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The benefits of coastal adaptation through conservation of foreshore vegetation

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Abstract

Due to rising sea levels and projected socio-economic change, global coastal flood risk is expected to increase in the future. To reduce this increase in risk, one option is to reduce the probability or magnitude of the hazard through the implementation of structural, Nature-based or hybrid adaptation measures. Nature-based Solutions in coastal areas have the potential to reduce impacts of climate change and can provide a more sustainable and cost-effective alternative to structural measures. In this paper, we present the first global scale assessment of the benefits of conserving foreshore vegetation as a means of adaptation to future projections of change in coastal flood risk. In doing so, we extend the current knowledge on the economic feasibility of implementing global scale Nature-based Solutions. We show that globally foreshore vegetation can contribute to a large decrease in both absolute and relative flood risk (13% of present-day and 8.5% of future conditions in 2080 of global flood risk). Although this study gives a first proxy of the flood risk reduction benefits of conserving foreshore vegetation at the global scale, it shows promising results for including Nature-based and hybrid adaptation measures in coastal adaptation schemes.

KEYWORDS

coastal, disaster risk reduction, flood damages, green infrastructure

1 | INTRODUCTION

Coastal zones are attractive areas for human settlement and almost two-thirds of urban settlements with population higher than 5 million are at least partly located in coastal zones (McGranahan, Balk, & Anderson, 2016). Recent research shows that 1.3% of the global population lives in coastal zones that are exposed to one in a 100-year flooding event (Muis, Verlaan, Winsemius, Aerts, & Ward, 2016) and future population in coastal zones is expected to grow, increasing the exposure to coastal flooding (Neumann, Vafeidis, Zimmermann, & Nicholls, 2015). Next to this increase in exposure, coastal flood hazard will change through climate change and subsidence (Nicholls & Cazenave, 2010; Vousdoukas et al., 2018a; Vousdoukas et al., 2018b). Due to rising global temperatures, sea-level rise is projected to accelerate during the 21st century (Oppenheimer et al., 2019), leading to an increase in coastal flood hazard (Vitousek et al., 2017). Next to sea-level rise, climate change is projected to lead to changes in flood hazard through changes in tides (Idier, Paris, Le Cozannet, Boulahya, & Dumas, 2017), surge levels (Little et al., 2015), extreme sea levels (Vousdoukas, Mentaschi, Voukouvalas, Verlaan, & Feyen, 2017) and wind-wave climate (Hemer, Fan, Mori, Semedo, & Wang, 2013). These changes of flood hazard and exposure will lead to increases in global coastal flood risk (Hallegatte, Green, Nicholls, & Corfee-Morlot, 2013; Hinkel et al., 2014; Neumann et al., 2015; Tiggeloven et al., 2020; Vousdoukas, Bouziotas, et al., 2018a; Vousdoukas, Mentaschi, et al., 2018b).

To prevent or reduce this increase in flood risk, adaptation measures are required. One option is to develop methods to reduce the probability or magnitude of the hazard, the so-called protect approach. This can be achieved through the implementation of structural, Nature-based Solutions or hybrid adaptation measures. Lincke and Hinkel (2018) show that adaptation through structural adaptation measures is economically feasible for 13% of the global coastline, which accounts for 90% of the global population living in regions prone to coastal hazard. In addition, Hinkel et al. (2014) show that the avoided damages of adaptation are much higher than the costs of adaptation and Tiggeloven et al. (2020) show that adaptation through structural measures shows high potential to reduce (future) coastal flood risk. Instead of only focusing on structural adaptation measures, Jongman (2018) argues that flood risk management needs to adopt holistic strategies to adapt to climate change, such as early warning systems, risk perception, Nature-based or hybrid solutions. Hybrid solutions combine structural measures with Nature-based Solutions, such as maintaining or restoring foreshore vegetation and foreshore geomorphology on the foreshore. Duarte, Losada, Hendriks, Mazarrasa, and Marbà (2013) show that Nature-based Solutions in coastal areas have potential to reduce the impacts of climate change. Moreover, recent studies argue that Nature-based Solutions can provide a more sustainable, cost-effective and ecologically sound alternative to structural measures, such as dikes, sea walls and embankments (Narayan et al., 2016; Temmerman et al., 2013; van Wesenbeeck, de Boer, Narayan, van der Star, & de Vries, 2017).

Foreshore vegetation plays a significant role in dissipating wave energy (Barbier et al., 2008; Shepard, Crain, & Beck, 2011), attenuating storm surges (Wamsley, Cialone, Smith, Atkinson, & Rosati, 2010; Zhang et al., 2012) and providing economic benefits through coastal flood protection (Menéndez, Losada, Torres-Ortega, Narayan, & Beck, 2020). Structural measures alone can have negative effects as they have a costly maintenance, and need continual heightening and widening to keep up with sea-level rise (Temmerman et al., 2013). On the other hand, ecosystems can respond to sea level rise by natural accretion of mineral and biogenic sediments (Fagherazzi et al., 2012; Kirwan et al., 2010; Mckee, Cahoon, & Feller, 2007). By providing additional benefits, such as improving water quality and recreation (Barbier et al., 2011), ecosystems could be more cost-effective in the long term than structural measures under similar scenarios (Broekx, Smets, Liekens, Bulckaen, & De Nocker, 2011; Turner, Burgess, Hadley, Coombes, & Jackson, 2007). However, the reduction of flood risk through the presence of foreshore vegetation under future change, and the benefits of using foreshore vegetation as future adaptation measures, have not been assessed at the global scale.

This paper aims to address this gap by providing a first proxy assessment on the benefits of conserving foreshore vegetation as a means of adaptation to future projections of change in coastal flood risk. We approach this aim in two ways. First, we show the reduction of coastal flood risk that could be attained by conserving foreshore vegetation under various combinations of future climate and socioeconomic scenarios. Here, we include foreshore dynamics (wave attenuation) through foreshore vegetation to assess flood risk reduction in terms of expected annual damage and expected annual population exposed. Second, we provide the first global scale study on the benefits of implementing adaptation measures using a combination of structural adaptation measures and conserving foreshore vegetation for future flood risk scenario projections.

2 | METHODS

This study extends the coastal flood risk assessment framework developed by Tiggeloven et al. (2020) to also include the effects of foreshore vegetation on global flood risk reduction. The latter is achieved using the approach of van Zelst et al. (2021). The main steps of this study are: (1) flood risk estimation; (2) wave attenuation estimation; and (3) estimating the benefits of adaptation measures. In brief, flood risk is estimated as a function of hazard, exposure and vulnerability (United Nations Office for Disaster Risk Reduction, 2016). Flood risk, expressed in terms of both expected annual damages (EAD) and expected annual population exposed (EAPE), is calculated over time for scenarios with and without adaptation measures. We calculate the benefits as the reduction in EAD with and without adaptation measures. These benefits for conserving foreshore vegetation are estimated in the adaptation objective 'Protection constant', in which it is assumed that present-day protection standards are kept the same in the future as the current protection standards. This section contains a brief description of the methods involved with the setup of the modelling framework, and is based on detailed descriptions by Tiggeloven et al. (2020) and Ward et al. (2020) for the modelling framework, and van Zelst et al. (2021) for details on global wave attenuation by mangroves and salt marshes in coastal areas.

2.1 | Flood risk estimation

We estimated coastal flood impacts using the GLOFRIS risk assessment framework of Ward et al. (2013) to combine data on flood hazard (inundation maps), exposure (current and future built-up exposure maps with associated maximum damage values) and vulnerability (depth-damage curves). We assess flood impacts at a horizontal resolution of 30' × 30' and simulate these for several return periods (2, 5, 10, 25, 50, 100, 250, 500 and 1000 years). This section contains an overview of the methods used to estimate flood hazard, exposure, vulnerability and risk.

Flood hazard is represented by maps of inundation depth for several return periods (2, 5, 10, 25, 50, 100, 250, 500 and 1000 years). These are simulated using a 2D topographic inundation modelling routine that accounts for water level attenuation. As underlying topography, we use the Multi-Error-Removed Improved-Terrain (MERIT) DEM (Yamazaki et al., 2017) at a 30″ × 30″ resolution. To simulate the reduction of flooding land inwards due to the limited time span of tides and storm surges, we included a resistance factor in the inundation routine similar to Vafeidis et al. (2019). As input for the inundation model, we use extreme sea level values from the global tide and surge reanalysis (GTSR) dataset by Muis et al. (2016) enriched with simulated tropical cyclones using the IBTrACS (International Best Track Archive for Climate Stewardship) archive, as described by Tiggeloven et al. (2020). Future inundation is simulated using sea-level rise to simulate future extreme sea levels and subsidence rates through groundwater extraction to estimate how the terrain may change. We use gridded projections of sea-level rise from the RISES-AM project, in which sea-level rise rates are regionalized using spatial variability associated with gravitational-rotational fingerprints (Jackson & Jevrejeva, 2016). For this study, we use a range of probabilistic outcomes (5th, 50th and 95th percentiles) for two representative concentration pathways (RCP), that is, RCP4.5 and RCP8.5. Subsidence is modelled through groundwater extraction and rates are taken from the SUB-CR model (Kooi, Bakr, de Lange, den Haan, & Erkens, 2018).The flood hazard maps are available through Ward et al. (2020).

