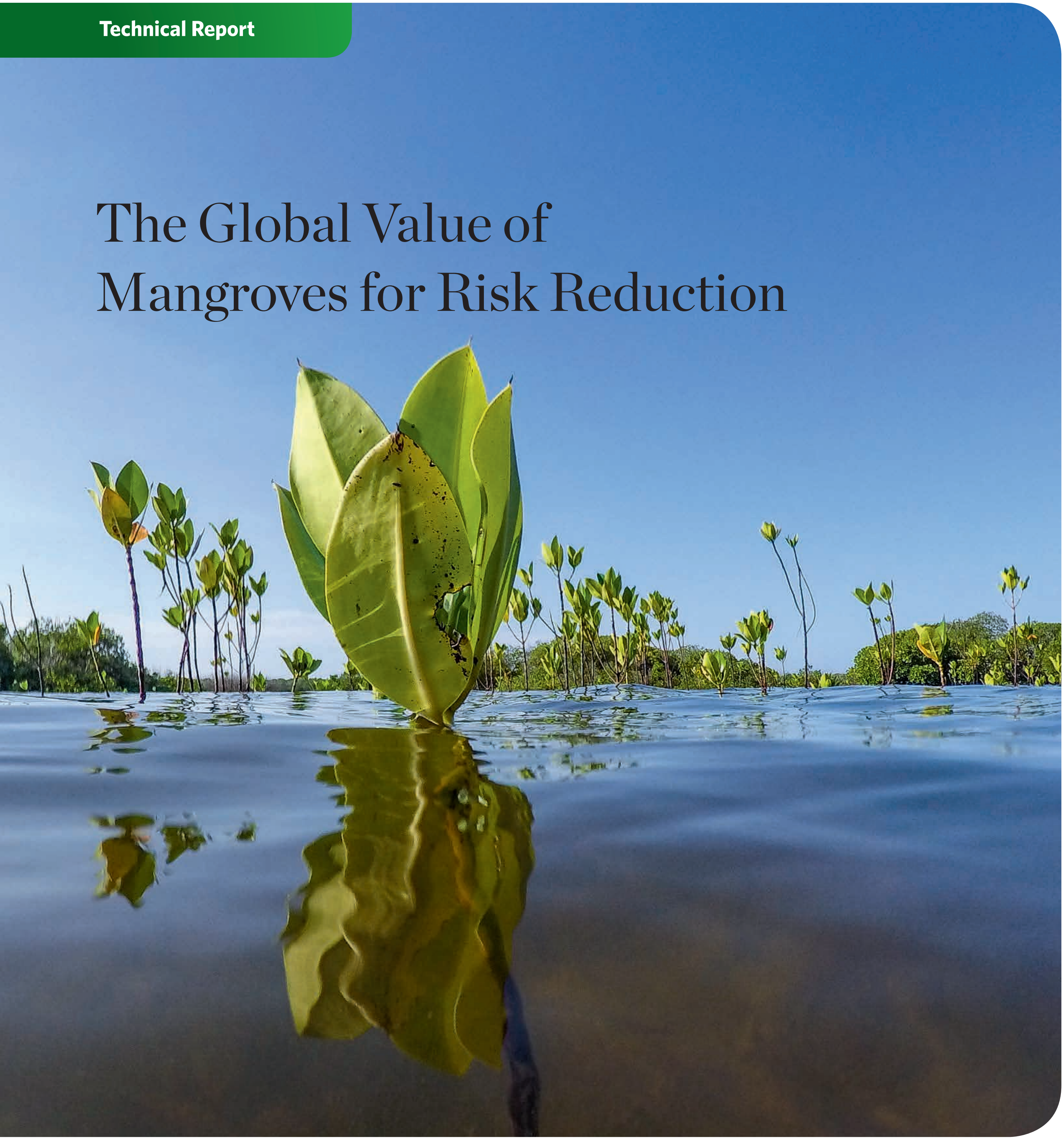
Technical Report

The Global Value of Mangroves for Risk Reduction



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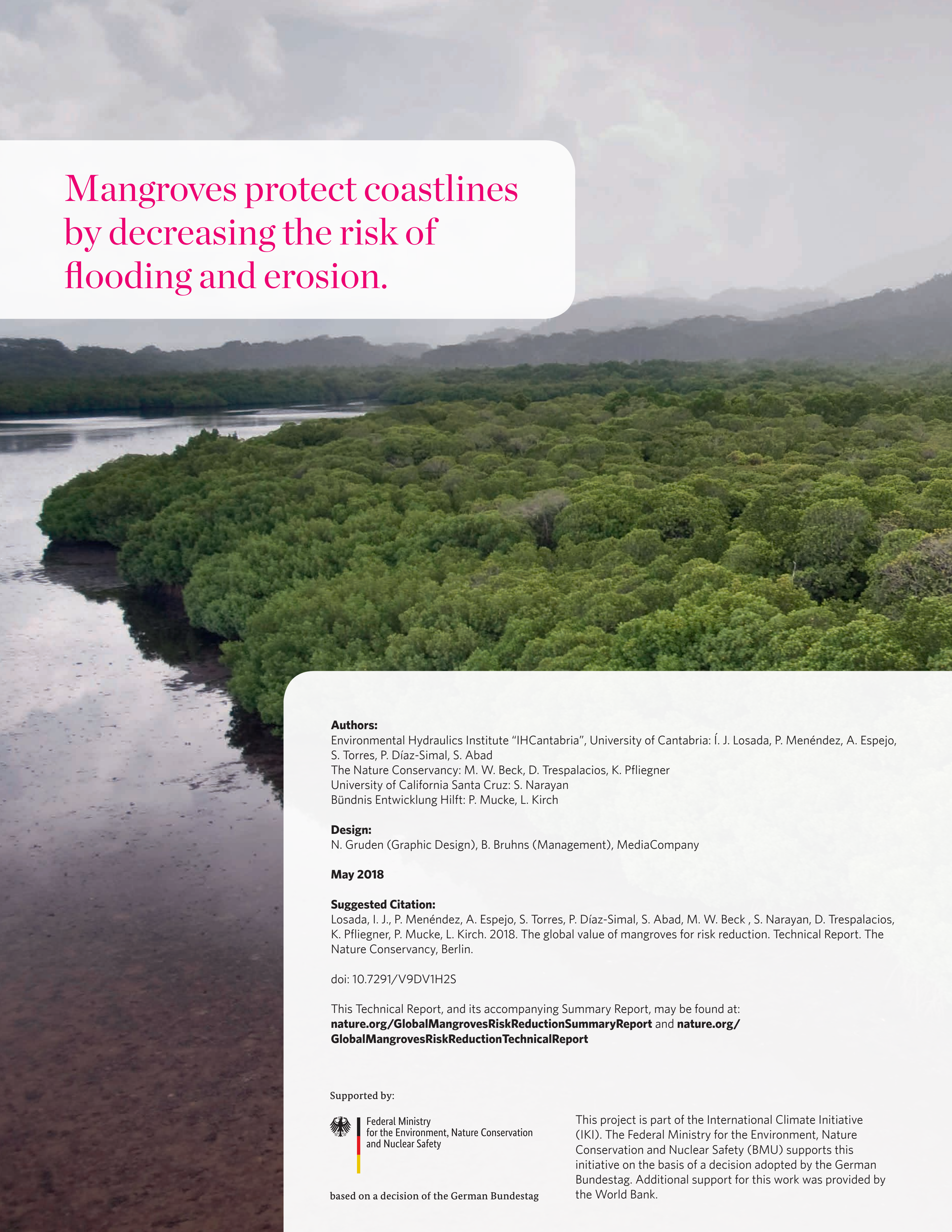

Mangroves protect coastlines by decreasing the risk of flooding and erosion.

