions analysed. Relatively high BCRs are also seen in Sub-Saharan

370 Africa and East Asia and the Pacific. Latin America and the Caribbean achieves relatively low BCRs due to the lower benefits achieved from employing the DRR measures there.

Sub-national values of each DRR measure's effectiveness in achieving the *relative-risk constant* targets and BCRs are displayed in Figures 5 and 6, respectively. Over 90% of all sub-national regions can meet their respective *relative-risk constant* targets using at least one of the measures. Of these, roughly 160 regions can do so by employing a non-structural DRR measure.

375 To gain further context regarding these DRR measures and their ability to modulate future coastal flood risk, the following subsections examine each measure individually, referring to the relative panels in the following figures.
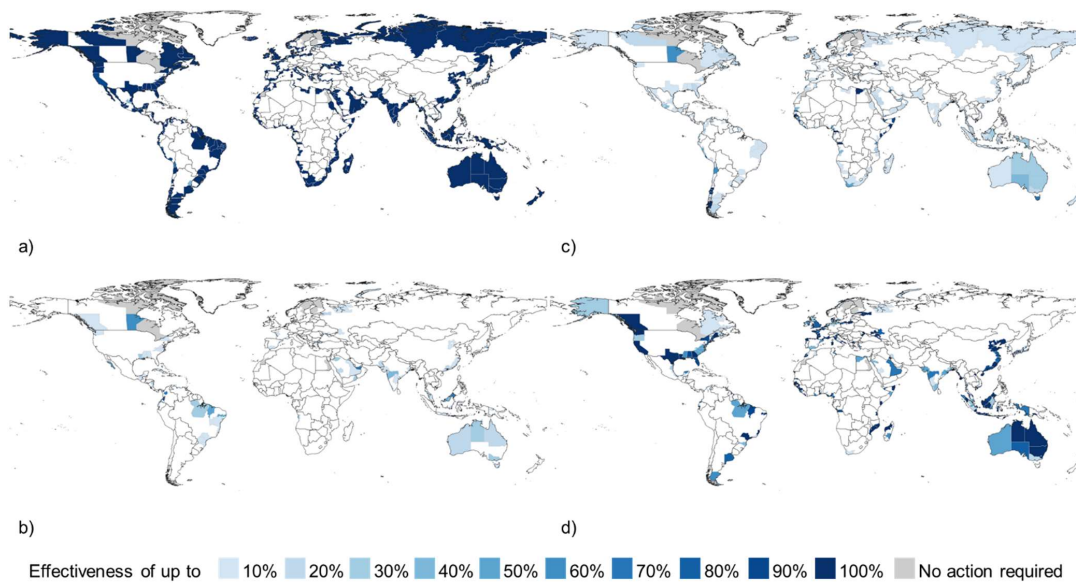
Figure 5: Effectiveness in achieving the *relative-risk constant* targets for a) dykes and coastal levees, b) foreshore vegetation, c) zoning restrictions, and d) dry-proofing on the sub-national scale, where light blue indicates lower effectiveness and dark blue higher effectiveness. Grey areas are sub-national regions where action is not required to achieve the *relative-risk reduction* targets.