Exposure data used in this study consist of current gridded built-up area taken from the HYDE database (Klein Goldewijk, Beusen, Van Drecht, & De Vos, 2011) and future built-up area from Winsemius et al. (2016) both at a resolution of 30″ × 30″. Current maximum economic damages are estimated using the methodology of Huizinga, Moel, and Szewczyk (2017) and future estimates are scaled with the GDP per capita per country from the Shared Socioeconomic Pathway (SSP) database. Based on a study by BPIE (2011) and EEA (2016), we set the area of occupancy type per grid cell to 75% residential, 15% commercial and 10% industrial. Following Huizinga et al. (2017), the density of buildings per occupancy types are set to 20% for residential and 30% for commercial/industrial. To calculate future risk relative to GDP per region, future gridded GDP values are taken from Van Huijstee, Van Bemmel, Bouwman, and Van Rijn (2018), which uses the national GDP per capita from the SSP database as input.

Vulnerability to flooding is estimated by using different global flood depth-damage functions for each occupancy type and are taken from Huizinga et al. (2017). The resulting damages are represented as a percentage of the maximum damage. Subsequently, flood impacts per cell are calculated by estimating the percentage of maximum damage per occupancy type at the inundation depth in a given cell, and are expressed in the following equation:

$$I_\theta(p) = \theta_r(p)M_r + \theta_c(p)M_c + \theta_i(p)M_i \quad (1)$$

where I_θ is the flood impact at the inundation depth associated with the annual probability of non-exceedance p (1 divided by the return period), θ is the vulnerability and M is the maximum damage assigned for residential (r), commercial (c) and industrial (i) occupancy types. To estimate flood risk in terms of EAD, we first estimate these flood impacts per return period at the resolution of 30″ × 30″. Subsequently, EAD can be estimated by taking the integral of the exceedance probability-impact (risk) curve (Meyer, Haase, & Scheuer, 2009) and is shown in the following equation:

$$D = \int_{p=0}^{1} I_\theta(p)dp \quad (2)$$

where D is the EAD. To fit a protection standard of a coastal region in the risk computation, the risk curve is truncated at the exceedance probability of the protection standard (expressed as a return period). To estimate the area under the curve, we use the trapezoidal approximation. Under the same conditions, higher protection standards indicate that EAD would decrease as the hinterland is protected for storms up to the corresponding protection standard. Similar to the EAD estimation, EAPE is estimated by taking the integral of exposed population associated with the recurrence intervals assessed. As data on protection standards of coastal regions are not available for many regions, we estimate current protection standards for coastal regions using the FLOPROS modelling approach (Scussolini et al., 2016). The resulting coastal protection standards are described and validated in Tiggeloven et al. (2020).

2.2 | Wave attenuation and crest height estimation

This study estimates the effects of wave attenuation through foreshore vegetation globally. To estimate these effects of foreshore vegetation on wave attenuation and required crest height estimation, we use the following procedure of van Zelst et al. (2021) to:

1. derive coastal segments and corresponding coast-normal transects;
2. construct bed-level profiles and vegetation cover;
3. derive representative hydrodynamic conditions and wave attenuation under these conditions; and
4. estimate required crest heights under current and future conditions.

We use OpenStreetMap to derive the coastlines and move them 100 m land inwards in order to find a likely position to establish a dike system. Detection of already established dike systems is not explicitly taken into account here. However, large geomorphological features as present in MERIT DEM are included and we use a baseline protection standard for each region using the FLOPROS database. For every cell containing a coastline segment at $1' \times 1'$ resolution, its coastline length and a transect perpendicular to the coast are derived at the centre of the segment resulting in 495,361 transects that are on average 1.1 km apart. For each transect, the foreshore width and slope and the vegetation width and type within the foreshore are derived along the same coast-normal transect. The following sections contain an overview of the methods involved for estimating the required crest heights; for details we refer to van Zelst et al. (2021).

The bed-level data consists of three datasets where the main source is derived from the FAST inter-tidal elevation product at 20 m horizontal resolution and 30–50 m vertical resolution (Calero, Hendriksen, Dijkstra, & Lelij, 2017). Bathymetry data are derived from GEBCO at $30'' \times 30''$ horizontal resolution and tens of meters vertically, and topography data are derived from the MERIT DEM at $3'' \times 3''$ horizontal resolution and 2 m vertically. Vegetation presence at 10 m resolution is derived from the FAST coastal vegetation map, which is based on Landsat-8 and Sentinel-2 satellite images. To determine the type of vegetation we use global salt marsh (Mcowen et al., 2017) and mangrove (Giri et al., 2011) maps, complemented with Corine Land Cover (CLC, Europe only) and GlobCover v2.2 maps where the former lack coverage. The properties of the vegetation relevant for wave attenuation (spatial density, height, diameter and drag coefficient) have been determined in the FAST project based on field measurements and literature. In this study, salt marshes in the temperate zone are represented by a parameterization that is typical for northwestern Europe winter-state salt marshes. Mangroves are represented as (young) pioneering mangroves. Details on the representation of vegetation in the numerical modelling activities can be found in van Zelst et al. (2021). Figure 1 displays an overview of the present-day foreshore vegetation (salt marshes and mangroves) used in this methodology. Countries that have the largest areal extent (km^2) of vegetation are Australia, Indonesia, the United States and Brazil. Figure 1 shows that mangroves are most dominant between the 30°N and 30°S latitude, and salt marshes are largely present in the northern hemisphere above the 30°N latitude. Note that data on foreshore vegetation are lacking in many regions in the Mediterranean Sea, which indicates that results in those regions should be interpreted with caution.

Wave conditions have been derived from a ERA-Interim (Dee et al., 2011) reanalysis using a peak-over-threshold approach. Offshore significant wave heights for the same range of return periods are transformed to a nearshore wave height that is limited by depth-induced breaking. To determine the wave attenuation over a foreshore and the resulting significant wave height relevant for the flood defence on a transect, we use a lookup-table by combing 668,304 XBeach (van Rooijen et al., 2016) hydrodynamic numerical modelling results for combinations of foreshore slopes, vegetation covers and hydrodynamic conditions (van Zelst et al., 2021). The values for these input conditions are based on the expected range of conditions, that is, the distribution functions of these parameters globally. This table contains wave heights modelled by XBeach (van Rooijen et al., 2016) at regular intervals along a steady slope, both with and without salt marsh or mangrove vegetation. Wave angle of incidence is assumed coast normal to represent a worst-case scenario. Wave attenuation along the vegetated coastlines is

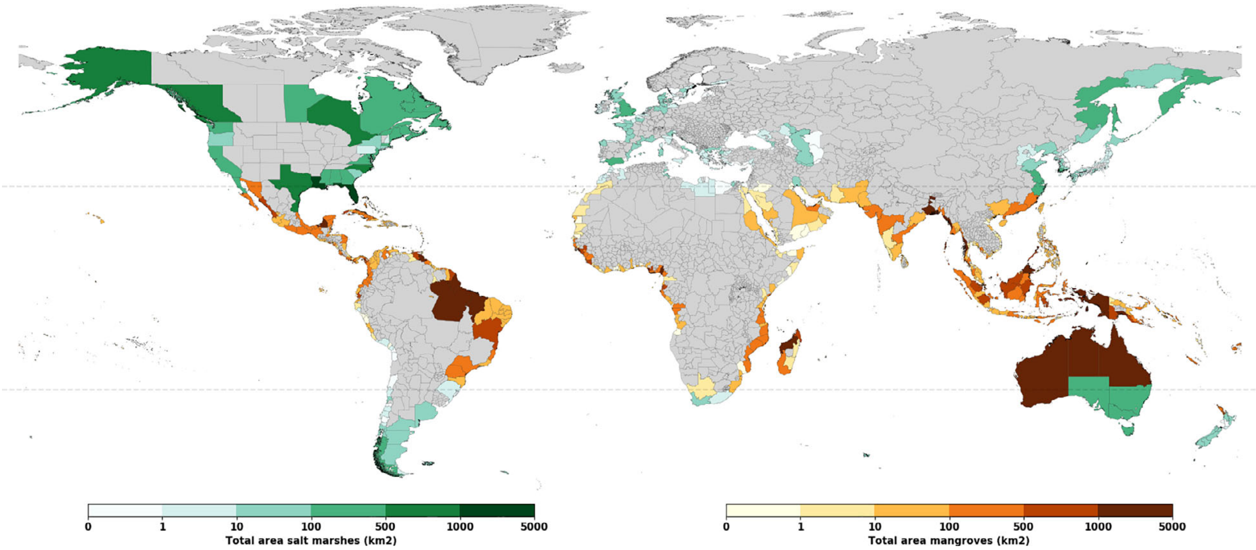

FIGURE 1 Total area of foreshore vegetation displayed for the most dominant type of the sub-national region (salt marshes and mangroves) assessed in wave attenuation calculations. The auxiliary lines of 30°N and 30°S latitude are added to show loosely the boundary of dominant foreshore vegetation type. Sub-national regions with no data are indicated with grey colour

determined based on the closest match between the derived transects characteristics and look-up table results.

