THE COASTAL FLOOD RISK BENEFITS OF MANGROVES AND TIDAL MARSHES

Summary report

VINCARR

Vegetation INtegration for Climate Adaptation and Risk Reduction

TU Delft Delft University of Technology

The Nature Conservancy

The coastal flood risk benefits of mangroves and tidal marshes

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Client The Nature Conservancy

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VINCARR
Vegetation Integration for Climate Adaptation and Risk Reduction
A PhD research trajectory that aims to quantify the performance and suitability of vegetation based coastal Nature-based Solutions.

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Contents

Key findings

- A first-ever high-resolution global map has been completed highlighting the role of coastal wetlands in reduction of storm surge flooding, using new 2-dimensional modelling techniques.

- Previous, lower resolution and 1D-models, did not allow for the complex processes of lateral water flows, hence tended to over-estimate local surge reduction of coastal wetlands.

- Wetlands remain of critical importance for surge reduction by reducing on average:
  - flood depths by 27%
  - flooding extent by 10%

- The benefits to people are considerable as coastal wetlands:
  - reduce damage to infrastructure by 3% in coastal wetland regions, or 230 USD million per year world-wide
  - protect around 93,000 people from coastal flooding yearly

- Mangrove forests are particularly effective in reducing surges, and mangrove nations including Indonesia, Colombia, Bangladesh and Tanzania are among the major beneficiaries.

- Tidal marshes have less impact on surge reduction, but in countries such as the United States and the United Kingdom they provide critical benefits.

- Future scenarios highlight the challenges posed by climate change. Under a high emissions scenario (RCP8.5) for 2100 we present two extremes:
  - If wetlands can keep pace with sea level rise, and/or migrate inland the benefits will remain broadly comparable in terms of effect, albeit with massive increases in the avoided damages and population numbers as these change with time.
  - If there is no change in wetland elevation over this time-frame, almost all of these benefits will be lost.

- Additional studies in Belize, Gabon and Jamaica tested the role of wind waves complementary to surges. However the role of wind waves in coastal flooding proved much lower than that of storm surges. This is in part because coastal wetlands are almost always located in highly sheltered locations.

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INTRODUCTION

ASSESSING COASTAL FLOOD RISK REDUCTION BY COASTAL WETLANDS

Flooding is the most frequently occurring natural disaster. It can originate from high river flows, extensive rainfall, ground water and sea water, or a combination of these hazards. The associated risk is a function of hazard (extreme water level), exposure (people and assets in flood prone area) and vulnerability (socioeconomic capacity to cope with the impacts). Specifically, coastal flood risk has a low probability of occurrence, but has potentially devastating effects and may impact 5.8 million people annually (Tiggeloven et al., 2020). In the future sea-level rise, changing weather patterns and changing demographics will exacerbate coastal flood risk affecting 17.5 million people annually by 2080. Conservation and restoration of coastal wetlands, such as tidal marshes and mangroves, is considered an effective solution to reduce coastal flood risk. However, the benefits are not easily quantified, due to the complexity of coastal wetland landscapes. Especially with respect to surges, currently available global studies offer coarse insights that give a first indication of potential effects at large spatial scales. However, these studies oversimplify surge propagation through a coastal landscape by using a 1D modelling approach and may thereby largely overestimate effects of wetlands on surge reduction. Recent improvements of data layers and development of fast 2D surge models, allow for a more reliable estimation of effects of wetlands on surge reduction. The current study, quantitatively assesses and maps the coastal protection benefits of mangroves and tidal marshes globally by applying a state-of-the-art data and 2D modelling approach.

OUTLINE

The Flood Risk Benefits of Coastal Wetlands Map, is based on thousands of 2D-numerical flood model simulations that are set-up using global data sources. These simulations are executed with configurations with current coastal wetland cover and without coastal wetlands. Flood depth differences induced by coastal wetlands are provided to a subsequent socioeconomic model to express the benefits in terms of affected people and avoided damages globally.

Report sections:

- Theoretical background
- Methods
- Results
- Concluding remarks

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Theoretical background

Coastal wetlands interact with flood components

Coastal water levels consist of the sum of tides, storm surges and wave-induced setup. Storm surges are elevated coastal waters caused by disturbances in atmospheric pressure and winds and they can last hours up to several days. Wave-induced setup is a local increase in water level caused by short-wave dissipation. Tides are periodic changes in sea level caused by the gravitational attraction of the earth and the moon, and of the earth and the sun. Storm surges, tides and wave-induced setup are so-called long-waves. The relative importance of these flood components varies regionally, due to different weather systems and coastal landscapes. For instance, in areas of shallow depth and gentle slopes (e.g. a wide continental shelf) storm surges can rapidly gain height.