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Executive Summary

Coastal development and climate change are significantly increasing the risks of flooding, erosion, and extreme weather events for millions of vulnerable people, important infrastructure, and trade. Coastal ecosystems, particularly mangroves, reduce risk by protecting coastlines against erosion, flooding, and sea level rise and by providing ecosystem services that reduce communities' vulnerability to hazards. Mangroves reduce exposure to coastal hazards by reducing wave heights and retaining sediments, decreasing the impacts of flooding and erosion and protecting coasts during storms. These natural defenses also provide a wide suite of ecosystem services- including food, livelihoods, carbon sequestration and climate regulation, that reduce the vulnerability of coastal communities to disasters and extreme events, thereby increasing coastal resilience. Mangroves can be managed as natural coastal infrastructure to reduce coastal risks. And unlike most built coastal infrastructure, mangroves adapt and keep pace with environmental change, and they are substantially less costly to maintain.

But mangroves are being lost at an alarming rate, in part because we have not adequately valued these natural defenses. Conventional approaches to measuring wealth focus only on built capital; many critical goods and services, such as flood protection, which rely on keeping ecosystems intact, are rarely valued. This lack of consideration encourages short-term over-exploitation and degradation. Better valuations of the protection services of coastal habitats can ensure that these services are accounted for in policy and management decisions, halting the loss of our natural capital and ensuring the provision of critical ecosystem services.

This report uses rigorous hydrodynamic and economic models to value the coastal flood protection services of mangroves globally, and identifies the places where mangroves provide the greatest risk reduction benefits to people and property. This work applies the Expected Damage Function approach, commonly used in engineering and insurance sectors and recommended for the assessment of coastal protection services from habitats, where the protection benefits provided by mangroves are assessed as the flood damages avoided by keeping mangroves in place. This work combines findings on flood exposure reduction from mangroves with vulnerability scores from the WorldRiskReport and Index to produce a ranking of countries that receive the greatest risk reduction benefits from mangroves relative to their vulnerability. The results are presented in terms of the number of people and the value of property flooded with and without mangroves.

These results demonstrate that mangrove conservation and restoration can be an important part of the solution for reducing the risks of coastal communities. This valuation can inform strategies for adaptation, disaster risk reduction, and environmental management, and can help identify sustainable and cost-effective approaches for risk reduction.

Key Findings:

- Mangroves reduce annual flooding to more than 18 million people.
- Without mangroves 39% more people would be flooded annually, and flood damages would increase by more than 16% and US $82 billion annually.
- Vietnam, India, Bangladesh, China, and the Philippines receive the greatest benefits from mangroves in terms of avoided flooding of people.
- China, USA, India, Mexico and Vietnam receive the greatest benefits in annual avoided flood damages to property.
- The countries that receive the greatest overall risk reduction benefits from mangroves are Guinea, Mozambique, Guinea-Bissau, Sierra Leone and Madagascar.

1. Introduction

A growing portion of the world's population lives on the coast (Neumann et al. 2015). Growing coastal development and climate change are significantly increasing the risks of flooding, erosion, and extreme weather events for millions of vulnerable people, important infrastructure, and trade. Already, the proportion of the world's GDP annually exposed to tropical cyclones has increased from 3.6 % in the 1970s to 4.3 % in the first decade of the 2000s, by more than US $1.5 trillion. Insurers alone have paid out more than US $300 billion for coastal damages from storms in the past 10 years (UNISDR 2011).

Risk is measured by considering the exposure to natural hazards such as floods, and the vulnerability in terms of social, economic and governance aspects (Bündnis Entwicklung Hilft 2017). Governments worldwide are dedicating billions of dollars to reduce risks from disasters and climate change. Unfortunately, most of our global investments in coastal protection are destined for "grey infrastructure", such as seawalls, that remain vulnerable to coastal risks and fail to adapt to changing environments (McCreless and Beck 2016).

Even when considering all natural hazards, from storms to earthquakes, the countries most at risk are all tropical, coastal, developing nations (Bündnis Entwicklung Hilft 2017). These are all countries where habitats such as mangroves and coral reefs can play significant roles in reducing risk to people. Coastal ecosystems, particularly mangroves, serve as the first line of defense against erosion, flooding, and sea level rise. Mangroves are regularly cited in both conservation and development literature for their role in reducing the impacts of coastal erosion and inundation during storms (Losada et al. 2017, McIvor et al. 2012a, McIvor et al. 2012b, Narayan et al. 2016, Narayan et al. 2017, Shepard et al. 2011). The aerial roots of mangroves retain sediments and prevent erosion, while the roots, trunks and canopy reduce the force of oncoming wind and waves and reduce flooding. The entire structure can reduce the force of wind waves and flood waters, reducing storm surge peak water level even providing some protection against tsunamis. Mangroves can reduce wave height as much as 66% over a 100-meter-wide belt, and by 50-100% over a 500-meter-wide mangrove belt. In low lying areas, even relatively small reductions in water levels can reduce flooding and prevent property damage (Gedan et al. 2011, Mazda et al. 2006, McIvor et al. 2012a, McIvor et al. 2012b, 2016, Quartel et al. 2007, Shepard et al. 2011, World Bank 2016, Zhang et al. 2012).