Subsequently, required crest heights are estimated with the empirical EuroTop formulations (Pullen et al., 2007) with respect to the surge level for a standard 1:3 dike profile without berms and an allowed overtopping discharge of 1 L/s/m. The reduction in required crest height is calculated by subtracting dike crest height for the scenarios with foreshore vegetation and all foreshore vegetation removed. We assume the same coastal profile with and without coastal vegetation, which is a conservative approach. We hereby cancel out the effect of the coastal profile and solely focus on the contribution of foreshore vegetation. Future crest heights are estimated using regional sea-level rise from Jackson and Jevrejeva (2016) and subsidence rates from Kooi et al. (2018). This is carried out by adding subsidence and sea-level rise rates directly on the crest heights. Thus, natural accretion on vegetated foreshores and changing foreshore hydrodynamics due to relative sea-level rise is not included in this study.

2.3 | Benefits of conserving foreshore vegetation and adaptation costs

We perform an analysis on the benefits of conserving foreshore vegetation in order to simulate the effects of foreshore vegetation on coastal flood protection. We first estimate the costs of structural adaptation measures and the benefits of foreshore vegetation in the adaptation objective 'Protection constant', where the present-day protection standards are kept the same in the future through structural adaptation measures. Then, in order to estimate the contribution of conserving foreshore geomorphology and vegetation as an adaptation measure (hereafter referred to as 'Conserving foreshore vegetation'), we estimate the benefits of conserving foreshore vegetation relative to the total benefits of the adaptation objective 'Protection constant'.

To calculate the investment costs associated with the dike dimensions we use the estimated required dike heights and the dike lengths from the coastlines from the OpenStreetMap. We then estimate the investment costs of structural measures by multiplying by a unit cost set to USD 7 million per km dike-length per m dike-heightening based on reported costs in New Orleans (Bos, 2008). This value of US $7 million km·m is within a reasonable range when compared to various studies (Aerts, Botzen, & De Moel, 2013; Jonkman, Hillen, Nicholls, Kanning, & van Ledden, 2013; Lenk, Rybski, Heidrich, Dawson, & Kropp, 2017), and is used in this study for both building a new dike system and heightening an already existing one. This includes investment costs, groundwork, construction and engineering costs, property or land acquisition, environmental compensation and project management. Subsequently, the costs are converted to US $2005 Power Purchasing Parity (PPP) by first adjusting to US $2005 values using GDP deflators from the World Bank Open Data website (https://data.worldbank.org/) and then using PPP to market exchange rates from OECD, taken from the IIASA SSP database (Riahi et al., 2017). Construction index multipliers, based on civil engineering construction costs, adjust the implementation costs of structural measures to account for differences between countries (Ward et al., 2010).

The benefits of the adaptation measures are expressed as flood risk reduction and estimated by computing the difference in EAD without the adaptation measure or foreshore vegetation and EAD with the adaptation measure, see Equation 3.

$$B_t = \int_{p=0}^{p=p_n} I_\theta(p)dp - \int_{p=0}^{p=p_a} I_\theta(p)dp, \quad (3)$$

where B_t is the benefit of adaptation at time step t, p_n is the non-exceedance probability with no adaptation and p_a the non-exceedance probability with adaptation. We estimate flood risk reduction by taking the difference between flood risk estimated with the scenario where foreshore vegetation is present and the scenario where foreshore vegetation is completely removed. We do this under present-day conditions and future conditions. To do so, we calculate the crest heights of all populated coastlines prone to flooding associated with FLOPROS protection standards with vegetation and project these crest heights on protection standards when no foreshore vegetation is assumed, in order to estimate the difference in protection standards. Subsequently, we use Equation 3 to estimate the present-day and future flood risk reduction through foreshore vegetation by filling in the different protection standards with and without foreshore vegetation. We estimate flood risk reduction relative to the flood risk in the scenario without foreshore vegetation presence. In these estimations, we take into account the current protection standards estimated with the FLOPROS modelling approach described earlier. Furthermore, we estimate the total benefits by summing the reduction in EAD up to 2100.

In this study, we use two scenario combinations to address future projections (van Vuuren et al., 2014), namely RCP4.5-SSP2 and RCP8.5-SSP5. The RCP4.5-SSP2 scenario combination can be linked to a 'middle of the road scenario' with medium challenges and adaptation (Riahi et al., 2017), which can be broadly aligned with the Paris agreement targets (Hope, Salawitch, Canty, Tribett, & Bennett, 2017). The RCP8.5-SSP5 scenario combination addresses a 'fossil-fuel development' world (Kriegler et al., 2017), in which the world faces high mitigation and low adaptation challenges. For uncertainty analysis within these scenario combinations, we use a probability range of sea-level rise.

3 | RESULTS

In this section, we present the results of the current risk reduction performance of the foreshore vegetation present, as well as the benefits of conserving foreshore vegetation in the future under the 'Protection constant' adaptation objective. First, we show the present-day reduction in flood risk, expressed in both EAD and EAPE. Additionally, we show the increase in protection standards that can be attributed to the foreshore vegetation that is currently present, indicating their current value in terms of flood protection. Then, we show the future reduction in flood risk and EAPE for different scenario combinations. Last, we show the benefits of conserving foreshore vegetation and the contribution to the total benefits of adaptation with uncertainty for sea-level rise projections. Table 1 provides a global overview of the results discussed for the reduction in EAD and EAPE under current conditions and for future scenarios in 2080. Next to this, the table shows the total benefits of conserving foreshore vegetation for the scenarios of RCP4.5/SSP2 and RCP8.5/SSP5.

3.1 | Present-day and future risk reduction through foreshore vegetation

Present-day coastal flood protection standards are affected by the effects of wave attenuation through foreshore vegetation. Globally, the total reduction in EAD provided by present-day foreshore vegetation is estimated at US $2.5 billion, which amounts to 13% of global EAD and 0.4% of total GDP exposed. Figure 2 shows the present-day relative reduction in EAD and EAPE, increase in protection standards, and absolute reduction in EAD in the horizontal bar plot through foreshore vegetation for continental regions. The absolute reduction in EAD provided by present-day foreshore vegetation is especially strong in the continental regions of southeastern Asia, eastern Asia, southern Asia and northern America. We also find that, globally, EAPE is reduced by 6% through wave attenuation by foreshore vegetation. Relative reduction through foreshore vegetation is found to be highest in Caribbean, western Asia, Australia and New Zealand. Additionally, we find that the absolute reduction in EAD provided by present-day foreshore vegetation for sub-national regions with high density of salt marshes in the United States and parts of Europe also contributes to a large share of present-day risk reduction (see Figures S1 and S2). We see that the relative increase in protection standards provided by foreshore vegetation is up to 25% in continental regions of Caribbean, Central America and Australia. The estimated relative increase of

TABLE 1 Global overview of the results discussed in this study for both absolute and relative reduction in EAD, reduction in EAPE and total benefits

	Reduction in EAD (US$ B)	Reduction in EAPE (k)	Total benefits (US$ B)
Current	2.5 (12.4%)	342 (5.9%)	—
RCP4.5/SSP2	71 (8.5%)	995 (5.7%)	280 (3.0%)
RCP8.5/SSP5	164 (8.0%)	902 (6.0%)	532 (2.9%)

Note: EAD and EAPE values for both scenarios are estimated for the year 2080. Note that no value is given for total benefits under current conditions as this value is only calculated for RCP/SSP scenarios. Abbreviations: EAD, expected annual damages; EAPE, expected annual population exposed; RCP, representative concentration pathway; SSP, shared socioeconomic pathway.