Mangrove and tidal marsh ecosystems do not block high waters, but can reduce the amount of energy in the water and thereby reduce water levels, wave heights and current velocities. This can potentially reduce flood depths, flood extent and wave impact. Extensive coastal wetlands, of over 500 metres width, can greatly reduce (short) wave heights (Möller et al., 2014; van Wesenbeeck et al., 2025). Even if vegetation is sparse, e.g. in winter in temperate areas, the substrate provides additional friction and limits the wave height by depth induced breaking. Short wave heights should not be confused with wave-induced-setup which is an increase in mean sea level. Moreover, it remains unclear if coastal wetland vegetation could provide a meaningful flood *depth* reduction by attenuating short-waves. Typically, mangroves and tidal marshes are located in sheltered regions or areas that are generally not exposed to large waves. For example, if facing the open coast the daily wave conditions are mild and/or the coastal profile is generally gently sloping. For this reason, large wave-setups are unlikely to develop in such areas. However, exceptions such as tropical islands exist. These locations receive mild wave action during daily conditions but could encounter large storm waves but limited storm surges due to steep and narrow shelves during tropical storms. This applies for instance for areas in the Caribbean Sea. However, even for such areas the role of coastal wetlands is not trivial. For example, in these areas mangroves are often fronted by reefs. During tropical storms, incoming waves break primarily on the reefs. In such instances, the set-up is already largely generated and thus the generation can no longer be prevented by coastal wetlands. However, the wave-setup can still be reduced.

For long waves, more extensive greenbelts are required to lower water levels. For example, storm surge attenuation rates are estimated to range between 5-50 cm/km (Baird et al., 2009; Chen et al., 2021; McIvor et al., 2012; Zhang et al., 2012). The storm surge reduction rate depends on the propagation speed and the duration of the storm surge. For example, slowly propagating storms that have a longer duration are less affected by vegetation presence than rapid and short storms (Zhang et al., 2012). Additionally, attenuation rates of storms are not spatially uniform. Modelling studies show that locally increasing water levels can occur in non-vegetated areas due to the presence of coastal wetland vegetation elsewhere (De Dominicis et al., 2023). Temmerman et al., 2023 highlights the importance of coastal geometry for future research, as it greatly influences storm surge propagation and likely influences the flood protection benefits of coastal wetlands.

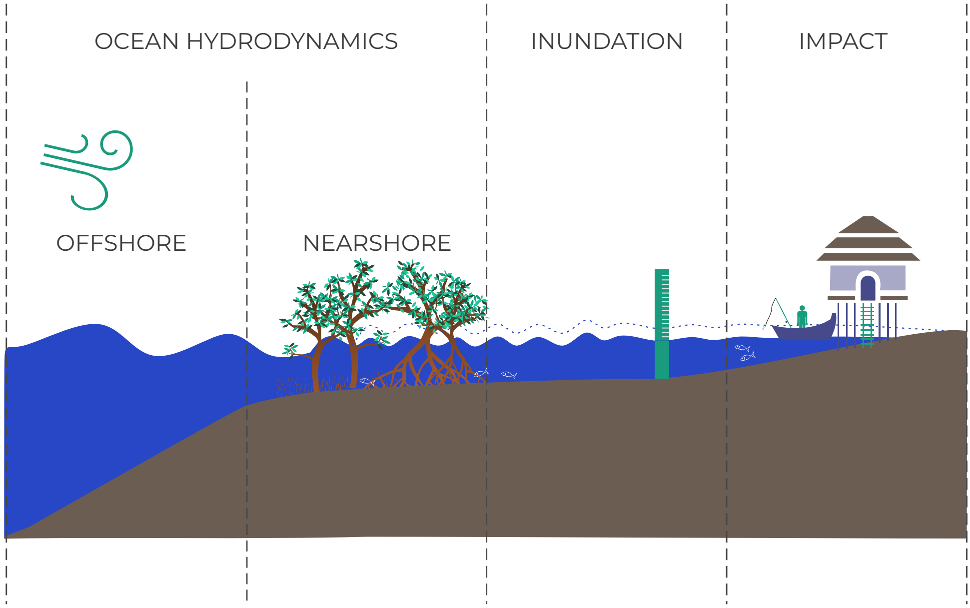

Figure 2.1: Storm water levels along an idealized coastal wetland profile

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Methods

Complex coastal landscapes require advanced modelling

Modelling approaches can be instrumental in estimating flood risk benefits of coastal wetlands. Typically, local and regional scale model assessments apply two-dimensional process-based models solving physical relations and giving reasonable estimations of reduction of waves and surges. Due to computational time, until now, global scale assessments reverted to simple methods consisting of a 1D transect approach with regression formulas or interpolation tables. This largely simplifies complex multidimensional processes, which are essential in properly predicting surge propagation through vegetation. For example, surges tend to bypass vegetation through tidal and river channels (Narayan et al., 2017; Temmerman et al., 2012, 2023). In a 1D transect approach, surges are forced through the vegetation, thereby over-estimating attenuation potential by vegetation. Such approaches may provide acceptable results at simple open coasts, but are unlikely to yield trustworthy results in more complex landscape configurations where coastal wetlands are typically found. The only prior 2D models run at global scales have been applied on a very coarse resolution (km scale) and/or rely on a limited physical basis. Hence, this still does not represent physical processes of surge propagation properly.