Mangroves can be managed as natural coastal infrastructure, either alone or in concert with built coastal infrastructure solutions, to substantially reduce exposure from coastal hazards. And unlike

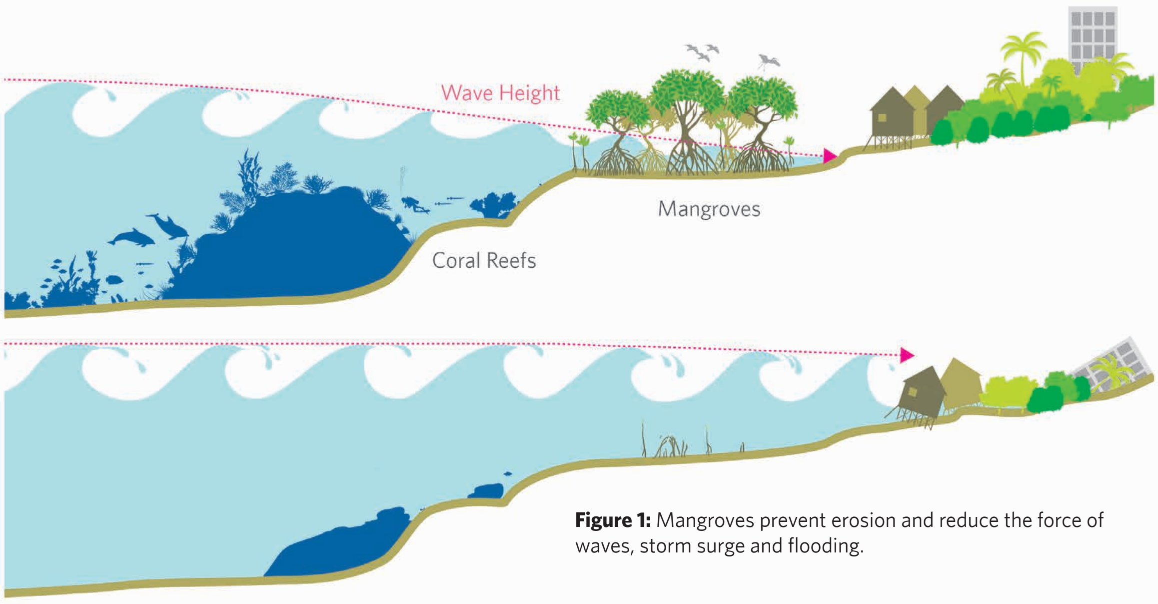


Figure 1: Mangroves prevent erosion and reduce the force of waves, storm surge and flooding.

Figure 2: In addition to reducing exposure by protecting against flooding and erosion, mangroves also decrease vulnerability by offering a wide suite of ecosystem services- including fisheries habitat, timber production, tourism, carbon sequestration, climate and water regulation, and provision of food and other natural resources that benefit coastal livelihoods. Above left, red mangroves (Rhizophora mangle) provide stability for sea grass beds, prime fish nursery habitat, in Baie Liberte, Haiti. © Tim Calver/The Nature Conservancy. Above right, a fisherman near Tarobi Village, West new Britain, Papua New Guinea. © Mark Godfrey/The Nature Conservancy.

most built coastal infrastructure, mangroves adapt to and keep pace with environmental change, including sea level rise and shifting hydrodynamic conditions, and they are substantially less costly to maintain (McKee 2011).

In addition to reducing exposure by protecting against flooding and erosion, mangroves also decrease vulnerability of coastal communities and contribute to human wellbeing and resilience by offering a wide suite of ecosystem services, including fisheries and timber production, tourism, carbon sequestration, climate and water regulation, provision of food, freshwater, wood, fiber and fuel benefitting coastal livelihoods, and other provisioning, regulating and cultural services (Beck et al. 2012, World Bank 2016, Butchart et al. 2005). Livelihood benefits provided by mangrove tend to be especially important for poor and vulnerable groups, serving as a fall-back in times of emergency or stress when other sources of income fail (FAO 2016). These ecosystem services enable coastal communities to cope with disasters and extreme events, thereby increasing coastal resilience.

But mangroves are being lost and degraded at alarming rates over the last 3 decades. Expanding coastal development often results in coastal habitat loss to housing, transportation, energy, agriculture and other land uses, and to coastal habitat degradation due to increased physical disturbance, eutrophication and sedimentation (Richards and Friess 2016, Valiela et al. 2001, World Bank 2016). A third of the world's mangroves have likely been lost over the last 50 years largely through conversion for aquaculture or agriculture (Alongi 2002). Annual mangrove deforestation rates from 2000–2005 were estimated at ~ 0.7% (Spalding et al. 2010), similar to or higher than those for tropical forests and three to five times greater than mean global rates of forest loss (FAO 2005). Often, the loss of these habitats is greatest around large settlements- the places were the impacts of coastal degradation are greatest, and where the most people stand to benefit from coastal ecosystems (Bündnis Entwicklung Hilft 2012, Spalding et al. 2010). When mangroves are degraded or destroyed, the loss of their aerial roots leads to erosion, coastal regression, soil destruction and increasing water depth. More exposed coastline are more vulnerable to the destructive impacts of storms (Bündnis Entwicklung Hilft 2012).

Mangrove loss is fueled in part by the failure to adequately value their coastal protection services in terms readily understandable to policy makers. Conventional approaches to measuring wealth and economic development fail to account for the value of the goods and services provided by natural capital, particularly non-extractive benefits like coastal protection. Many critical goods and services, such as flood protection, which rely on keeping ecosystems intact, are rarely valued (Narayan et al. 2016). This lack of consideration encourages short-term over-exploitation, which leads to degradation and loss. Better valuations of the protection services of coastal habitats can ensure that these services are recognized and accounted for in policy and management decisions, halting the loss of our natural capital and ensuring the provision of critical ecosystem services for current and future generations.

In many places, particularly where their coastal protection services have been recognized, the rate of mangrove loss has slowed. Disaster risk reduction and environmental conservation groups have partnered to restore mangroves. Hundreds of thousands of hectares of mangroves have been restored in places like Vietnam, representing some of the most successful cases of large scale habitat restoration (see Case Study in Section 4.1 in this report)(World Bank 2016).

There have been a handful of evaluations of the flood defense benefits of mangroves at local and national levels (World Bank 2016, Narayan et al. 2016). While these are useful demonstrations of the potential of ecosystems to protect coastlines, they do not rigorously quantify the value of this protection. Many studies have used a replacement cost method, which estimates the value of a mangrove forest based on the cost of an equivalent structure that will replace the flood protection service of the mangrove forest (Boyer and Polasky 2004). This method is most suited for single projects, but it can over-estimate values and can be difficult to integrate into larger-scale risk and value assessments (Barbier 2011). The World Bank recommends an Expected Damage Function (EDF) approach, which directly values a mangrove forest based on its role in reducing expected storm damages (Barbier 2007, World Bank 2016).

The EDF approach is adapted from methods commonly used in the engineering and insurance sectors to assess risks and benefits. The approach provides scalability from local to national scales and easy integration with wider coastal risk assessments and models (Sanchirico et al. 2016). There are five core steps to estimating coastal protection benefits from any kind of infrastructure: (1) Estimate offshore hydrodynamics (wind, waves and sea levels); (2) Estimate nearshore hydrodynamics; (3) Estimate effects of coastal structures (habitat) on hydrodynamics; (4) Estimate flooding or erosion; and (5) Assess expected and averted damages (i. e., value coastal protection benefits). These five steps allow an assessment of coastal habitat protection benefits in terms of damages averted by conserving or restoring the habitats in question.

Using high-resolution engineering and economic assessment tools, the EDF approach was recently applied in the Philippines as a pilot study to facilitate inclusion of mangrove coastal protection values into the country's system of national accounts (Losada et al. 2017). For this global mangrove study, we applied these tools and the EDF approach globally to estimate the flood protection benefits of all existing mangrove ecosystems across a number of hazard, exposure and vulnerability conditions.