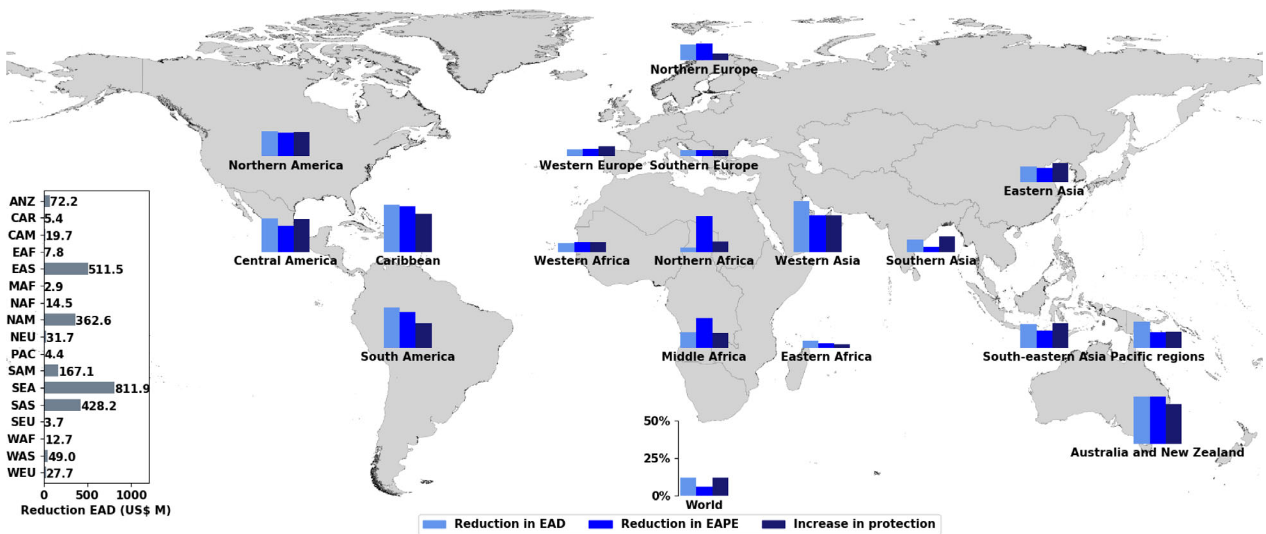

FIGURE 2 Present-day relative reduction to risk without foreshore vegetation of EAD and EAPE, and, increase in protection standards through foreshore vegetation. ANZ, Australia and New Zealand; CAR, Caribbean; CAM, Central America; EAD, expected annual damages; EAF, eastern Africa; EAPE, expected annual population exposed; EAS, eastern Asia; MAF, middle Africa; NAF, northern Africa; NEU, northern Europe; PAC, Pacific regions that include Melanesia, Polynesia and Micronesia; SAM, South America; SEA, southeastern Asia; SAS, southern Asia; WAF, Western Africa; WAS, Western Asia; WEU, Western Europe

protection standards for sub-national regions are shown in Figure S3, which shows that the increase in protection standards provided by present-day foreshore vegetation is especially strong in regions in northern America, Australia, southeastern Asia and South America.

With sea-level rise, subsidence and socio-economic change, future flood risk increases. We find that by conserving present-day foreshore vegetation, EAD in 2080 could be reduced by 71 US$ billion, which amounts to 8.5% of total EAD globally under the scenario combination RCP4.5-SSP2. For the scenario combination RCP8.5-SSP5, we find values of 168 US$ billion and 8% of global EAD. We further estimate that the risk reduction relative to total exposed GDP is doubled to 0.8% for both scenario combinations compared to present-day estimates. The results of estimated future reduction in EAD and EAPE through foreshore vegetation for sub-national regions for the scenario combinations RCP4.5-SSP2 and RCP8.5-SSP4 are shown in Figure 3. The largest future flood risk reduction is found in sub-national regions of West Bengal (India; from current to US $243 million to future US $24.9 billion) which is located in the Sundarbans, Maharashtra (India; from current US $158 million to future US $4.7 billion) which is one of the sub-national regions in India with the largest share of mangroves; Guangdong (China; from current US $266 million to future US $4.2 billion) which has one of the largest shares of mangroves in all of China (Chen et al., 2017); Louisiana (USA; from current US $216 million to future US $1.2 billion) which contains a large share of wetlands of the United States; and Sarawak (Malaysia; from current US $105 million to future US $969 million) for the scenario combination RCP4.5-SSP2 (see Figure S1 for results on present-day flood risk reduction provided by foreshore vegetation for sub-national regions). Globally, we see a reduction in EAPE of 6%, with the largest share in the sub-national regions of West Bengal (India; from current 98,000 to future 310,000 population exposed),

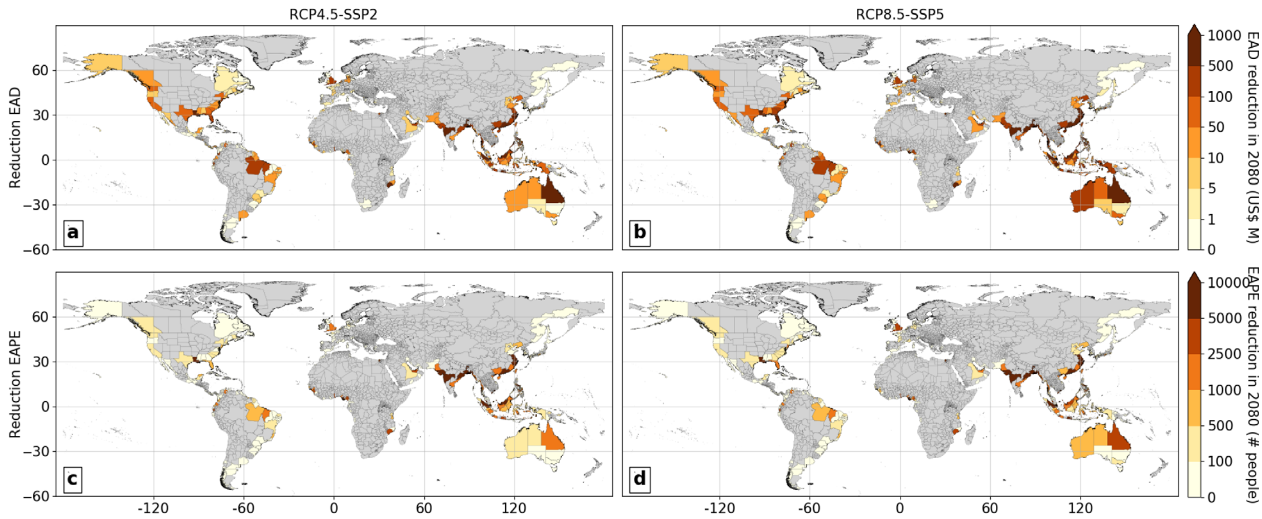

FIGURE 3 Relative reduction in EAD (a and b) and EAPE (c and d) through wave attenuation of foreshore vegetation in 2080 for the scenario combinations RCP4.5-SSP2 (a and c) and RCP8.5-SSP5 (b and d). Sub-national regions with no data are indicated with grey colour. EAD, expected annual damages; EAPE, expected annual population exposed; RCP, representative concentration pathway

Khulna (Bangladesh; from current 21,000 to future 58,000 population) and Camarines Sur (Philippines; from current 13,000 to future 46,000 population exposed) for the scenario combination RCP4.5-SSP2. We see that compared to present-day relative risk reduction, future relative risk reduction will for most sub-national regions be in the same order of magnitude for most sub-national regions, with some sub-national regions having a lower relative reduction.

We find that although relative risk reduction does not change much, absolute risk reduction through foreshore vegetation increases for most sub-national regions due to an increase in future flood hazard and exposure. We show that flood risk reduction is highest for sub-national regions in northern America, Brazil, western Europe, southern Asia, China, southeastern Asia and Australia due to high exposure to flood risk and/or large areas of foreshore vegetation. We see that sub-national regions with a lower share in risk reduction have high absolute values for flood risk reduction due to a high value of exposed assets in deltas (e.g., sub-national regions in China, southern Asia and Louisiana).

3.2 | Benefits and reduction in adaptation costs of conserving foreshore vegetation

In this section, the results are shown for the total discounted benefits of conserving foreshore vegetation with the adaptation objective 'Protection constant'. The total global discounted benefits of conserving foreshore vegetation up to 2100 are estimated at US $274 billion for the scenario combination RCP4.5-SSP2, which amounts to 2.9% of the total benefits for keeping protection standards the same. The highest values of foreshore vegetation benefits relative to total benefits are found in sub-national regions in southern Asia, southeastern Asia, eastern Asia, South America and Australia (see Figure 4). The error bars show the sensitivity of the results to the different sea-level rise probabilistic projections within the RCP scenario while using the same coastal profile, which is found to be within a couple of percentage points. For the scenario combination RCP8.5-SSP5, we find that the global total discounted benefits are twice the amount of the value for RCP4.5-SSP2 and estimated at US $533 billion, which also amounts to approximately 2.9% of total benefits of adaptation (see Figure S5). We find that, due to a higher rate of sea-level rise, the total benefits will increase for most sub-national regions and that the sensitivity of the results to the different sea-level rise probabilistic projections within the RCP scenario are smaller.

To keep current protection standards constant with rising sea-level, adaptation is necessary. We show that through conserving foreshore vegetation, a reduction in required dike heights can be achieved. In Figure 5, we show the reduction of adaptation costs of structural adaptation measures through conserving foreshore vegetation, as well as the remaining costs required for structural adaptation measures (leftover structural adaptation costs). We find that globally the total adaptation costs of structural measures are reduced by US $34 billion if foreshore vegetation is conserved. The highest reductions of adaptation costs through conserving foreshore vegetation, both in absolute and relative terms, are found in Australia. We further estimate savings in adaptation costs through conserving foreshore vegetation of higher than US $4 billion in northern America, southeastern Asia, southern America and eastern Asia.