Global storm surge reduction model in brief

In this study, we model inundation induced by a combination of tides and storm surges with a resolution of 100 m for all global coastlines vegetated with tidal marshes and/or mangroves. This resolution is unprecedented on a global scale and is only possible due to advances in hydrodynamic models and computational facilities. The reduced physics hydrodynamic model SFINCS (Leijnse et al., 2021) that solves the simplified shallow water equations (SSWE) is applied to simulate propagation from shallow water (a few km seaward) towards the coastline and overland inundation. Next, outputs are used in a socioeconomic analysis to express the coastal protection benefits provided by coastal wetlands in terms of avoided damages and a reduction in the number of people exposed to coastal flooding.

MODEL COMPONENTS

Flood model

SFINCS models with vegetation and without vegetation presence are generated. Comparison of the output of these models provides insights into the flood protection value of the present-day coastal wetlands (Figure 3.1). A staggered equidistant grid with a resolution of 100 metres is used. The storm water levels at the model boundary are derived from Dullaart et al. (2023). This study created storm hydrographs by selecting 36hrs before and 36 hrs after storm surge peak events from the COASTRP dataset (Dullaart et al., 2021). The COASTRP combines GTSM v3 (Muis et al., 2020) and cyclone tracks from Bloemendaal et al. (2019). Mangrove extent is obtained from Global Mangrove Watch year 2020 (Bunting et al., 2022) and 2020 tidal marsh extent from Worthington et al. (2024). The influence of vegetation presence on storm surge propagation is modeled using an increased Manning roughness value following (Rezaie et al., 2020; Zhang et al., 2012). Topographic data (bathymetry and elevation) is generated by combining open-source global data sources; DeltaDTM (Pronk et al., 2024), EMODNET bathymetry (v2022) (Schaap & Moussat, 2013), GEBCO bathymetry (v2020) (Becker et al., 2009), Global Surface Water data (Pekel et al., 2016), GTSM tidal statistics (Muis et al., 2020) and river trajectories (Lin et al., 2019).

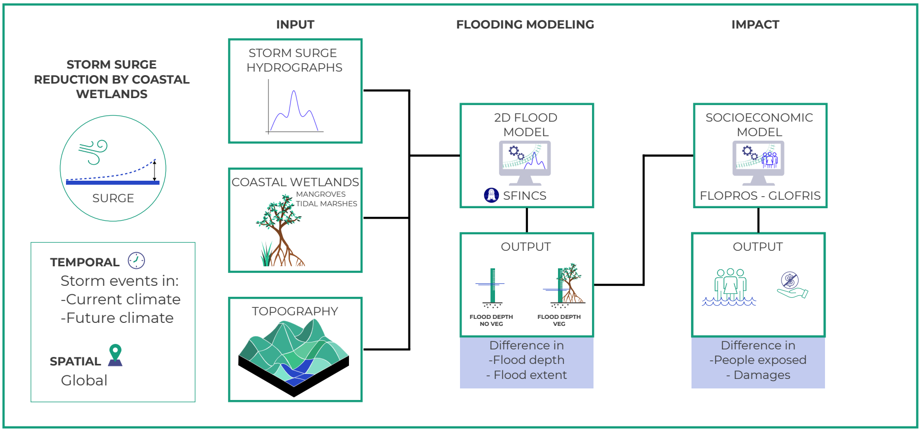

Figure 3.1: Model components

Wave modelling case studies

In addition to the global storm surge models, numerical model simulations are executed for case study regions in Belize, Jamaica and Gabon to assess the relative importance of storm surges and waves and the ability of coastal wetlands to reduce coastal flooding induced by waves, tides and storm surges combined. The models consist of a combination of a full-physics hydrodynamic model (Delft Flexible Mesh model) and a wave model (SWAN), which are online coupled, meaning that the results of the flow model are provided to the wave model and vice-versa.

Socioeconomic model

We estimate flood impact as a function of hazard, exposure and vulnerability (UNISDR, 2016) using the GLOFRIS risk assessment framework of Ward et al. (2013). The flood depth and flood extent maps orginating from the global surge modelling, are taken as hazard data. People in areas with flood depths exceeding 0.05 m are considered to be affected by flooding. Exposure data used in this study consist of current gridded built-up area taken from the Global Human Settlement Layer at 3 arcseconds resolution and future built-up area from the 2UP dataset at a resolution of 30 arcseconds (van Huijstee et al., 2018). We follow Huizinga et al. (2017) to estimate the current maximum damages, and scaled this with GDP per capita per country from the Shared Socioeconomic Pathway (SSP) database for future estimates. Following Huizinga et al. (2017), the density of buildings per occupancy types is set to 0.2 for residential and 0.3 for commercial/industrial, and next to this we use the depth-damage functions that follow their methodology. To estimate flood risk in terms of people affected and expected damages, we take the integral of the exceedance probability-impact (risk) curves (Meyer et al., 2009). We use coastal protection standards as calculated by Tiggeloven et al. (2020) following the FLOPROS modelling approach (Scussolini et al., 2016), to estimate risk levels with and without the influence of engineered coastal protection, such as levees and flood walls. These coastal protection standards allow local modification of impact risk curves in terms of people and expected damages based on social and economic indicators.