There is a growing body of work that assesses risk based on exposure and even considers the role of ecosystems in exposure reduction. For example, the insurance risk modeling sector has begun to consider the protective role of ecosystems more explicitly in their models (Narayan et al. 2017). And the insurance sector is now harnessing the exposure reduction role of ecosystems to create innovative sustainable funding sources that both incentivize and fund ecosystem management for disaster risk reduction (Flavelle 2017, Harvey 2017). However, there has been much less quantitative work on how social and economic vulnerability influences risk and in particular how ecosystems can reduce vulnerability. While it is widely asserted that mangroves play important roles in improving lives and livelihoods, the direct evidence is thinner than that for reducing exposure (McIvor et al. 2016). The WorldRiskReport addresses these measures of vulnerability and directly considers the role of environment in risk reduction (Bündnis Entwicklung Hilft 2012); it has also served as the basis for a specific focus on coastal nations and the role of reefs, mangroves and fisheries in reducing overall risk (Beck 2014).

In this report, we rigorously value the coastal protection services of mangroves globally to identify the places where mangroves provide the greatest risk reduction benefits to people and property. This valuation can inform strategies for adaptation and environmental management and can help identify sustainable and cost-effective approaches for risk reduction.

2. Methods

2.1 Methods at a Glance

This study follows the Expected Damage Function (EDF) approach to measure the coastal protection service values of mangrove habitats. This is the methodology recommended in the Guidelines for the Valuation of Natural Coastal Protection (World Bank 2016) (see Figure 3). These methods and models were piloted and validated at a national scale in the Philippines (Losada et al. 2017) and follow a multistep approach:

- Step 1: Characterization of the offshore dynamics for both regular climate conditions and tropical cyclones
- Step 2: Downscaling of the offshore dynamics to the nearshore location of mangrove fields considering the relevant dynamics transformation processes
- Step 3: Evaluation of the role of coastal habitats (mangroves and corals) on nearshore dynamics
- Step 4: Calculation of flood heights and corresponding flood maps at mangrove protected areas for different mangrove cover scenarios
- Step 5: Calculation of flooding consequences on population and built stock or property using an expected damage function approach for different mangrove cover scenarios.

Extending the application of these steps from a single country to global scale and using a probabilistic approach present a series of challenges. Addressing these challenges requires a combination of good quality data sets at the appropriate spatial resolution, with process-based models including a number of simplifications, to allow thousands of numerical simulations at affordable computational times.

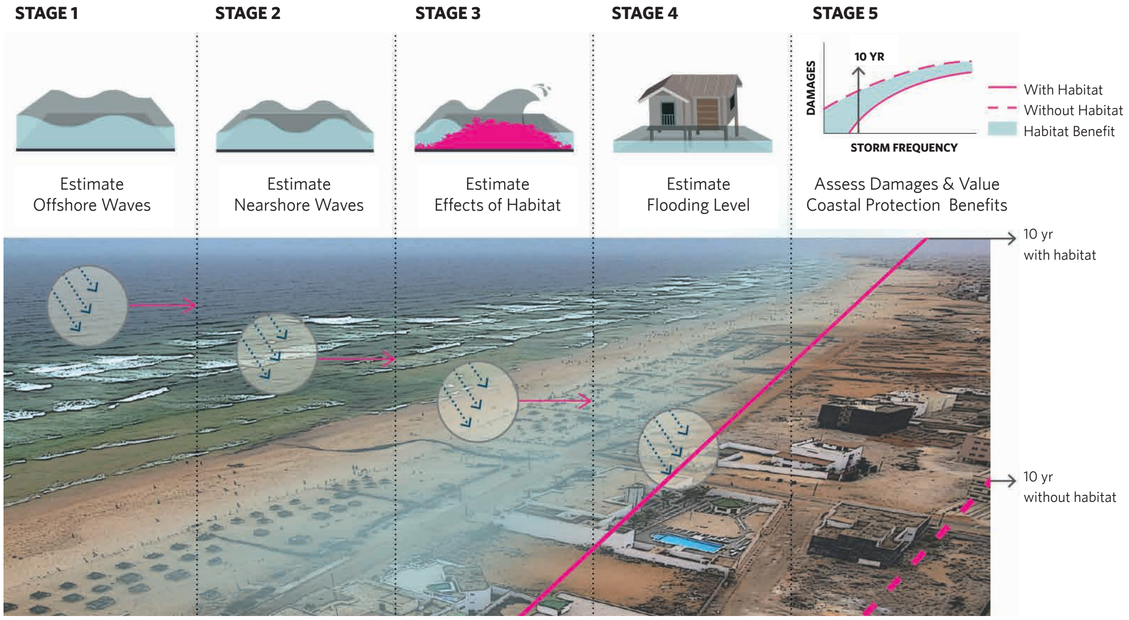


Figure 3: The key steps for estimating the coastal protection benefits provided by mangroves, following the Expected Damage Function approach (World Bank 2016).

Figure 4: Regional subdivision of existing mangrove areas in the world.

2.2 Study Domain Description

This study considers 700,000 km of coastline protected by mangroves spread across 5 continents including 9,533 islands ranging in perimeter from 5,000 km to 5 km. The coastline used in this study is the high resolution (0.2 km) from the NOAA database GSHH (Global Self-consistent, Hierarchical, and High-resolution Geography Database). In this study, islands smaller than 5 km in perimeter are not considered. To constrain the global scale models and analyses, the whole world was subdivided into 68 regions and 27 continental polygons (Figure 4) based on a number of criteria including land type (i. e. island or continental), coastline orientation, and coastal climate (i. e. countries with similar coastal wave and storm surge climates). For example, all Caribbean island nations were grouped and analysed together as they experience the same tropical cyclone season. Collecting good bathymetry and topography is critical for these flooding analyses (World Bank 2016). Though some regions and countries have good bathymetry and topography datasets, the global availability and quality of these vary greatly, and we used the best available global data throughout to maintain consistency across regions in the coastal protection valuation. Similarly, the study uses global datasets for mangrove occurrence and coral reef occurrence. Coral reefs can often occur near mangroves and can significantly affect nearshore waves and water levels, and we therefore include these habitats in the models.

To achieve a global scale model we adopted a quasi-2D modelling approach, since a fully 3D or 2D modelling of steps 2 and 3 in the methodology is not computationally affordable at a global scale. To achieve this, 1D profiles were drawn at 1 km spacing over 700,000 km of global coastline. Each profile extends 10 km onshore and till 50 m water depth offshore, resulting in different profile lengths depending on local bathymetry. These profiles were then intersected with the Global Mangrove Cover 2010 (Spalding et al. 2010) data set to obtain mangrove length and average depth of occurrence for each profile. Figure 5 is an example of the profiles distribution along the Caribbean Islands with a zoom in one specific transect of Cuba's shoreline covered by mangroves (green area). In addition to this coastal segmentation, we included a series of statistical and classification techniques, to be described later, that allow the use of a probabilistic approach at global scale. The probabilistic approach facilitates the use of an expected damage function approach to assess the consequences of mangrove habitat loss, consistent with the methodology outlined above.