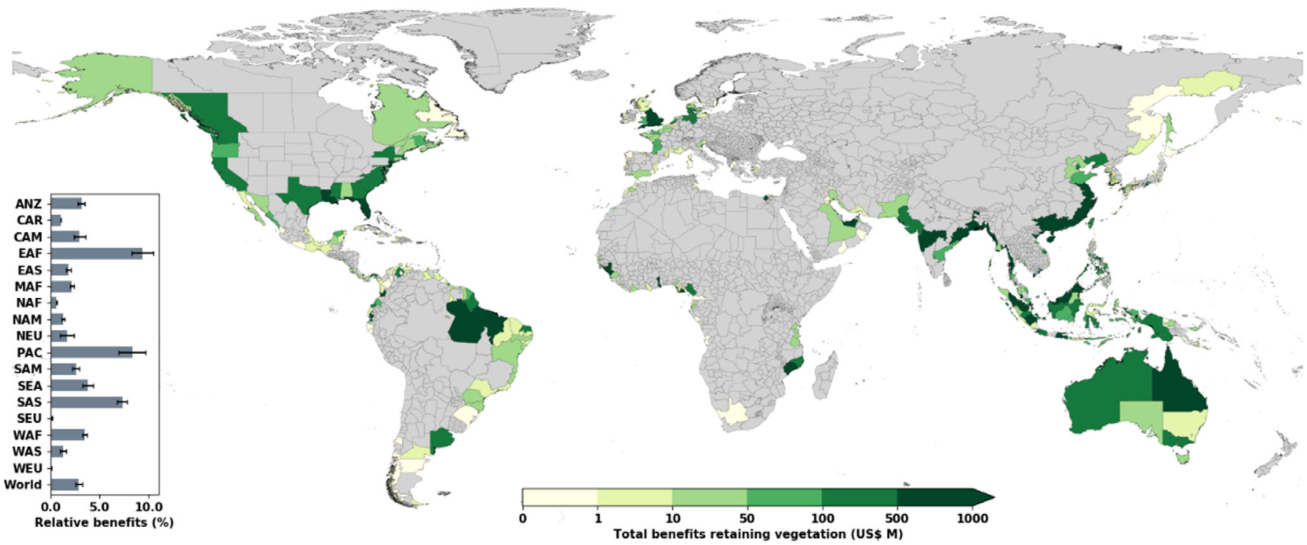

FIGURE 4 Total discounted benefits of conserving foreshore vegetation in the adaptation objective 'protection constant' for the scenario combination RCP4.5/SSP2. Sub-national regions with no data are indicated with grey colour. The error bars in the horizontal bar plot indicate the uncertainty range for the probabilistic sea-level rise projections of the 5th and 95th percentile. ANZ, Australia and New Zealand; CAR, Caribbean; CAM, Central America; EAF, eastern Africa; EAS, eastern Asia; MAF, middle Africa; NAF, northern Africa; NEU, northern Europe; PAC, Pacific regions that include Melanesia, Polynesia and Micronesia; RCP, representative concentration pathway; SAM, South America; SEA, southeastern Asia; SAS, southern Asia; WAF, Western Africa; WAS, Western Asia; WEU, Western Europe

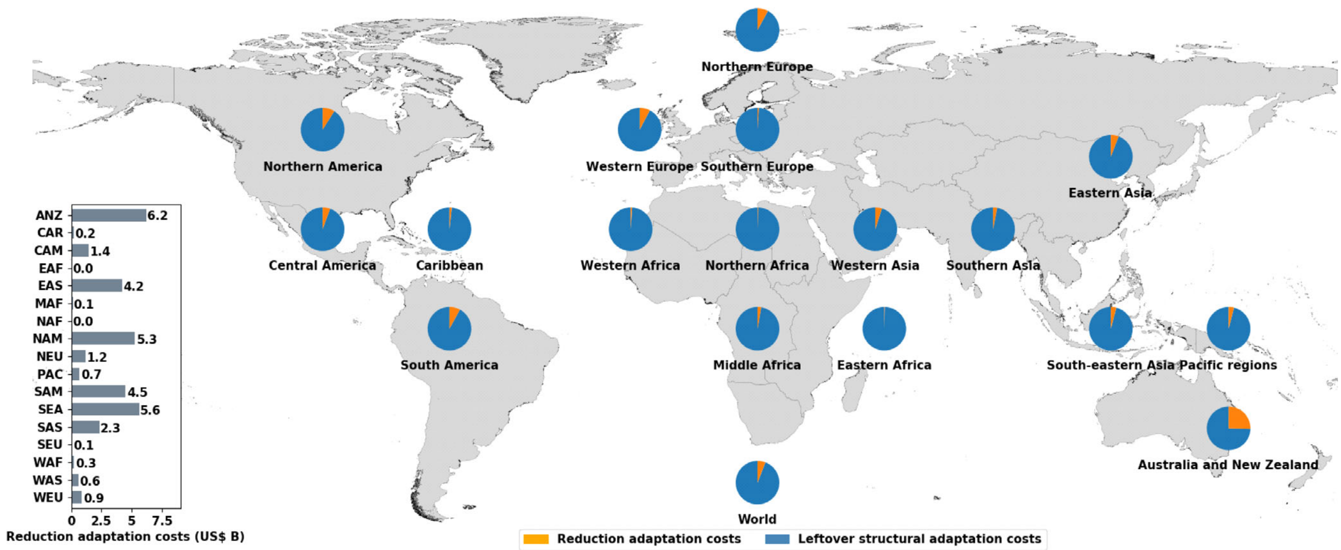

FIGURE 5 Reduction in adaptation costs of conserving foreshore vegetation and leftover structural adaptation costs in the adaptation objective 'protection constant' for the scenario combination RCP4.5/SSP2. ANZ, Australia and New Zealand; CAR, Caribbean; CAM, Central America; EAF, eastern Africa; EAS, eastern Asia; MAF, middle Africa; NAF, northern Africa; NEU, northern Europe; PAC, Pacific regions that include Melanesia, Polynesia and Micronesia; SAM, South America; SEA, southeastern Asia; SAS, southern Asia; WAF, Western Africa; WAS, Western Asia; WEU, Western Europe

4 | DISCUSSION

We present the first global scale assessment of future flood risk reduction through conserving foreshore vegetation and the benefits of conserving foreshore vegetation under future scenarios and adaptation objective 'Protection constant'. We show that foreshore vegetation contributes a large share of flood risk reduction and that absolute EAD reduction is estimated to increase if foreshore vegetation is conserved under future projections of sea-level rise and socioeconomic change. Our estimates point out that conserving foreshore vegetation is an effective measure to reduce future flood risk. We further show that the benefits of conserving foreshore vegetation for flood risk reduction are estimated at approximately US $274 billion, which can account for up to 20% of the total benefits in the protection constant adaptation objective for some sub-national regions. This indicates that ecosystem-based flood protection and Nature-based Solutions constitute promising alternatives or complementary measures to other adaptation measures (e.g., structural measures), which is in line with recent studies on Nature-based Solutions (Borsje et al., 2011; Duarte et al., 2013; Shepard et al., 2011; Spalding et al., 2014; Temmerman et al., 2013; van Zelst et al., 2021; Vuik, Jonkman, Borsje, & Suzuki, 2016).

Assessing the present-day global coastal flood protection of foreshore vegetation in economic terms, we estimated avoided damages of US $2.5 Billion per year, which amounts to 13% of global coastal flood risk in terms of EAD. Menéndez et al. (2020) assessed the benefits of present-day global coastal flood protection of mangroves and found that mangroves provide flood protection benefits exceeding US $65 Billion per year, which is 9% of their estimated global EAD. We see that their estimated global EAD is more than 40 times higher than our estimate, and also higher than values reported in other studies (Hallegatte et al., 2013; Hinkel et al., 2014; Tiggeloven et al., 2020). Moreover, it is more than twice as high as reported values for all natural hazards in the Munich Reinsurance for the period 1980–2017 (Löw, 2018). This may be accounted for as they do not use present-day protection standards in their analysis. In relative terms of flood risk reduction relative to GDP, we find that mangroves reduce 9.8% of global EAD, which is in the same magnitude as estimates found by Menéndez et al. (2020). In a study reporting the value of coastal wetlands on flood risk reduction, Narayan et al. (2017) estimated flood risk reduction through salt marshes on average to be 18% and up to 70% in some regions within the Ocean County in the United States, while we show for the whole state of New Jersey that flood losses could be reduced by 35.6%. While local scale studies show potential benefits of foreshore vegetation on wave load reduction (Horstman et al., 2014; Vuik et al., 2016), it is difficult to compare their results to our study on extreme events as those measurements are often done under daily conditions.

This study only shows the benefits of conserving foreshore vegetation in terms of flood risk reduction, while in reality foreshore vegetation also provides other nature contributions to people as co-benefits such as fishery, recreation (Barbier et al., 2011; Cheong et al., 2013), carbon storage (Mitsch, Bernal, & Hernandez, 2015) and climate change mitigation (Duarte et al., 2013), for example by accumulation of sediments (Kirwan et al., 2010). Next to this, adaptation using a range of different measures might be more feasible in the long run (Jongman, 2018; Sutton-Grier, Wowk, & Bamford, 2015). In this study, we only assume conserving present-day vegetation and structural measures as adaptation measures to reduce flood risk while there are also other adaptation measures. For instance, such adaptation measures include dry and wet proofing (Aerts et al., 2014), migration to less flood prone areas (McLeman & Smit, 2006) or a combination of adaptation through pathways (de Ruig et al., 2019).