Scenarios

Surge modelling is executed for scenarios covering current and future climate conditions. For the current climate, multiple storm intensities are considered. Storm intensity is expressed by the water level return period (RP). Four return periods are included: 5 years, 25 years, 100 years and 1000 years. To represent future climate conditions, a 100 year storm intensity is applied in combination with sea-level rise predictions for the year 2100 in line with SSP5/RCP8.5 from the Sixth IPCC assessment report (Intergovernmental Panel on Climate Change (IPCC), 2023). In the future climate, persistence of coastal vegetation is threatened by sea-level rise. The resulting higher inundation frequency and duration could potentially drown coastal vegetation at its current position. Consequently, vegetation extent could be reduced if possibilities for landward migration are marginal. The ability of coastal vegetation to adapt to SLR is not explicitly modelled in the study. Instead, we consider two adaptation scenarios that represent the *best* and *worst* case future vegetation cover. The best-case scenario assumes that all vegetation that is present in the current climate scenario will be present in the future at the same location. By contrast, the worst-case scenario assumes that the vegetation partly drowns. Vegetation die-off is estimated based on elevation at which the vegetation is present in the current climate scenarios.

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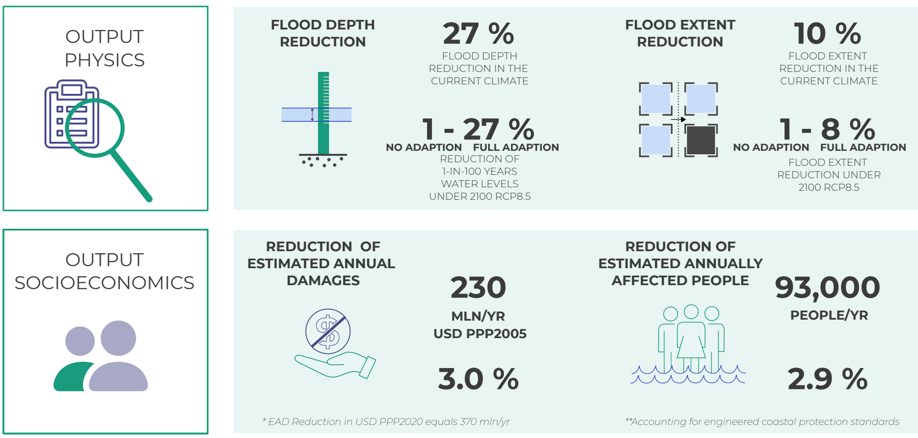
Results

Coastal flood risk benefits of coastal wetlands in numbers

We assessed the coastal protection benefits of tidal marshes and mangroves, at a global scale by deploying an advanced 2D process-based modelling approach with an unprecedented resolution of 100 metres. Results show that coastal wetlands reduce flood depths on average by 27 % by decelerating and redirecting storm surges under current climatic conditions. Mangrove-dominated areas receive far greater reduction (37 %) compared to tidal marsh areas (15 %). Reduction increases over distance as the surge penetrates further in the wetlands and can reach up to 100%. This can ultimately prevent surrounding lands from flooding. On average, flood extent is reduced by 10 % (average of period 5-1000 years). The number of people exposed to flooding is reduced by 93.000 (-2.9%) annually and estimated annual damages (EAD) are reduced by 230 million/yr USD PPP2005 (-3%) (370 million/yr USD PPP2020) when accounting for current engineered coastal protection standards.



Flood depth reduction

Results indicate that in the current climate for a return period of 100 years, coastal wetlands reduce maximum flood depths in adjacent inland areas by 31% and flood extent by 10% on average. This underlines that coastal wetlands considerably lower flood depth, but in general do not fully prevent flooding. Additionally, model results show larger flood reduction values for mangrove dominated areas than tidal marsh areas (Figure 4.1). For future scenarios, where coastal wetlands are unaffected and bed level increases with SLR, flood depth reduction is 27% on average. For worst-case scenarios, where we assume partial loss of coastal wetlands and no increase of bed level, coastal wetland vegetation reduces flood depths by only 1% on average (Figure 4.1). Hence, results for future scenarios, are strongly dependent on the ability of mangroves and marshes to keep pace with sea level rise.