380
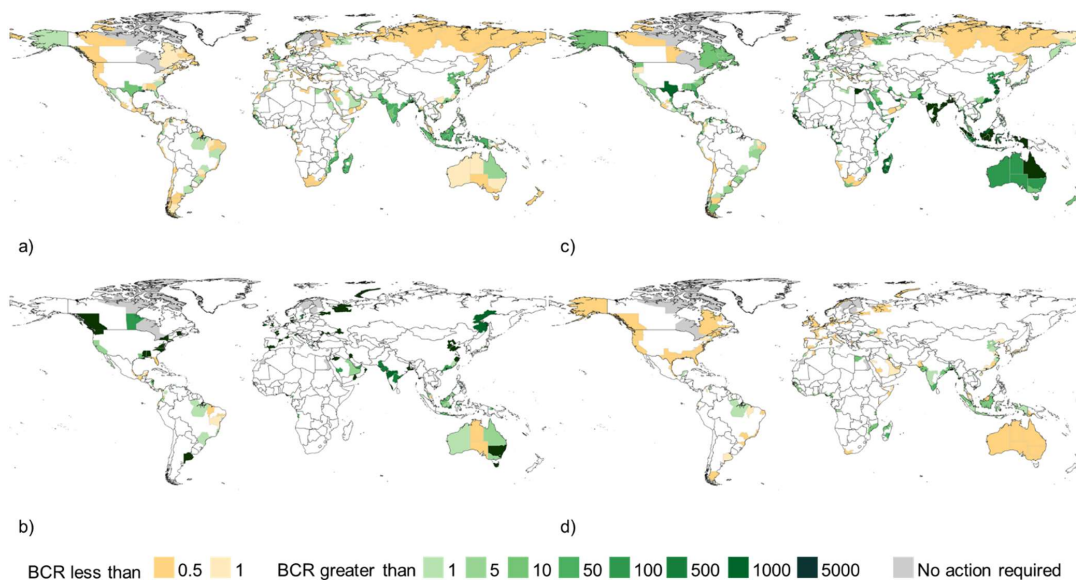
Figure 6: Benefit-cost ratio values for a) dykes and coastal levees, b) foreshore vegetation, c) zoning restrictions, and d) dry-proofing on the sub-national scale, where yellow indicates overall direct costs outweighing overall benefits and green overall benefits
385 **outweighing overall direct costs. Grey areas are sub-national regions where action is not required to achieve the *relative-risk reduction* targets.**

3.3.1 Dykes and coastal levees

Overall, the results show that implementing dykes and coastal levees has a global effectiveness of 98% towards achieving
390 *relative-risk constant* targets and global benefits of over $493 billion (Table 2). A considerable share of the monetary benefits, namely $421 billion, can be achieved in South Asia and East Asia and the Pacific. Globally, the cost of implementing dykes and coastal levees to meet the *relative-risk constant* targets sums to just over $86 billion. The slightly lower effectiveness for dykes and coastal levees observed in regions like Europe and Central Asia can be explained by high existing protection standards that require increases above the 1000-yr return period.

395 Using this DRR measure, almost every sub-national region in the world can achieve their *relative-risk constant* target (Figure 5a), with some exceptions. For Singapore and the Netherlands, protection standards exceeding their current levels would be required to achieve their targets. These two countries are both assumed to have existing protection against a 1000-yr return period flood. Since this level of protection is also the maximum cap within this modelling framework, the simulated residual risk remains above the target. Certain portions of Northern Africa, where coasts are largely unprotected, and the area
400 surrounding the Gulf of Mexico, where substantial amounts of subsidence and sea-level rise are projected to occur (thus degrading existing protection standards), would also require a protection standard exceeding 1000 years. It may be possible to build structural measures that provide a protection standard greater than 1000 years, as is indeed already the case in the Netherlands (Kabat et al., 2009).

Despite high costs, in many sub-national regions the benefits outweigh the costs (Figure 6a). Only in specific sub-national
405 regions, generally those that are sparsely populated or with high projected sea-level rise, do costs outweigh the benefits. The benefits of building new and heightening existing dykes and coastal levees most strongly outweigh the costs of doing so in sub-national areas that have high amounts of current development, and especially those with only limited projected sea-level rise. Likewise, the lowest BCRs are found in lower-income countries with moderate- to low-levels of coastal development. Interestingly, the capital regions of Papua New Guinea, Guinea-Bissau, Cuba, and Suriname all have BCRs < 1 and are unable
410 to reach their risk reduction targets by 2080 using solely dykes and coastal levees. This may be explained by the fact that these growing regions have high levels of concentrated, low-wealth urbanisation which is exposed to high levels of sea-level rise.

3.3.2 Foreshore vegetation

The global effectiveness of foreshore vegetation in achieving *relative-risk constant* targets is roughly 6%, and global reductions to EAD total to more than $17.2 billion (Table 2). The largest reductions are seen in South Asia, East Asia and the Pacific, and
415 Sub-Saharan Africa. Of the $12.4 billion in EAD reduction that is achieved via mangrove restoration, $8.7 billion is found in India, Vietnam, and Nigeria. Conserving salt marshes, meanwhile, shows the most potential in China, representing just over

$4.6 billion of the $4.8 billion in reductions to global EAD. In the case of salt marshes, many of these ecosystems have been degraded or lost completely, meaning current marshes may not provide protection for the urban setting.