The values found in this study for the effects of conserving foreshore vegetation under future change are estimated by assuming that all foreshore vegetation is conserved compared to when all foreshore vegetation is lost due to sea-level rise. In reality, foreshore vegetation will not be lost completely when no human maintenance is carried out, but only a part of the vegetation may disappear due to sea-level rise, erosion and conversion to urban or agricultural land-use (Blankespoor, Dasgupta, & Laplante, 2014; Schuerch et al., 2018; Vousdoukas et al., 2020). Therefore, the values found in this study need to be interpreted as the maximum added value of foreshore vegetation for flood risk reduction and adaptation costs reduction. For instance, if all foreshore vegetation were lost then flood risk would be estimated to increase with the values found in this study. Furthermore, we assume the same coastal profile for all scenarios in this study so the results solely focus on the effects of foreshore vegetation, while in reality the coastal profile is governed by hydrodynamics (e.g., wave heights and currents) and geomorphology (e.g., sediment availability) (Winterwerp, Erftemeijer, Suryadiputra, Van Eijk, & Zhang, 2013). Next to this, this study does not take into account the costs of conserving foreshore vegetation and future work could include an assessment of feasibility of conservation costs under climate change.

Several more limitations and uncertainties exist in this study and are discussed in more detail in Tiggeloven et al. (2020) and van Zelst et al. (2021) such as wave dampening effects and required crest heights estimation methodology. First, several uncertainties exist on the cost calculation and the flood risk calculation. In this study, we use linear costs for structural measures, since according to Lenk et al. (2017), using a linear cost function for large scale assessments is a reasonable assumption. Although we include construction costs and market exchange rates, locally the costs might differ due to both physical and socioeconomic local conditions. Secondly, we estimate flood hazard (inundation) using a GIS-based approach rather than a fully dynamic inundation model (Vousdoukas, Bouziotas, et al., 2018a; Vousdoukas, Mentaschi, et al., 2018b), but we do account for water-level attenuation similar to Vafeidis et al. (2019). Moreover, we estimate flood risk using a number of assumptions on the share of building occupancy and present-day protection standards using the FLOPROS modelling approach (Scussolini et al., 2016). Next to this, because this study uses extreme storm surges, the effects of wave load reduction for extreme events are uncertain and less known as most case studies focus on daily conditions (Horstman et al., 2014; Vuik et al., 2016; Vuik, van Vuren, Borsje, van Wesenbeeck, & Jonkman, 2018).

The results of this study can be used to highlight flood risk reduction through foreshore vegetation at the sub-national scale and the importance of conserving foreshore vegetation under future change. However, we stress that this study aims to give a first proxy of the benefits of conserving foreshore vegetation through flood risk reduction. Local assessments should be used for the design and implementation of individual adaptation measures. At the sub-national and global scale, this study provides insights in Nature-based Solutions by showing the potential of flood risk reduction through foreshore vegetation. Even though the results can only be seen as indicative, we believe that it is valuable to gain insight into the effects of conserving foreshore vegetation on the global scale, and to support the need to include this more in both global assessments and detailed assessments at the regional scale. Going further, this study can be improved by including other Nature-based Solutions strategies, such as restoring wetlands or mangroves, and including an uncertainty analysis of future responses of global coastal wetlands to sea-level rise. Furthermore, an improvement can be made by including a global scale study on the benefits and costs of nature-based, hybrid and structural adaptation measures.

5 | CONCLUSION

We present the first global scale assessment of reducing future flood risk through conserving foreshore vegetation. We find that globally the reduction in flood risk through conserving foreshore vegetation is estimated to increase in the range of 28 up to 67-fold compared to present-day conditions, which amounts to US $71 billion for RCP4.5-SSP2 and US $168 billion for RCP8.5-SSP5 in terms of EAD in 2080. We further find that the relative reduction in flood risk through foreshore vegetation is estimated at 8.5% globally, compared to 13% under current conditions. For individual sub-national regions, risk reduction can reach up to 50% of the total estimated future flood risk. Assessing the benefits of hybrid adaptation measures in the adaptation objective to keep protection standards constant with hybrid adaptation measures, we find that the benefits of conserving foreshore vegetation can reach up to US $1 billion for sub-national regions in southeastern Asia, south Asia, China, Australia and Brazil. Globally, the total benefits of conserving vegetation in the adaptation objective are estimated at US $274 billion. We further show that the relative benefits of conserving foreshore vegetation are estimated at 2.9% of the total benefits of flood protection for keeping protection standard constant under the RCP4.5/SSP2 scenario combination and reach more than 20% for some sub-national regions. Therefore, the results of this study show that Nature-based Solutions can be effective adaptation measures. Although this study only provides a first proxy of the flood risk reduction benefits of conserving foreshore vegetation at the global scale, it shows promising results for including nature-based and hybrid adaptation measures in coastal adaptation schemes.

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DATA AVAILABILITY STATEMENT

The results of this study for all RCP and SSP combinations are available at DOI: 10.5281/zenodo.5878864. Figures of the results of RCP8.5-SSP5 combination are available in the Supplement.

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REFERENCES

Aerts, J. C., Botzen, W., & De Moel, H. (2013). Cost estimates of flood protection and resilience measures. *Annals of the New York Academy of Sciences*, *1294*(1), 39–48.

Aerts, J. C. J. H., Botzen, W., Emanuel, K., Lin, N., De Moel, H., & Michel-Kerjan, E. (2014). Evaluating flood resilience strategies for coastal megacities. *Science Science*, *344*(6183), 473–475.

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, *81*(2), 169–193. https://doi.org/10.1890/10-1510.1

Barbier, E. B., Koch, E. W., Silliman, B. R., Hacker, S. D., Wolanski, E., Primavera, J., Granek, E. F., Polasky, S., Aswani, S., Cramer, L. A., Stoms, D. M., Kennedy, C. J., Bael, D., Kappel, C. V., Perillo, G. M. E., & Reed, D. J. (2008). Coastal ecosystem-based management with nonlinear ecological functions and values. *Science (New York, N.Y.)*, *319*(5861), 321–323. https://doi.org/10.1126/science.1150349

Blankespoor, B., Dasgupta, S., & Laplante, B. (2014). Sea-level rise and coastal wetlands. *Ambio*, *43*(8), 996–1005. https://doi.org/10.1007/s13280-014-0500-4

Borsje, B. W., van Wesenbeeck, B. K., Dekker, F., Paalvast, P., Bouma, T. J., van Katwijk, M. M., & de Vries, M. B. (2011). How ecological engineering can serve in coastal protection. *Ecological Engineering*, *37*(2), 113–122. https://doi.org/10.1016/J.ECOLENG.2010.11.027

Bos, A. J. (2008). *Optimal safety level for the New Orleans East polder; A preliminary risk analysis* [Doctoral dissertation, MSc Thesis University of Amsterdam].

BPIE. (2011). *Europe's buildings under the Microscope - a country by country review of the energy performance of buildings*. Buildings Performance Institute Europe.

Broekx, S., Smets, S., Liekens, I., Bulckaen, D., & De Nocker, L. (2011). Designing a long-term flood risk management plan for the Scheldt estuary using a risk-based approach. *Natural Hazards*, *57*(2), 245–266. https://doi.org/10.1007/s11069-010-9610-x

Calero, J., Hendriksen, G., Dijkstra, J. & Lelij, A. van der (2017). FAST MI-SAFE platform: Foreshore assessment using space technology. Delft, the Netherlands: Deltares.

Chen, B., Xiao, X., Li, X., Pan, L., Doughty, R., Ma, J., Dong, J., Qin, Y., Zhao, B., Wu, Z., Sun, R., Lan, G., Xie, G., Clinton, N., & Giri, C. (2017). A mangrove forest map of China in 2015: Analysis of time series Landsat 7/8 and Sentinel-1A imagery in Google Earth Engine cloud computing platform. *ISPRS Journal of Photogrammetry and Remote Sensing*, *131*, 104–120. https://doi.org/10.1016/j.isprsjprs.2017.07.011

Cheong, S. M., Silliman, B., Wong, P. P., Van Wesenbeeck, B., Kim, C., & Guannel, G. (2013). Coastal adaptation with ecological engineering. *Nature climate change*, *3*(9), 787–791.

de Ruig, L. T., Barnard, P. L., Botzen, W. J. W., Grifman, P., Hart, J. F., de Moel, H., Sadrpour, N., & Aerts, J. C. J. H. (2019). An economic evaluation of adaptation pathways in coastal mega cities: An illustration for Los Angeles. *Science of the Total Environment*, *678*, 647–659. https://doi.org/10.1016/j.scitotenv.2019.04.308

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., … Vitart, F. (2011). The ERA-interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828

Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., & Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change*, *3*(11), 961–968. https://doi.org/10.1038/nclimate1970

EEA (2016). Corine Land Cover 2012 seamless 100m raster database (version 18.5). European Union, Copernicus Land Monitoring Service 2018, European Environment Agency (EEA).