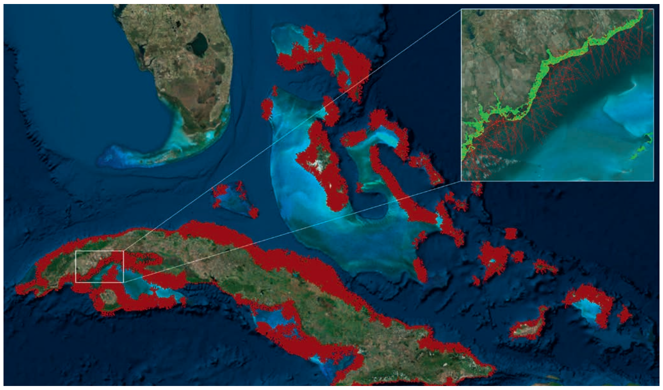


Figure 5: Coastal profiles in the Caribbean Islands (Region 46) with a zoom in Cuba. Red lines are the coastal profiles and the green surface represents the current mangrove extension

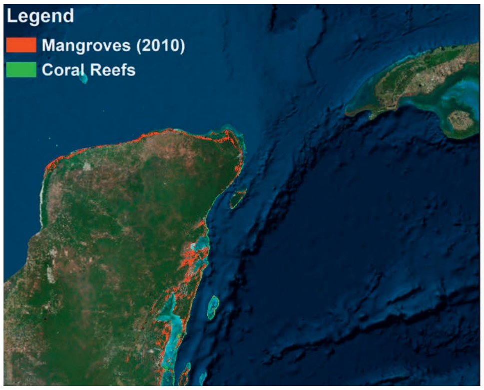


Figure 6: The coral reef (green) and mangrove cover (red) along Mexico and Belize coastline

2.3 Data Sources Overview

This section summarizes the sources of data used in the analysis of global coastal protection provided by mangrove forests (Table 1). Datasets of the best possible resolution at a global scale for coastline, topography, bathymetry, mangrove cover, climate, exposure assets and damage functions are applied in the study and are described in this section. The following sections describe the dynamics, bio-physical and socio-economic datasets. A summary can be found in Table 1.

For bathymetry, we used GEBCO 1.6 km resolution global database combined with SEAWIFS 1 km resolution of coral reefs bathymetry worldwide. In tropical countries, the bathymetry of shallow nearshore coral reefs is critical for predicting flooding, because coral reefs play an important role in wave energy dissipation, reducing waves reaching mangrove shorelines. With a spatial resolution of 1 km, SEAWIFS bathymetry is the most accurate database to account for coral reef bathymetry globally. For that reason, SEAWIFS bathymetry is combined with GEBCO to obtain a hybrid mesh with high quality water depth values nearshore. Adequate flooding analyses requires a good Digital Terrain Model (DTM) based on high resolution topography data. We used SRTM (Shuttle Radar Topography Mission) at 30 m resolution, to our knowledge the best available global dataset.

Mangroves extend over 150,000 km^2 in the world, distributed across 123 countries. This study uses one global dataset for mangrove cover created in 2010 for the World Atlas of Mangroves (Spalding et al. 2010). The effect of coral reefs is represented by bottom friction and wave breaking processes over reef topography. This study uses the 2010 Millennium Reef Map Project, released by the United Nations Environmental Programme World Conservation Monitoring Center (UNEP-WCMC), to obtain a global spatial distribution of tropical and subtropical coral reefs. An example of coral reef and mangrove cover along the coastline of Mexico and Belize is shown in Figure 6.

Crucial to the analyses are long-term time series of various offshore components that contribute to coastal flooding. Data on offshore waves, storm surge and astronomical tide are obtained from a combination of globally available data and models such as the International Best Track Archive for Climate Stewardship (IBTrACS (Knapp et al. 2010)) provided by NOAA for storms, and hindcast models developed in-house, for waves and tides (http://ihpedia.ihcantabria.com/wiki/IH_DATA). These data sources and the methods by which the offshore data used in this study are derived are described in detail in Sections 2.4 and 2.5.

To estimate the consequences of the modelled flooding extents (i. e. people affected and property damaged) we make use of global exposure data on socio-economic parameters such as population, GDP and infrastructure. For population we use the fourth version of Gridded Population of the World at a 1km spatial resolution (http://sedac.ciesin.columbia.edu/) which is freely available and can be viewed online (http://sedac.ciesin.columbia.edu/mapping/viewer/). Global GDP data are obtained from the World Bank Database (https://data.worldbank.org/data-catalog/world-development-indicators). We obtain global distributions of residential and industrial stock (or property) using data from the 2015 Global Assessment Report on Disaster Risk Reduction (GAR15) (Desai et al. 2015) on the economic value of residential and industrial stock. The GAR15 provides a global exposure database with a standard 5 km spatial resolution and a 1 km detailed spatial resolution on coastal areas, estimating the economic value of the exposed assets, as well as their physical characteristics in urban and rural agglomerations. Finally, we use the latest database of global depth-damage functions from the EU Joint Research Centre (JRC) which proposes unique damage functions for residential and industrial stock, commerce, transport, infrastructure and agriculture for different global regions including Africa, Asia, Oceania, North America, South America and Central America (Huizinga et al. 2017).

A summary of the relevant datasets used to define waves, tides, storm surges and tropical cyclones is presented in Table 1 and described in detail in Section 2.4.

Component	Database	Variables	Spatial Resolution	Temporal Resolution	Time Length
Coastline	GSHH (NOAA)	Global Coastline shapefile	0.2 km	-	-
Bathymetry	GEBCO	Global bathymetry raster	1.6 km	-	-
	SEAWIFS	Reefs bathymetry raster	1 km	-	-
Topography	SRTM	Elevation raster	30 m	-	-
Coral Reefs	Millennium Reef Map Project	Global Coral reefs distribution shapefile	-	-	2010
Mangroves	World Atlas of Mangroves	Global Mangroves distribution shapefile	-	2010	2010
Waves	GOW 2.0	Hs, Tm, Tp, Dir	0.25ºx0.25º	1 hour	1979-2017
Storm Surge	DAC (extended)	SS 95%	2ºx2º	1 hour	1871-2010
Astronomical Tide	GOT	Mean AT	0.25ºx0.25º	Any	Any
Mean Sea Level	AVISO (Satellite Altimeted Data)	MSL	1ºx1º	1 month	1950-2010
Sea Level Rise	Slangen 2014	RSLR	1ºx1º	No	2081-2100
Tropical Cyclones	IBTrACS Global-STM	Lon, Lat, Pressure, Wind	-	6 hours	1951-2014
Population	GPW (SEDAC)	Nº of people	1km	2016	-
Stock/Property	GAR 15 (UNISDR 2015)	Residential stock and industrial stock (US $)	5km downscaled to 1km	2015	-
GDP	World Bank	US $	Per country	1 year	1960-2016
Damage Functions	EU Joint Research Center (JRC)	% damage/flood level	Per country	-	2017

Table 1: Databases used in this study.