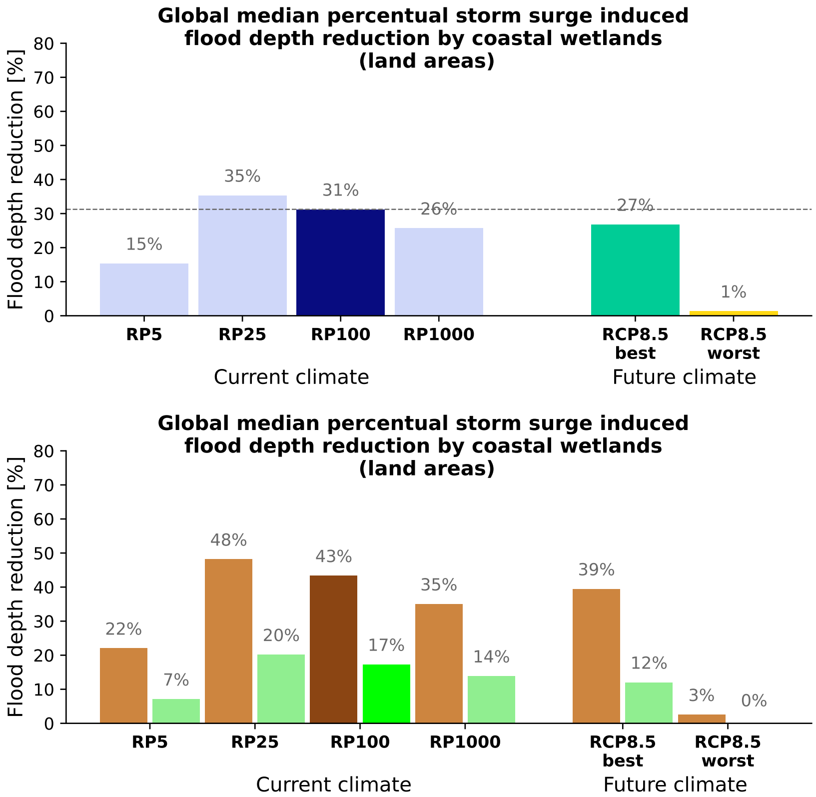


Figure 4.1: Average flood depth reduction by coastal wetlands in the current and future climate. (Top) Mangroves and tidal marshes areas combined. (Bottom) Split in benefits provided by mangroves and tidal marshes. (Current climate with four return periods (RP), future climate outcomes correspond to RP100.)

Flood protection benefits of coastal vegetation vary globally, due to differences in coastal geometry, vegetation cover and storm characteristics. Flood depth reduction hotspots are observed globally, but mainly in the tropics and subtropics where mangroves are present. For example, in South-America along the coastlines of Columbia, Panama, Guyanas and Brazil. In North-America, the largest reductions are observed along the Gulf of Mexico. In Africa, the largest reductions in flood depths are observed in Mozambique, Madagascar, Tanzania and Kenya. In Europe, the influence of tidal marshes is smaller compared to tropical areas. Even so, considerable reductions are observed in South-East England and the Eastern Wadden-Sea. In Asia, protection benefits from mangroves are observed along large tracts of coastline. For example, Bangladesh (Ganges-Bramaputra Delta), Myanmar (Irrawaddy Delta, Mergui Archipelago region), Vietnam (Mekong Delta and Red River Delta) and numerous locations in both Indonesia and the Philippines. In Oceania, areas benefiting from mangroves for flood protection can be found along many stretches of Australia's north coast (Figure 4.2).

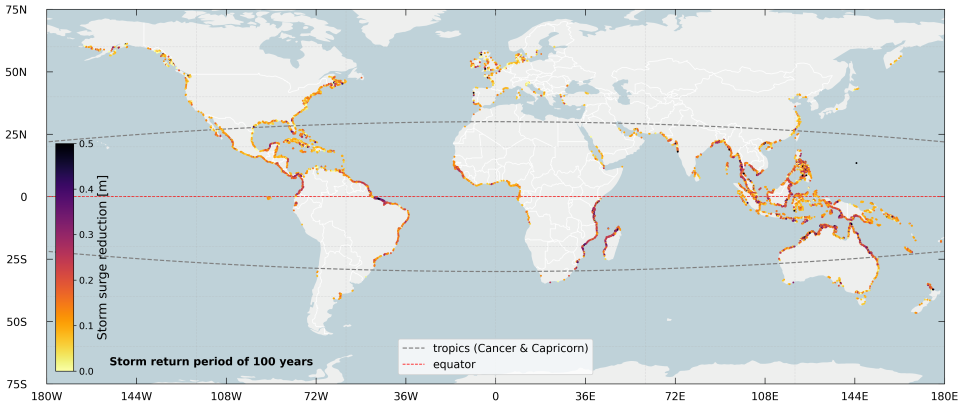


Figure 4.2: Global distribution of storm-surge induced flood depth reduction by coastal vegetation for a 1 in 100 years extreme water levels

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Patterns in flood protection vary at broad scales around the world, but the models also highlight local variability. This is exemplified by the increased levels of flood depth reduction moving landswards, as exemplified by the location Cape Coral in Figure 4.3.