Fagherazzi, S., Kirwan, M. L., Mudd, S. M., Guntenspergen, G. R., Temmerman, S., D'Alpaos, A., van de Koppel, J., Rybczyk, J. M., Reyes, E., Craft, C., & Clough, J. (2012). Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors. *Reviews of Geophysics*, *50*(1), RG1002. https://doi.org/10.1029/2011RG000359

Giri, C., Ochieng, E., Tieszen, L. L., Zhu, Z., Singh, A., Loveland, T., Masek, J., & Duke, N. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography*, *20*(1), 154–159. https://doi.org/10.1111/j.1466-8238.2010.00584.x

Hallegatte, S., Green, C., Nicholls, R. J., & Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. *Nature Climate Change*, *3*(9), 802–806. https://doi.org/10.1038/nclimate1979

Hemer, M. A., Fan, Y., Mori, N., Semedo, A., & Wang, X. L. (2013). Projected changes in wave climate from a multi-model ensemble. *Nature Climate Change*, *3*(5), 471–476. https://doi.org/10.1038/nclimate1791

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., Marzeion, B., Fettweis, X., Ionescu, C., & Levermann, A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(9), 3292–3297. https://doi.org/10.1073/pnas.1222469111

Hope, A. P., Salawitch, R. J., Canty, T. P., Tribett, W. R., & Bennett, B. F. (2017). Paris INDCs. https://doi.org/10.1007/978-3-319-46939-3_3

Horstman, E. M., Dohmen-Janssen, C. M., Narra, P. M. F., van den Berg, N. J. F., Siemerink, M., & Hulscher, S. J. M. H. (2014). Wave attenuation in mangroves: A quantitative approach to field observations. *Coastal Engineering*, *94*, 47–62. https://doi.org/10.1016/j.coastaleng.2014.08.005

Huizinga, J., Moel, H. de, & Szewczyk, W. (2017). Global flood depth-damage functions: Methodology and the database with guidelines. JRC Working Papers, JRC105688.

Idier, D., Paris, F., Le Cozannet, G., Boulahya, F., & Dumas, F. (2017). Sea-level rise impacts on the tides of the European shelf. *Continental Shelf Research*, *137*, 56–71. https://doi.org/10.1016/j.csr.2017.01.007

Jackson, L. P., & Jevrejeva, S. (2016). A probabilistic approach to 21st century regional sea-level projections using RCP and high-end scenarios. *Global and Planetary Change*, *146*, 179–189. https://doi.org/10.1016/j.gloplacha.2016.10.006

Jongman, B. (2018). Effective adaptation to rising flood risk. *Nature Communications*, *9*(1), 1986. https://doi.org/10.1038/s41467-018-04396-1

Jonkman, S. N., Hillen, M. M., Nicholls, R. J., Kanning, W., & van Ledden, M. (2013). Costs of adapting coastal defences to sea-level rise—New estimates and their implications. *Journal of Coastal Research*, *290*, 1212–1226. https://doi.org/10.2112/JCOASTRES-D-12-00230.1

Kirwan, M. L., Guntenspergen, G. R., D'Alpaos, A., Morris, J. T., Mudd, S. M., & Temmerman, S. (2010). Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters*, *37*(23), 23401. https://doi.org/10.1029/2010GL045489

Klein Goldewijk, K., Beusen, A., Van Drecht, G., & De Vos, M. (2011). The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecology and Biogeography*, *20*(1), 73–86. https://doi.org/10.1111/j.1466-8238.2010.00587.x

Kooi, H., Bakr, M., de Lange G., den Haan E. & Erkens, G. (2018). A user guide to SUB-CR: A modflow land subsidence and aquifer system compaction package that includes creep. Delft, the Netherlands: Deltares.

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J.-P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., … Edenhofer, O. (2017). Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, *42*, 297–315. https://doi.org/10.1016/J.GLOENVCHA.2016.05.015

Lenk, S., Rybski, D., Heidrich, O., Dawson, R. J., & Kropp, J. P. (2017). Costs of sea dikes—Regressions and uncertainty estimates. *Natural Hazards and Earth System Sciences*, *17*(5), 765–779. https://doi.org/10.5194/nhess-17-765-2017

Lincke, D., & Hinkel, J. (2018). Economically robust protection against 21st century sea-level rise. *Global Environmental Change*, *51*, 67–73. https://doi.org/10.1016/J.GLOENVCHA.2018.05.003

Little, C. M., Horton, R. M., Kopp, R. E., Oppenheimer, M., Vecchi, G. A., & Villarini, G. (2015). Joint projections of US East Coast sea level and storm surge. *Nature Climate Change*, *5*(12), 1114–1120. https://doi.org/10.1038/nclimate2801

Löw, P. (2018). Hurricanes cause record losses in 2017—The year in figures (Munich Re NatCatSERVICE). Retrieved from Munich Re: https://www.munichre.com/topics-online/en/climate-change-and-natural-disasters/natural-disasters/the-natural-disasters-of-2018-in-figures.html

McGranahan, G., Balk, D., & Anderson, B. (2016). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, *19*(1), 17–37. https://doi.org/10.1177/0956247807076960

Mckee, K. L., Cahoon, D. R., & Feller, I. C. (2007). Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography*, *16*(5), 545–556. https://doi.org/10.1111/j.1466-8238.2007.00317.x

McLeman, R., & Smit, B. (2006). Migration as an adaptation to climate change. *Climatic Change*, *76*(1–2), 31–53. https://doi.org/10.1007/s10584-005-9000-7

Mcowen, C. J., Weatherdon, L. V., Van Bochove, J.-W., Sullivan, E., Blyth, S., Zockler, C., Stanwell-Smith, D., Kingston, N., Martin, C. S., Spalding, M., & Fletcher, S. (2017). A global map of saltmarshes. *Biodiversity Data Journal*, *5*, e11764. https://doi.org/10.3897/BDJ.5.e11764

Menéndez, P., Losada, I. J., Torres-Ortega, S., Narayan, S., & Beck, M. W. (2020). The global flood protection benefits of mangroves. *Scientific Reports*, *10*(1), 4404. https://doi.org/10.1038/s41598-020-61136-6

Meyer, V., Haase, D., & Scheuer, S. (2009). Flood risk assessment in European River basins—Concept, methods, and challenges exemplified at the Mulde River. *Integrated Environmental Assessment and Management*, *5*(1), 17–26. https://doi.org/10.1897/IEAM_2008-031.1

Mitsch, W. J., Bernal, B., & Hernandez, M. E. (2015). Ecosystem services of wetlands. *International Journal of Biodiversity Science, Ecosystem Services and Management*, *11*(1), 1–4. https://doi.org/10.1080/21513732.2015.1006250

Muis, S., Verlaan, M., Winsemius, H. C., Aerts, J. C. J. H., & Ward, P. J. (2016). A global reanalysis of storm surges and extreme sea levels. *Nature Communications*, *7*(1), 1–12. https://doi.org/10.1038/ncomms11969

Narayan, S., Beck, M. W., Reguero, B. G., Losada, I. J., van Wesenbeeck, B., Pontee, N., Sanchirico, J. N., Ingram, J. C., Lange, G.-M., & Burks-Copes, K. A. (2016). The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS One*, *11*(5), e0154735. https://doi.org/10.1371/journal.pone.0154735

Narayan, S., Beck, M. W., Wilson, P., Thomas, C. J., Guerrero, A., Shepard, C. C., Reguero, B. G., Franco, G., Ingram, J. C., & Trespalacios, D. (2017). The value of coastal wetlands for flood damage reduction in the northeastern USA. *Scientific Reports*, *7*(1), 9463. https://doi.org/10.1038/s41598-017-09269-z

Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding—A global assessment. *PLoS One*, *10*(3), e0118571. https://doi.org/10.1371/journal.pone.0118571

Nicholls, R. J., & Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *Science (New York, N.Y.)*, *328*(5985), 1517–1520. https://doi.org/10.1126/science.1185782

Oppenheimer, M., Glavovic, B. C., Hinkel, J., van de Wal, R., Magnan, A. K., Biesbroek, R., Buchanan, M. K., Abe-Ouchi, A., Gupta, K., Pereira, J., Glavovic, B., Hinkel, J., van de Wal, R., Magnan, A., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R., Pörtner, H., … Weyer, N. (2019). Sea level rise and implications for low-lying islands, coasts and communities. In: H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer, (Eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, IPCC.