2.4 Step 1: Characterization of the Offshore Dynamics

Coastal flooding is the result of the interaction of a hazard represented by a flood height or total water level (TWL) at the coast with coastal topography. The spatial extent of this coastal flooding is represented using flood maps and is used to estimate the extent and severity of damage to people and property by flooding. Producing these flood maps requires the local height (i. e. the total water level) at the coastline. This flood height is therefore, one of the most relevant parts of this work and is estimated as the local combination of multiple components including the mean water level, astronomical tides, storm surge and wind waves contribution (run-up/setup) (Figure 7).

The flood height at each point on the coastline is a result of the offshore (boundary) values of each of these components and their transformation due to bathymetric changes and the presence of local coastal ecosystems as they propagate towards the shore. The relative importance of each component, from offshore to nearshore, can show significant spatial variability (Rueda et al. 2017). For example, on coastlines exposed to tropical cyclone activity storm surge may be the dominant contribution to the flood height, relative to astronomical tides or wind waves. To adequately represent this variability we first characterize the different components in the offshore region, where these are not (yet) influenced by coastal bathymetry. Thus, we characterize flood heights separately for 'regular climate' conditions including astronomical tides, storm surges (extratropical storms) and waves; and for 'tropical cyclone' conditions including tides, storm surges (from tropical cyclone events) and waves. This distinction is important for two reasons: a) each of these climate conditions has distinct offshore dynamics, and b) the inclusion of 'regular climate' conditions allows assessment of mangrove protection values for the more frequent, non-cyclone waves and water levels that can cause significant flooding and damages throughout the year.

2.4.1 Regular Climate

The first step consists of obtaining the offshore total water level as the combination of the time series of waves (GOW 2), storm surge (DAC) and astronomical tide (GOT). For wave data, we use the Global Ocean Waves database, GOW 2.0 (http://ihpedia.ihcantabria.com/wiki/IH_DATA), a hindcast database created by running WAVEWATCH III (Tolman 2014) on a 0.25º spatial resolution grid (Perez et al. 2017). This database provides hourly information of the most characteristic sea state parameters: significant wave height (Hs), peak period (Tp) and

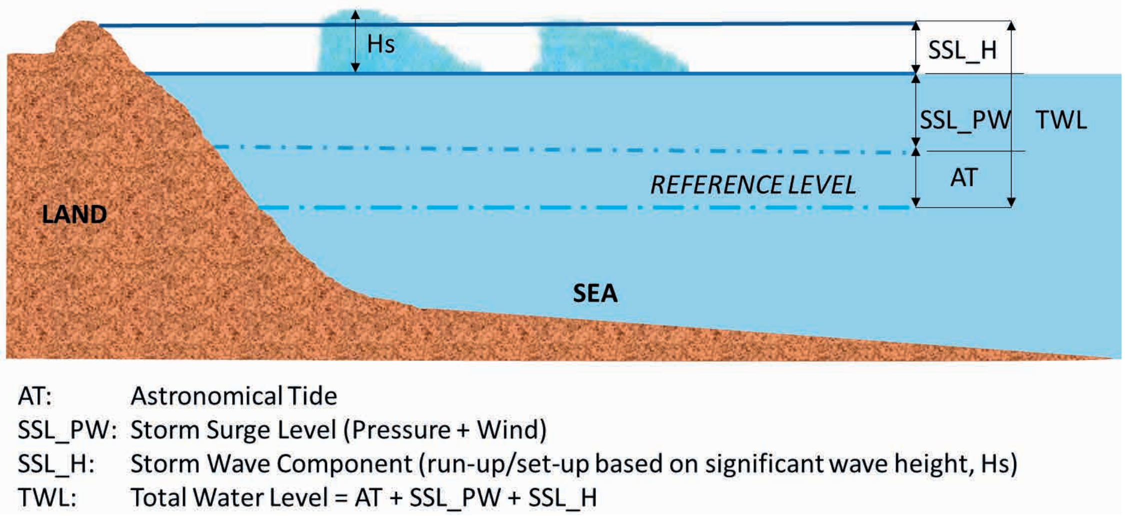


Figure 7: Definition of flood height of total water level as the combined effect of mean water level, astronomical tide, storm surge (extratropical and tropical cyclones) and waves (set-up/run-up).

mean direction (Dir) from 1979 to 2016. Astronomical tide is a deterministic component of sea level and is historically reconstructed (hindcast) as well as forecasted. These data are part of the GOT (Global Ocean Waves) database with a spatial resolution of 0.25º (http://ihpedia.ihcantabria.com/wiki/IH_DATA). This study assumes current conditions of mean sea level and does not consider future sea-level trends. Storm surge information is given by a statistical global reconstruction with spatial resolution of 2º, covering the period 1871-2010. This long time-series was generated from the DAC (Dynamic Atmospheric Correction) database developed by AVISO (Cid et al. 2017). The model was forced by the pressure and wind speeds at 10m altitude provided by the European Centre for Medium-Range Weather Forecasts (www.ecmwf.int/en/research/climatereanalysis) reanalysis. The extension of the storm surge database for the period 1871-2010 was developed by using the 20th Century Reanalysis ensemble (Compo et al. 2011) as a predictor to reconstruct global 20th century surge.

The time-length of this analysis is limited by the available data to 32 years, for the period from 1979-2010. These time series can be associated to the most offshore point of each coastal transect. Since, the resolution of the global offshore datasets is 25 km (0.25º) and the resolution of the transects resolution is 1 km, on average we use the same offshore time series every 3 to 4 transects. After a preliminary statistical analysis, it is found that for regular climate conditions, the offshore climate characteristics can be clustered into 3,787 series of waves and sea level parameters.

To avoid double-counting, the extreme events associated with tropical cyclones detected between 1979 and 2010 in the resulting time series are filtered out of the record using information from the cyclone occurrence databases described below in 2.4.2.

2.4.2 Tropical Cyclones

In order to identify tropical cyclones affecting each region we use historical tropical cyclones extracted from the International Best Track Archive for Climate Stewardship (IBTrACS, (Knapp et al. 2010)) provided by NOAA, which provides 6-hourly information about tropical cyclone centre location (latitude and longitude in tenths of degrees) and intensity (maximum 1-minute surface wind speeds in knots and minimum central pressures in millibars) for all Tropical Storms and Cyclones observed from 1951 to date, with some uncertainties and non-homogeneities before 1966 when global satellite-based observations became available. Historical cyclones are subdivided in 5 basins: Atlantic Ocean, East Pacific, West Pacific, Indian Ocean and South Hemisphere (Figure 8). The temporal coverage and the total TC registered within each period is summarized as follows:

- Atlantic Ocean 165 years (1851-2015): 1804 TCs (11 TCs/year)
- East Pacific 67 years (1949-2015): 1050 TCs (16 TCs/year)
- West Pacific 71 years (1945-2015): 1980 TCs (28 TCs/year)
- Indian Ocean 43 years (1972-2015): 218 TCs (5 TCs/year)
- South Hemisphere 60 years (1956-2015): 1127 TCs (19 TCs/year).