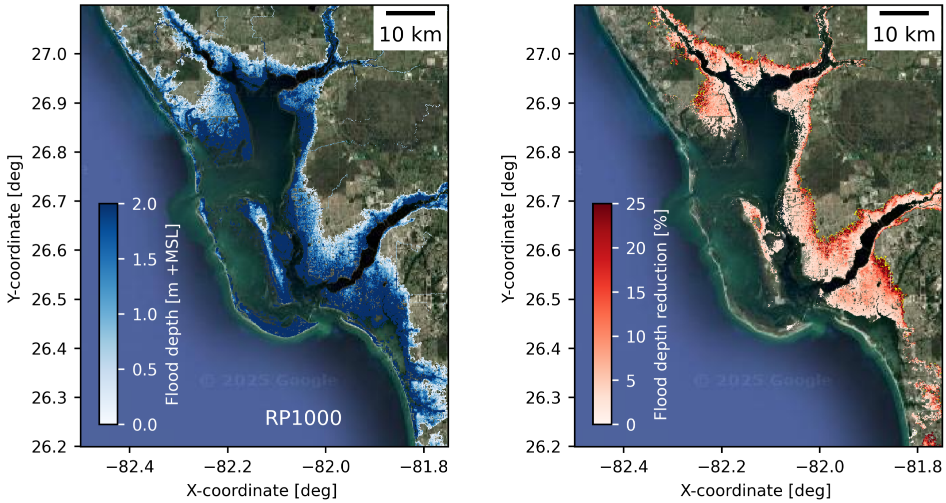

Figure 4.3: Example of processed model output for Cape Coral, Gulf of Mexico for 1 in 1000 years water level conditions.

Flood depth is dominated by storm surges

Modelling case studies conducted for Belize, Jamaica, and Gabon indicate that flood depths in flood-prone regions are mainly influenced by storm tide, which is the combination of tides and storm surges, as opposed to waves and wave set-up. These case study sites encompass diverse coastal landscapes, of which Jamaica displayed the greatest contribution of (short) waves to the total flood depth. This is explained by the coastal typology consisting of a narrow continental shelf and high energetic waves from the Atlantic Ocean and the Caribbean Sea. Overall findings from this work highlight that wave height in front of coastal wetlands is only a fraction of the offshore wave height. This also implies that wave-setup is primarily generated in non-coastal wetland regions. Coastal wetland vegetation still reduces wave-setup, although this component of flood reductions is considerably less important than the role played by coastal wetlands in reducing storm tide impacts. The exact mechanisms behind wave-setup reduction by coastal wetlands are not yet fully understood and therefore, our modelling employs a conservative strategy assuming that reductions in wave energy are fully transformed into water flow, thereby resulting in vegetation-induced wave setup notably in the outer margins of mangrove areas.

REDUCTION OF PEOPLE EXPOSED AND AVOIDED DAMAGES

The differences in flood depth and flood extent are expressed in terms of a reduction in estimated annually affected people (EAAP) and estimated annual damages (EAD). The findings emphasize that the location of people and assets relative to coastal wetlands is crucial in determining flood risk mitigation benefits. Consequently, areas witnessing substantial decreases in flood depths are not automatically aligned with hotspots for flood risk reduction. For instance, while the coasts of China and India do not very prominently feature in flood depth reduction, dense coastal populations mean that there are regions in both countries where the number of people exposed to flooding is substantially reduced (Figure 4.5). Accounting for current protection standards, coastal wetlands can reduce estimated annual damages by 370 million USD PPP2020 (3.0 %) and reduce the number of estimated annually affected people by 93,000 (2.9 %). The top five countries experiencing the greatest reduction in the number of people exposed to coastal flooding are Indonesia, Nigeria, India, Vietnam, and the Philippines. When it comes to avoided damages, the United States, Vietnam, India, Japan, and Thailand benefit the most (Figure 4.4).

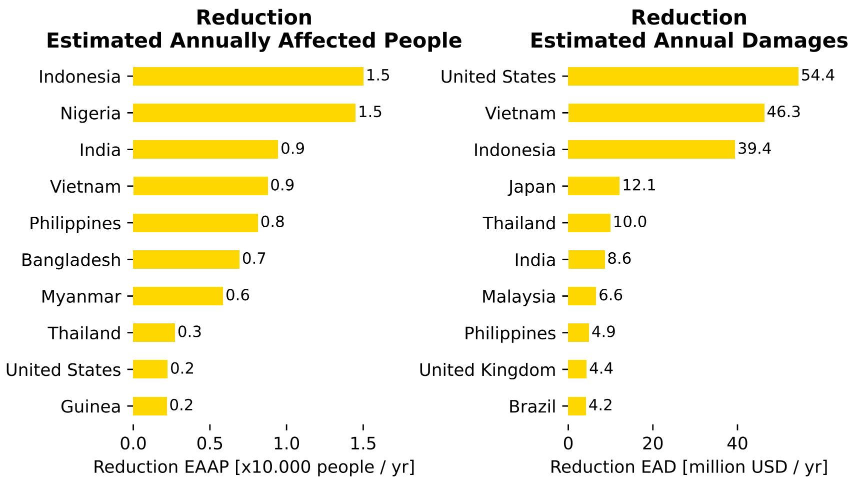

Figure 4.4: Barplots indicating the top-10 countries in terms of reduction EEAP (left) and EAD (right) in the current climate. These are present-day annual reductions in USD PPP 2005.

In the future climate, avoided damages by coastal wetlands can increase substantially to 1,644 billion USD for RCP8.5 2100 RP100 if present-day coastal wetlands persist and fully adapt to SLR. This is an substantial increase compared to the present-day RP100 avoided damages of 4.5 billion USD. The top ten countries partly shifts in comparison to the current climate. For instance, the top three countries with the highest estimated avoided damages consist of Guinea (294 billion USD), Nigeria (224 billion USD) and Indonesia (160 billion USD). On the contrary, in the worst case scenario, the benefits largely diminish.