Although certain salt marsh ecosystems, such as those in northern China and the eastern seaboard of the United States, remain in the vicinity of urbanised areas, the global economic benefits of salt marshes are much lower than those of mangroves. Seeing the larger magnitude of benefits achieved by restoring mangroves as compared to conserving existing salt marshes, it can be suggested that higher BCRs can be achieved using foreshore vegetation as a DRR measure if these areas are not only maintained and conserved, but actively cultivated beyond current extents.

Foreshore vegetation is simulated to reduce risk in one-quarter of all subnational regions with (future) coastal flood risk. Twelve sub-national regions meet or exceed 100% of their risk targets. The average efficiency seen in the global sub-national regions evaluated as having foreshore vegetation is 20%, while the median is 5.7% (Figure 5b). The sub-national regions which do not see reductions as a result of foreshore vegetation are either fully urbanised with minimal potential to support foreshore vegetation, located in unfavourable climate regions for foreshore vegetation, or have favourable conditions to support foreshore vegetation but not near any flood-prone populations

The global costs of foreshore vegetation are estimated to be $544 million. Sub-national regions within China, Vietnam, and the Philippines all possess among the highest BCRs, with similarly high BCRs in upper-latitude sub-national regions in Canada and Russia. The lowest BCRs are found in several countries within Latin America and the Caribbean and Sub-Saharan Africa (Figure 6b). This is likely because many major mangrove areas within this part of the world are not around major population centres, but rather on small islands and sparsely populated coastlines.

3.3.3 Zoning restrictions

Zoning restrictions achieve EAD reductions of $46 billion by 2080 worldwide (Table 2). Generally, exposure reduction as a single solution is only effective in certain contexts, namely in areas where current coastal urbanisation is limited but future urbanisation is widely projected. Just over half of the risk reductions are realized in East Asia and the Pacific, the region of the world that shows the highest projected levels of population growth through the 21st century. The Middle East and North Africa, Sub-Saharan Africa, and South Asia also experience large risk reductions through zoning restrictions. Meanwhile, Latin America and the Caribbean experiences limited risk reduction via this measure due to limited coastal regions where additional urbanisation can occur, even though moderate amounts of growth are projected. Meanwhile, North America as well as Europe and Central Asia show low potential because their coastlines are already highly urbanised, and therefore the zoning measures are not implemented in the model. Notably, three countries count for almost two-thirds of total global risk reduction: India, China, and Indonesia. Other countries that do not experience large risk reduction via other measures, such as Guinea, Senegal, and Cameroon, do show high effectiveness towards achieving their *relative-risk constant* targets through zoning restrictions.

Japan and Australia are the high-income countries that experience the largest risk reductions, with $423 million and $373 million fewer damages, respectively, expected by 2080.

450 The global effectiveness of zoning restrictions towards achieving *relative-risk constant* targets is approximately 11%. Sub-national regions within 20 countries, mainly low-income, but also in countries such as Japan and Spain, can achieve their respective risk reduction targets by limiting future exposure in the 1000-yr floodplain. One-fifth of sub-national regions achieve 20% or more of their *relative-risk constant* targets (Figure 5c). Zoning restrictions, as modelled in this research framework, show the highest effectiveness towards achieving *relative-risk constant* targets in sub-national regions within low-income countries. Often, these countries are projected to urbanise substantially along the coasts.

455 While the benefits of zoning restrictions are less than one-tenth of those provided by dykes and coastal levees globally, this DRR measure is highly cost effective. The minimal costs associated with this DRR measure mean that, globally, zoning restrictions achieve the highest BCR of any modelled measure (Figure 6c). The cost-effective nature of this measure is compounded in certain global regions because low-income countries within these regions have both the highest levels of projected population growth (which can be spatially altered by this DRR measure) as well as lower costs of implementation 460 when compared to high-income countries. Costs run the highest in Europe and Central Asia for zoning restrictions because of the high-income nature of its countries as well as the large amount of sub-national regions within these countries, each requiring their own zoning policy development and administration. As mentioned, for our analysis we assume these administrative costs are the only direct costs of this DRR measure. The limitations of this specific assumption are discussed further in section 3.4.