A climatology frequency analysis indicates that, except in the Indian Ocean, tropical cyclones can occur in every calendar month depending on the region. The greatest cyclone activity is concentrated between June and November in the Atlantic Ocean, between May and November in the Pacific and between November and March in the Southern Hemisphere. Based on this analysis, tropical cyclones passing through each region are obtained.

Every single tropical cyclone is characterized by the maximum wind speed and the cyclone centre location at each time step (track). However, with the aim of calculating the wave climate at the most offshore point of coastal profiles, additional tropical cyclone parameters must be calculated: The distance between the tropical cyclone eye and each profile (Dist), the wind speed of the eye of the tropical cyclone (Wind), the displacement velocity of the storm along the track (Velocity) and the angle between the wind direction and the profile (Angle) are the 4 key variables that will affect waves and storm surge generation.

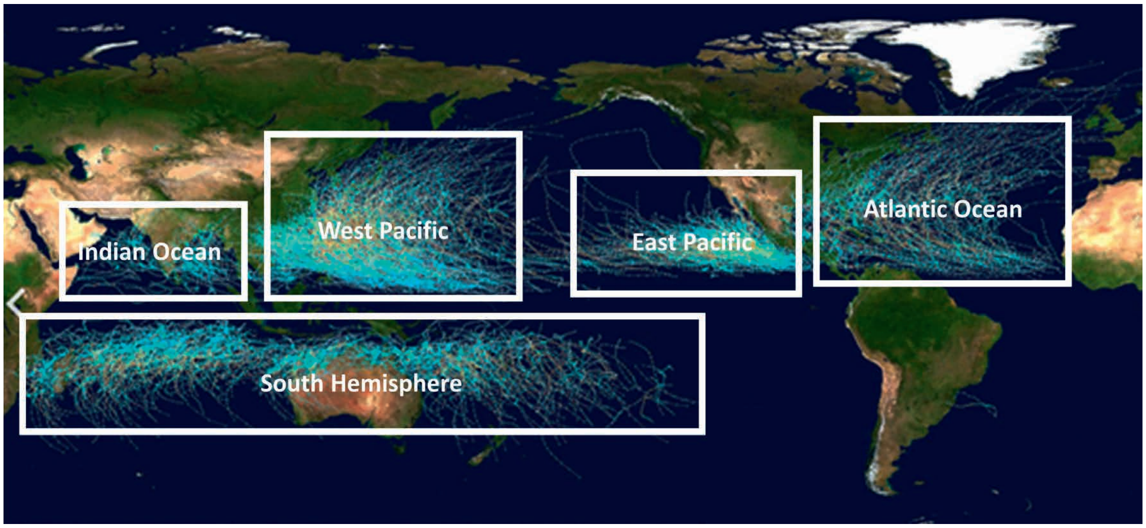


Figure 8: Sub-division of historical tropical cyclone tracks into 5 distinct basins.

The IBtRACS database has about 6,000 tropical cyclones and if we multiply it by the 700,000 profiles), we have 6,000 TC x 700,000 profiles x 3 combinations = 12.6 Billion cases.

Given the numerous possible combinations of these predictors, three alternatives are proposed and compared with the aim of identifying the best means of reducing the uncertainty in waves and sea level prediction:

- Parameters associated to the closest point of the track to the head of each profile: Dist = min (Dist)
- Parameters associated to the point of maximum winds: Wind = max (Wind)
- Parameters averaged along the track of the tropical cyclone: Dist, Wind, Vel, Angle = mean(Dist, Wind, Vel, Angle).

To illustrate the selection process, Figure 9 shows the 4 parameters obtained for each tropical cyclone and associated to a single profile. The selection of the optimal combination of these 4 parameters will be explained in the following sub-section, based on the numerical model results (DELFT 3D) obtained for the tropical cyclones analysis in the Philippines (Losada et al. 2017).

Reducing the dimensions of the problem will be crucial to achieve the goal of obtaining the flood height along the coast produced by every tropical cyclone at each profile. This is done by neglecting:

- Tropical cyclones farther than 500 km off the head of the profile (Dist>500km)
- Tropical cyclones blowing in the opposite direction of the profile (Angle>90º)
- 2 of the 3 combinations of Distance, wind, velocity and angle.

After applying these three simplifications, the number of cases goes down to 166 million, i.e. 1.3% of the initial value.

In this study, in order to calculate offshore wave and storm surge parameters associated to TCs we use pre-calculated waves and storm surge numerical model results to establish mathematical relationships between them. This library of relationships is based on extensive modelling of 548 representative TCs in the Philippines (Losada et al. 2017) using a high resolution 2D mesh of the DELFT 3D numerical model (https://oss.deltares.nl/web/delft3d). The model was forced with the available data of historical TC tracks and wind speed to obtain the significant wave height, peak period, storm surge height and storm surge duration. In order to assure the validity of this approach two requirements must be met:

- The results of Losada et al. (2017) must be validated with existing parametric expressions
- Pre-calculated results must cover a wide range of tropical cyclones representative of the rest of the world.

Before starting with the regression analysis, the numerical results (DELFT 3D; Losada et al., 2017) are compared with some existing parametric models (Equation 1; Ruiz-Martinez et al., 2009). The difference between the parametric model and the numerical simulations is calculated in percentage at each profile and for every single tropical cyclone. The numerical model is shown to perform better at predicting significant wave heights, particularly in the presence of reefs and barrier islands.

$$H_s = 0.2887 \cdot F_h \cdot \left(1 - \frac{6.69 \cdot N_c}{1+10.3 \cdot N_c - 3.25 \cdot {N_c}^2}\right) \cdot \sqrt{R \cdot (P_N - P_0)} \cdot \left(1 + \frac{V_F \cdot cos(\theta+\beta)}{2 \cdot U_R \cdot F_V}\right)^2 \quad (1)$$

Then we created wave and surge response functions from a regression analysis technique to find relationships between the input tropical cyclone (Dist, Wind, Velocity, Angle) and the waves and sea level induced parameters (Hs, Tp, SS, SS_duration), and finally reconstructing wave climate at each profile. The significant wave height (Hs), peak period (Tp), storm surge (SS) and storm duration (SS_duration) are calculated at each coastal profile and for every single tropical cyclone. The reconstruction process simply involves associating each combination of (Dist, Wind, Velocity, Angle) of each profile to one of the 150 families selected from the regression analyses, and then reading the value of the pre-calculated output variables (Hs, Tp, SS, SS_duration). To extrapolate the simulations carried out in the Philippines to the whole world, the variability of each parameter was studied. We plotted the histograms of the variables involved, to validate that the range of variation of the data of the interpolation table covers all the alternatives of wave height, peak period, storm surge, storm duration, mangrove length and mangrove depth.