Pullen, T., Allsop, N. W. H., Bruce, T., Kortenhaus, A., Schüttrumpf, H., & Van der Meer, J. W. (2007). *EurOtop, European overtopping manual-wave overtopping of sea defences and related structures: assessment manual*. Boyens Medien GmbH.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., … Tavoni, M. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/J.GLOENVCHA.2016.05.009

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M. L., Wolff, C., Lincke, D., McOwen, C. J., Pickering, M. D., Reef, R., Vafeidis, A. T., Hinkel, J., Nicholls, R. J., & Brown, S. (2018). Future response of global coastal wetlands to sea-level rise. *Nature*, *561*(7722), 231–234. https://doi.org/10.1038/s41586-018-0476-5

Scussolini, P., Aerts, J. C. J. H., Jongman, B., Bouwer, L. M., Winsemius, H. C., De Moel, H., & Ward, P. J. (2016). FLOPROS: An evolving global database of flood protection standards. *Natural Hazards and Earth System Sciences*, *16*(5), 1049–1061. https://doi.org/10.5194/nhess-16-1049-2016

Shepard, C. C., Crain, C. M., & Beck, M. W. (2011). The protective role of coastal marshes: A systematic review and meta-analysis. *PLoS One*, *6*(11), e27374. https://doi.org/10.1371/journal.pone.0027374

Spalding, M. D., Mcivor, A. L., Beck, M. W., Koch, E. W., Möller, I., Reed, D. J., Rubinoff, P., Spencer, T., Tolhurst, T. J., Wamsley, T. V., van Wesenbeeck, B. K., Wolanski, E., & Woodroffe, C. D. (2014). Coastal ecosystems: A critical element of risk reduction. *Conservation Letters*, *7*(3), 293–301. https://doi.org/10.1111/conl.12074

Sutton-Grier, A. E., Wowk, K., & Bamford, H. (2015). Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy*, *51*, 137–148. https://doi.org/10.1016/J.ENVSCI.2015.04.006

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T., & De Vriend, H. J. (2013). Ecosystem-based coastal defence in the face of global change. *Nature*, *504*(7478), 79–83. https://doi.org/10.1038/nature12859

Tiggeloven, T., De Moel, H., Winsemius, H. C., Eilander, D., Erkens, G., Gebremedhin, E., Diaz Loaiza, A., Kuzma, S., Luo, T., Iceland, C., Bouwman, A., Van Huijstee, J., Ligtvoet, W., & Ward, P. J. (2020). Global scale benefit-cost analysis of coastal flood adaptation to different flood risk drivers. *Natural Hazards and Earth System Sciences*, *20*, 1025–1044. https://doi.org/10.5194/nhess-2019-330

Turner, R. K., Burgess, D., Hadley, D., Coombes, E., & Jackson, N. (2007). A cost–benefit appraisal of coastal managed realignment policy. *Global Environmental Change*, *17*(3–4), 397–407. https://doi.org/10.1016/J.GLOENVCHA.2007.05.006

United Nations Office for Disaster Risk Reduction. (2016). Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction United Nations Office for Disaster Risk Reduction.

Vafeidis, A. T., Schuerch, M., Wolff, C., Spencer, T., Merkens, J. L., Hinkel, J., Lincke, D., Brown, S., & Nicholls, R. J. (2019). Water-level attenuation in global-scale assessments of exposure to coastal flooding: A sensitivity analysis. *Natural Hazards and Earth System Sciences*, *19*(5), 973–984. https://doi.org/10.5194/nhess-19-973-2019

Van Huijstee, J., Van Bemmel, B., Bouwman, A., & Van Rijn, F. (2018). *Towards and urban preview: Modelling future urban growth with 2UP, background report*. PBL Netherlands Environmental Assessment Agency.

van Rooijen, A. A., McCall, R. T., van Thiel de Vries, J. S. M., van Dongeren, A. R., Reniers, A. J. H. M., & Roelvink, J. A. (2016). Modeling the effect of wave-vegetation interaction on wave setup. *Journal of Geophysical Research: Oceans*, *121*(6), 4341–4359. https://doi.org/10.1002/2015JC011392

van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., & Winkler, H. (2014). A new scenario framework for climate change research: Scenario matrix architecture. *Climatic Change*, *122*(3), 373–386. https://doi.org/10.1007/s10584-013-0906-1

van Wesenbeeck, B. K., de Boer, W., Narayan, S., van der Star, W. R. L., & de Vries, M. B. (2017). Coastal and riverine ecosystems as adaptive flood defenses under a changing climate. *Mitigation and Adaptation Strategies for Global Change*, *22*(7), 1087–1094. https://doi.org/10.1007/s11027-016-9714-z

van Zelst, V. T. M., Dijkstra, J. T., van Wesenbeeck, B. K., Eilander, D., Morris, E. P., Winsemius, H. C., Ward, P. J., & de Vries, M. B. (2021). Cutting the costs of coastal protection by integrating vegetation in flood defences. *Nature Communications*, *12*(6533), 6533. https://doi.org/10.1038/s41467-021-26887-4

Vitousek, S., Barnard, P. L., Fletcher, C. H., Frazer, N., Erikson, L., & Storlazzi, C. D. (2017). Doubling of coastal flooding frequency within decades due to sea-level rise. *Scientific Reports*, *7*(1), 1–9. https://doi.org/10.1038/s41598-017-01362-7

Vousdoukas, M. I., Bouziotas, D., Giardino, A., Bouwer, L. M., Mentaschi, L., Voukouvalas, E., & Feyen, L. (2018a). Understanding epistemic uncertainty in large-scale coastal flood risk assessment for present and future climates. *Natural Hazards and Earth System Sciences*, *18*(8), 2127–2142. https://doi.org/10.5194/nhess-18-2127-2018

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Bianchi, A., Dottori, F., & Feyen, L. (2018b). Climatic and socioeconomic controls of future coastal flood risk in Europe. *Nature Climate Change*, *8*(9), 776–780. https://doi.org/10.1038/s41558-018-0260-4

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., & Feyen, L. (2017). Extreme sea levels on the rise along Europe's coasts. *Earth's Future*, *5*(3), 304–323. https://doi.org/10.1002/2016EF000505

Vousdoukas, M. I., Ranasinghe, R., Mentaschi, L., Plomaritis, T. A., Athanasiou, P., Luijendijk, A., & Feyen, L. (2020). Sandy coastlines under threat of erosion. *Nature Climate Change*, *10*(3), 260–263. https://doi.org/10.1038/s41558-020-0697-0

Vuik, V., Jonkman, S. N., Borsje, B. W., & Suzuki, T. (2016). Nature-based flood protection: The efficiency of vegetated foreshores for reducing wave loads on coastal dikes. *Coastal Engineering*, *116*, 42–56. https://doi.org/10.1016/j.coastaleng.2016.06.001

Vuik, V., van Vuren, S., Borsje, B. W., van Wesenbeeck, B. K., & Jonkman, S. N. (2018). Assessing safety of nature-based flood defenses: Dealing with extremes and uncertainties. *Coastal Engineering*, *139*, 47–64. https://doi.org/10.1016/j.coastaleng.2018.05.002

Wamsley, T. V., Cialone, M. A., Smith, J. M., Atkinson, J. H., & Rosati, J. D. (2010). The potential of wetlands in reducing storm surge. *Ocean Engineering*, *37*(1), 59–68. https://doi.org/10.1016/J.OCEANENG.2009.07.018

Ward, P. J., Jongman, B., Weiland, F. S., Bouwman, A., Van Beek, R., Bierkens, M. F. P., Ligtvoet, W., & Winsemius, H. C. (2013). Assessing flood risk at the global scale: Model setup, results, and sensitivity. *Environmental Research Letters*, *8*(4), 044019. https://doi.org/10.1088/1748-9326/8/4/044019

Ward, P. J., Strzepek, K. M., Pauw, W. P., Brander, L. M., Hughes, G. A., & Aerts, J. C. J. H. (2010). Partial costs of global climate change adaptation for the supply of raw industrial and municipal water: A methodology and application. *Environmental Research Letters*, *5*(4), 044011. https://doi.org/10.1088/1748-9326/5/4/044011

Ward, P. J., Winsemius, H. C., Kuzma, S., Luo, T., Bierkens, M. F. P., Bouwman, A., de Moel, H., Diaz Loaizaa, A., Eilander, D., Englhardt, J., Erkens, G., Gebremedhind, E., Iceland, C., Kooi, H., Ligtvoet, W., Muis, S., Scussolini, P., Sutanudjaja, E. H., van Beek, R. & Tiggeloven, T. (2020). Aqueduct floods methodology technical note. WRI: Washington, D.C., United States

Winsemius, H. C., Aerts, J. C. J. H., Van Beek, L. P. H., Bierkens, M. F. P., Bouwman, A., Jongman, B., Kwadijk, J. C. J., Ligtvoet, W., Lucas, P. L., Van Vuuren, D. P., & Ward, P. J. (2016).

Global drivers of future river flood risk. *Nature Climate Change*, *6*(4), 381–385. https://doi.org/10.1038/nclimate2893

Winterwerp, J. C., Erftemeijer, P. L. A., Suryadiputra, N., Van Eijk, P., & Zhang, L. (2013). Defining eco-morphodynamic requirements for rehabilitating eroding mangrove-mud coasts. *Wetlands*, *33*(3), 515–526. https://doi.org/10.1007/s13157-013-0409-x

Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O'Loughlin, F., Neal, J. C., Sampson, C. C., Kanae, S., & Bates, P. D. (2017). A high-accuracy map of global terrain elevations. *Geophysical Research Letters*, *44*(11), 5844–5853. https://doi.org/10.1002/2017GL072874

Zhang, K., Liu, H., Li, Y., Xu, H., Shen, J., Rhome, J., & Smith, T. J. (2012). The role of mangroves in attenuating storm surges. *Estuarine, Coastal and Shelf Science*, *102–103*, 11–23. https://doi.org/10.1016/J.ECSS.2012.02.021

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