3.3.4 Dry-proofing

465 Dry-proofing can be highly effective in reducing EAD, with a global reduction to EAD by as much as $242 billion (Table 2), or nearly half of the reductions needed to achieve the set *relative-risk constant* targets. While half of this risk reduction is found in East Asia and the Pacific ($158 billion), the benefits of dry-proofing are generally spread across all global regions. The smallest risk reductions are seen in Latin America and the Caribbean (under $2 billion), with relatively few major urban centres along vulnerable coastlines when compared to the eastern hemisphere, the exception being the (east) coast of Brazil. 470 Europe and Central Asia also exhibit lower reductions when compared to other global regions; here, existing high protection standards limit the impact of a DRR measure that mainly takes aim at lower return period events.

The countries that are projected to experience the highest reductions are China (with the Shanghai direct-administered municipality alone accounting for one-third of total countrywide reductions), Vietnam, Indonesia, and India, each with reductions in the order of magnitude of tens-of-billions. With roughly $4.5 billion in dry-proofing reductions, the high-income 475 country with the largest amount of damage reductions to be achieved via dry-proofing is the United States of America, with a large portion of these reductions found in the states of New York and Texas. This DRR measure can meet *relative-risk constant*

targets in sub-national regions within 46 countries of varying income levels and urbanisation patterns, ranging from Singapore and France to Yemen and Somalia (Figure 5d). While dry-proofing is not applicable in all contexts within this modelling framework (e.g., not modelled for rural settings or in semi-urban or peri-urban settlements, which are prevalent in certain

480 global contexts), roughly two-thirds of the coastal sub-national regions where dry-proofing is applicable achieve at least 50% their *relative-risk constant* targets. These results show that dry-proofing is a measure that is most effective in highly urbanised coastal settings with low projected future inundation depths (of less than 1m).

Sub-national regions with existing patterns of intensive urbanisation along coastlines, for example the eastern seaboard of the United States of America and eastern China, show the highest potential for risk reduction with this DRR measure.

485 Coincidentally, the highest costs for this measure are also found in these areas, with dry-proofing within the United States of America alone costing an estimated $53 billion and China $33 billion, leading to low BCR values (Figure 6d). In fact, in the United States of America only New Hampshire scores a BCR > 1. Total global costs sum to $151 billion, meaning that while benefits still outweigh costs, the return-on-investment of this measure is smaller than other DRR measures. This, combined with the fact that this measure is a solution employed by individuals and not on larger scales, could make a dry-proofing

490 strategy a challenging one for much of the world. Although they observe high levels of risk reduction, low BCRs in North America and Europe and Central Asia mean that a decision maker may select a different DRR measure. BCRs are largest in Sub-Saharan Africa and South Asia, particularly in India and Indonesia, both of which have several major urban centres on their coastlines.

3.4 Limitations and recommendations for future research

495 While the benefits provided by the modelled DRR measures are determined in a similar fashion for each measure, the costs associated with these measures are determined in different manners (as described in the subsections of 2.2) out of necessity. With certain DRR measures there are additional costs which could also considered; we do not include these indirect costs in this analysis. For instance, infrastructure disruptions might occur more frequently if no dykes and coastal levees are built but instead regions rely on dry-proofing, while zoning restrictions could also prevent infrastructure disruptions (Koks et al., 2022;

500 Nirandjan et al., 2022). Other examples of indirect costs that are not included in this analysis but could provide additional value to the field of risk assessment include the cost of ecosystem disruptions with structural measures, opportunity costs associated with not developing in flood-prone areas, and so on. Moreover, the nature contributions to humans of the DRR measures are not included in the analysis. Any one of these indirect costs or benefits are strongly recommended as a future avenue of research.