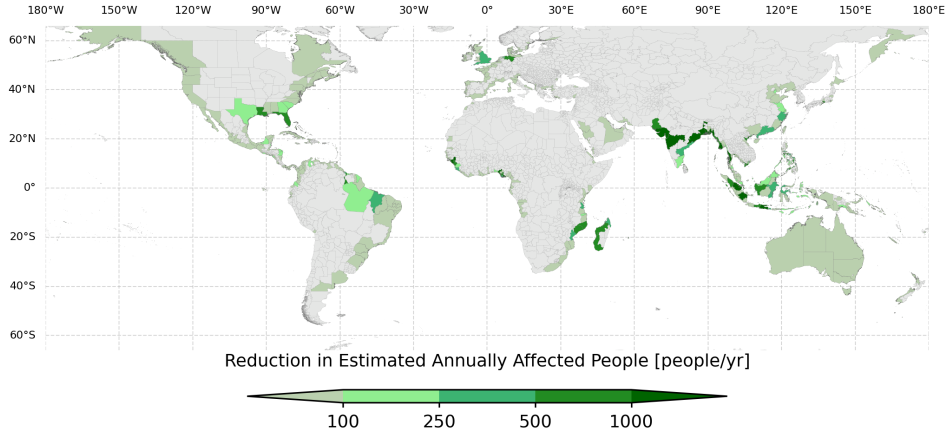

Figure 4.5: Global map of the reduction in estimated annually affected people (EAAP) in the current climate due to storm surge reduction by coastal wetland vegetation, accounting for current coastal protection standards. Illustrated coastal regions are the administrative sub-divisons from GADM (2020) for each country.

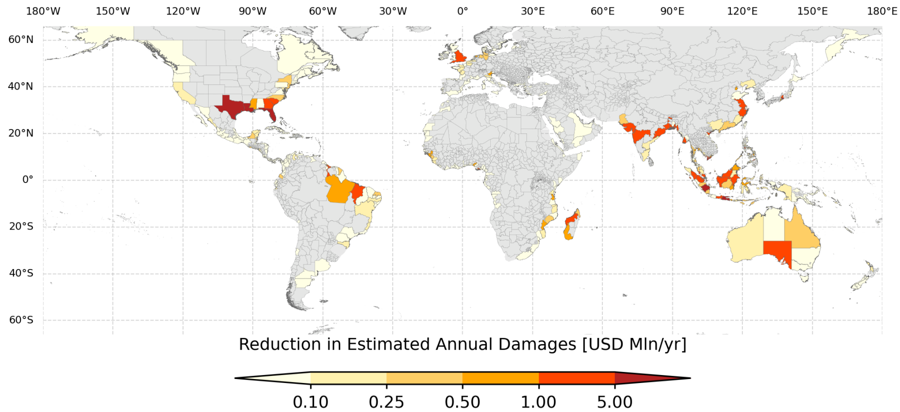

Figure 4.6: Global map of the reduction in estimated annual damages (EAD) in the current climate due to storm surge reduction by coastal wetland vegetation, accounting for current coastal protection standards.

5

Concluding remarks

Bypassing flows lead to lower coastal protection benefits

This work continues to highlight the critical importance of coastal wetlands in protecting coasts, people and infrastructure from the impacts of storm surges. At the same time, the overall benefits are considerably lower than previous estimates. There are a few key aspects that may, at least partly, explain the differences. A 2D modelling approach in which surges can also be redirected and bypassing wetlands via channels or non-vegetated low-lying lands. This approach also lowers the total risk that is reduced by the presence of mangroves and tidal marshes, but is a lot more realistic compared to a transect approach, which assumes that the storm surge propagates fully through the coastal wetlands. Further differences between this work and earlier studies are driven by differences in the methods applied to different methods are applied to derive offshore storm conditions. In the current study, extreme offshore water levels are derived by a global process-based Delft3D-Flexible Mesh model, the Global Tide and Surge Model (GTSM), which has been developed and validated for the last decade. In comparison, Menéndez et al. (2020) used a regression formula derived from case study results for a single country (the Philippines)to estimate extreme water levels for the entire globe. However, the Philippines has a very specific coastal topography, characterized by a short continental shelf bordering extremely deep water. In combination with the high incidence of typhoons on this coast, the extreme conditions observed here are not representative for many other mangrove coasts. This is likely to result in an over-estimation of areas that are prone to flood risk world wide. Table 5.1 highlights the substantial difference between the projected financial exposure to flood risk calculated in this particular study (797 billion USD/yr) and a number of others (6 to 20 billion USD/yr) prior to modelled impacts of protection by coastal wetlands. A further important factor driving difference in our model is that our headline numbers incorporate the likely role of engineered coastal protection which we expect to work alongside coastal wetlands in mitigating impacts. This approach has also been taken by others, as the existence of such structures is widespread in places where people and infrastructure are at risk. Our approach still includes an estimation of the variability in the efficacy of such structures in different social and economic settings. The total flood risk benefits by mangroves, estimated by Menéndez et al. (2020) at 65 billion USD anually, are also substantially larger compared to other studies and are considerably higher than the total GDP at risk calculated by other studies.