505 We also recommend the continued expansion of modelled DRR measures within the same risk assessment framework to allow for a more comprehensive view of coastal flood risk. Candidates for incorporation into global flood risk modelling frameworks could include other Nature-based Solutions, for example salt marshes and coral reef restoration, and managed retreat. Beck et

al. (2022) did recently assess the potential for coral restoration; as with the foreshore vegetation modelled in this study, the measure may have limited spatial applicability on the global scale but could have high levels of impact on small island developing nations and other settings highly vulnerable to climate change. Managed retreat, meanwhile, in theory can be applied in some locations around the world but may be difficult to implement in a practical sense. The modelling of this DRR measure could involve agent-based modelling, as performed on the global scale by Tierolf et al. (2022).

By employing any of the modelled DRR measures individually, we find that 84 sub-national regions cannot achieve their respective *relative-risk constant* targets by 2080. While here we investigated the measures individually, the actual implementation of a DRR strategy will often consist of executing several DRR measures at once, or in a hybrid form (Dedekorkut-Howes et al., 2020; Dissanayaka et al., 2021; Lawrence et al. 2019). Indeed, DRR measure hybridisation could help increase the DRR potential in many sub-national regions while minimising costs (Sutton-Grier et al., 2015, Tiggeloven et al., 2022). Future research could further investigate DRR measures hybridisation, as has been the case already with combining zoning restrictions and dry-proofing (Richert et al., 2019), or mangroves and dykes (Tiggeloven et al., 2022). If DRR measure hybridisation is to be explored further, additional information on nature contributions to people, indirect costs, and unintended side effects, such as increased urbanization in safer areas (Haer et al., 2020), would be required to create a more comprehensive and holistic view of coastal flood risk reduction in the future. Building upon the methodology presented in this study, additional research on any of these facets can provide insights into such complexities.

4 Conclusions

We project immense increases to coastal flood risk will occur in coming decades if no action is taken to limit the growth of disaster risk; expected annual damages are projected to exceed $2 trillion by 2080. Without action, leaders and decision makers in all countries, regardless of income level, will see their societies negatively impacted. Disaster risk reduction is needed to prevent or reduce these impacts. We show how different DRR measures can be implemented to reach a certain risk reduction (i.e., risk reduction targets set by the *relative-risk constant* objective). We show that, globally, dykes and coastal levees achieve $493 billion in risk reductions, dry-proofing $242 billion, zoning restrictions $46.5 billion, and foreshore vegetation $17.2 billion. The global effectiveness of these four DRR measures meanwhile, is 98%, 49%, 11%, and 6%, respectively. While the global aggregates of effectiveness and BCRs favour dykes and coastal levees, regionally and sub-nationally we show that the modelled alternatives can yield similar levels of effectiveness and higher BCRs.

As illustrated by our work, 90% of all sub-national regions in the world can achieve their respective *relative-risk constant* targets by using at least one of the modelled DRR measures. Over 160 of these sub-national regions can achieve their *relative-risk constant* targets via a non-structural DRR measure. This suggests to decision makers in these areas that alternatives to traditional coastal flood risk reduction could be embraced while often lowering overall direct costs. For 84 sub-national regions,

none of the DRR measures investigated here meet the *relative-risk constant* target, meaning that something extra must be done in these areas, such as exploring other DRR measures and/or the hybridization of different DRR measures.

5 Code availability

The code used to perform this analysis is available for public use.

6 Data availability

The input data for hazard and exposure values were created specifically for this analysis by project partners and are available upon request. The vulnerability values are taken from an open-source publication. The results of our analysis are available for public use.

7 Author contribution

EM, TT, TH, and PW expanded the existing GLOFRIS framework to include new modules that allowed for the modelling of alternative DRR measures. EM conducted the main analysis, with guidance from TT in operationality of GLOFRIS. DLB, SM, DE, and FSW contributed to the development of hazard data. BB, AB, and WL contributed to the development of exposure data. TH and PW assisted EM in the framing of the analysis for this written text. All authors reviewed the text and provided suggestions for revisions to the final manuscript as presented here.

8 Competing interests

One of the co-authors listed is a member of the NHESS editorial board.

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