We observed that our approach, which is based on more locally representative conditions, provides systematically lower offshore water levels and lower flood risk values without mangroves. As a result, the amount protected by mangroves is substantially lower.

Study	**EAD** $_{current}$	**Spatial scale**
(Hallegatte et al., 2013)	6 billion USD/yr	136 major cities
(Vousdoukas et al., 2018)	1.25 billion EUR/yr	Europe
(Tiggeloven et al., 2020)	19.6 billion USD/yr	Global
(Menéndez et al., 2020)	797 billion USD/yr	Global mangrove areas
Current study	7.6 billion USD/yr	Global coastal wetland areas

Table 5.1: Estimations of present-day annual coastal flood damages. All the listed studies, except the study by Menéndez et al. (2020), do account for coastal protection that is for example provided by levees or flood walls.

Future coastal protection benefits of wetlands

Generally, coastal wetlands promote shoreline stability by accumulating and consolidating sediments. Under climate change and associated sea level rise, coastal wetlands may have the capacity to trap sediment and grow with sea level rise, depending on the availability of sediment and the rate of sea level rise. Alternatively, wetlands can migrate landwards, but with increasing presence of sea walls and coastal development, wetlands will be restricted in landwards migration and may drown (Schuerch et al., 2018), referred to as 'coastal squeeze'. Here, we explored the future protection benefits of coastal wetlands by examining two potential future configurations; a best-case scenario where wetland elevation accretes with sea level rise (SLR) and the current extent is maintained, and a worst-case scenario where elevation does not grow with sea level rise and landward migration is not possible, leading to partial drowning of wetlands. In the best-case scenario, the proportional reduction in both flood extent and depth is slightly lower than the present day, however projected changes in the values of coastal assets and populations means that the reduction in estimated damages for RP100 can increase to 1,644 billion USD in 2100. This is a very substantial increase relative to 4.5 billion USD in the current climate. Additionally, the reduction in the number of people exposed to 1 in 100 year water levels, is expected to increase by a factor of five. In the worst-case, the coastal protection benefits of coastal wetlands are almost entirely lost, illustrating the importance of wetland conservation for future flood protection benefits.

THE USE OF GLOBAL STUDIES

Global flood risk studies are useful because they allow comparative risk assessment across different regions and thereby provide insights for international organizations and governments to develop policies for coastal flood risk mitigation and adaptation (Ward et al., 2015). In addition, they are useful tools to illustrate overall mechanisms and the importance of ecosystem benefits for societal needs. Nevertheless, global studies typically have a lower accuracy compared to regional and local scale models. Consequently, output values should be interpreted with caution and should not be used alone to form the basis for local designs and decisions. Rather, global values should be treated as plausible ranges and should ideally be used in combination with additional validation, analyses or interpretation by (local) experts.

A NEW GLOBAL DATASET TO SUPPORT THE FUNDAMENTAL ROLE OF TIDAL MARSHES AND MANGROVES TO REDUCE COASTAL FLOOD RISK

The role of coastal wetlands in mitigating coastal flood risk is well-recognized. However, the patterns of such benefits are complex and nuanced. Firstly, the combination of exposure and hazard determines if people and assets are at risk of coastal flooding. Flood risk is high at locations where high extreme water levels occur in low-lying locations with people and assets being present. Secondly, the interaction between the hazard and the coastal wetlands can yield a reduction in flood hazard. However, a reduction of flood hazard does not automatically result in a reduction in flood risk. This is explained by the fact that a reduction in flood hazard is only relevant for people if the flood depth is reduced in the right areas. Coastal communities could be situated in front of the wetlands; or wide channels and open spaces within wetlands may limit the protective function of these systems. Hence, taking these considerations into account, global models can be instrumental in indicating potential risk reduction by coastal wetlands, but findings should be interpreted with care and contextualized appropriately.

The present study, includes state of the art data layers for water levels, coastal topography and presence of mangroves and marshes, and combines these with the newest suite of 2D numerical models applied to coastal areas with marshes and mangroves across the globe. This results in advanced global estimates of flood risk reduction by coastal wetland vegetation. The results of this study have been extensively explored and checked, and are likely a slight underestimation of global risk reduction potential due to conservative modelling assumptions. More local and finescale validation studies for different storm surge return periods, preferably including more extreme conditions could enhance such models, however such data remain sparse. The exclusion of wave-induced setup in our models adds to the likely conservative nature of our findings, although our case studies give a clear indication that the storm surge component has a far greater impact on coastal flooding than wind-waves. Nevertheless, wave-setup could contribute to the total flood depth in some settings such that, locally, coastal wetlands can further reduce flooding. Thus, expanding the global surge modeling framework with a wave model would likely show enhanced coastal protection benefits by coastal wetlands.

Overall, the findings of this study strongly support that coastal wetlands fulfill a fundamental role in reducing coastal risk, and that they will become even more important under future sea level rise. Hence, there is an urgent need to conserve tidal marshes and mangroves and to include these ecosystems as an integral part of coastal protection strategies.

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