2.5 Step 2: Characterization of Nearshore Dynamics

Waves and storm surges are transformed as they approach the coast due mainly to their interactions with bathymetry and island features. The combined effect of shoaling, refraction, diffraction and breaking may induce changes in heights and directions that need to be accounted for in the evaluation of flood heights. Ideally, we aim to reconstruct the offshore times series nearshore, which requires the propagation of the entire offshore time series. Since this is practically unfeasible at the global scale due to the length of the time series of water levels, waves and TCs, a downscaling of offshore dynamics to the nearshore is carried out using a combination of analytical formulations, numerical modelling results, and statistical and clustering methods. Together these approaches allow considerable reduction of computational effort at a reasonable scale. This approach is explained next.

2.5.1 Regular Climate

As already explained in 2.4.3 for regular climate conditions, the 700,000 profiles of offshore climate characteristics were clustered into 3,787 series of waves and sea level parameters that need to be propagated to the nearshore. When selecting the relevant offshore point to carry out the propagation to a coastal point two conditions are followed in assigning these points: (1) the offshore point must be inside the influence area of the coastal point, which is defined by a triangle oriented +/-300 seaward; (2) where there are multiple points within a triangle, the nearest point to the coastline point is chosen. This method minimizes errors in choice of appropriate offshore points that can be critical in island regions where the directionality of waves is highly conditioned by the side of the island being considered.

Estimating the total amount of cases to be propagated highlights the need to reduce the dimensions of the problem. In total 3,787 different combinations of waves and sea level datasets are to be propagated over 700,000 coastal profiles in the globe. The datasets have hourly resolution, which means that 32 years contains 280,320 sea states, resulting in a total of 196,224 million propagations (280,320 sea states per profile x 700,000 profiles). It is therefore essential to reduce the dimensions of the problem to make it practically feasible. We do this in the following way:

- Reduce the number of profiles using a statistical classification and clustering (K-MEANS). This reduction method simplifies the 700,000 profiles into 1,173 representative combinations of mangrove length and depth.

- Reduce the number of waves + sea level combinations using the K-MEANS method of statistical classification, for the sea-state time series, to reduce the 3,787 combinations into 10 representative clusters.

- After applying these two simplifications the number of cases to be solved goes down from 196,224 million to 44 million (3,787 unique combined datasets x 10 sea states per dataset x 1,173 profiles), which nevertheless still represents significant computational effort.

Snell's law is applied to propagate waves from deep water to the reef front. In this case, only shoaling and refraction processes are considered, affecting the wave's direction and height (waves tend to be parallel to the bathymetry and they increase their height in shallow water). The breaking model is applied in the reef environment, i. e., just offshore and over the reef. Wave refraction tends to reduce the wave front's angle with the bathymetry. Applying Snell's law, the new direction is obtained (Equation 2) as well as the new wave height (Equation 3):

$$Snell\ law\colon \frac{c_1}{sin\alpha_1} = \frac{c_2}{sin\alpha_2} = constant \tag{2}$$

$$Shoaling + Refraction\colon H_2 = H_1 \cdot \sqrt{\frac{c_1}{c_2}} \cdot \sqrt{\frac{cos\alpha_1}{cos\alpha_2}} \tag{3}$$

We finally obtained the significant wave height (Hs), peak period (Tp) and mean direction (Dir) at each profile for the 10 representative clusters.

2.5.2 Tropical Cyclones

For tropical cyclones, this step 2 is integrated with step 3, following Losada et al. (2017) based on a library of numerical simulations.

2.6 Step 3: Modelling the Role of Coastal Habitats on Nearshore Dynamics

As waves and storm surge propagate along coral reefs or mangrove fields they experience a transformation affecting the Total Water Level reaching the area protected by these habitats. Consequently, we need to model this transformation along the coastal transects using the nearshore dynamics characteristics calculated in step 2.

In this case the method followed is the same for both, tropical cyclones and regular climate. It is based on a pre-calculated set of high resolution numerical model results covering a wide range of cases (different wave heights, peak periods, sea level and mangrove length and depth).

2.6.1 Tropical Cyclones

A look-up table or, in other words, an interpolation table, generated within the Philippines project (Losada et al. 2017) is used to interpolate the Total Water Level (TWL) along the coast. This table identifies key variables that affect the TWL (i. e. flood height) for a combination of parameters that have been assessed extensively in prior models. The look-up table allows us to quickly interpolate values of TWL based on these previously assessed parameters. Particularly, in this case we calculate the TWL from the offshore dynamics variables (Hs, Tp, SS, SS duration) and mangrove characteristics (mangrove width and mangrove depth). The total amount of simulations carried out in The Philippines using DELFT 3D model was 37,500 (750 combinations of mangrove length and depth and 50 combinations of waves and storm surge). Figure 9 is an example of the steps followed to obtain the flood height for a specific transect and tropical cyclone. For the global model, this process is repeated for the total number of cases in the whole world (700,000 profiles x 6,000 tropical cyclones = 4,260 million cases).

As mentioned earlier, to extrapolate the simulations carried out in the Philippines to the whole world, the variability of each parameter was studied. We plotted the histograms of the variables involved, to ensure that the range of the data of the interpolation table covers all possible combinations of wave height, peak period, storm surge, storm duration, mangrove length and mangrove depth. The significant wave height obtained in the Philippines covers values up to 15 meters and peak periods between 2 and 20 seconds. Meanwhile, storm surge heights in the Philippines are in the range of 0 to 2 meters, with some extreme values reaching 6 meters and typical durations of 50-100 hours. Thus, both the ocean dynamics and the parameters that define the mangrove forests (cross shore length and average depth), include a sufficiently broad spectrum of cases to create an extensive and reliable interpolation database, generated from high resolution numerical simulations (DELFT 3D). Two scenarios are to be studied and compared: with and without mangroves. The "without mangroves" scenario also includes wave and surge propagations over non-vegetated profiles.

2.6.2 Regular Climate

The interpolation table was obtained from the 90,000 simulations (1 hour long each) carried out in the Philippines (Losada et al. 2017) using Delft-3D resolving 1-dimensional profiles. The numerical boundary conditions assume a non-stationary process with a triangular time-evolution of Hs and a constant sea level within each sea state. The output of each simulation provides flood height time series every 10 m along the profile. However, we are only interested in the maximum Total Water Level at the shoreline (referred to as "flood height"). With this information a look-up table is constructed to interpolate the flood height for any given conditions of significant wave height, peak period, sea level, mangrove length and mangrove depth. The interpolation of waves and sea levels along the 1D representative profiles results in 44 million theoretical values of flood height (3,787

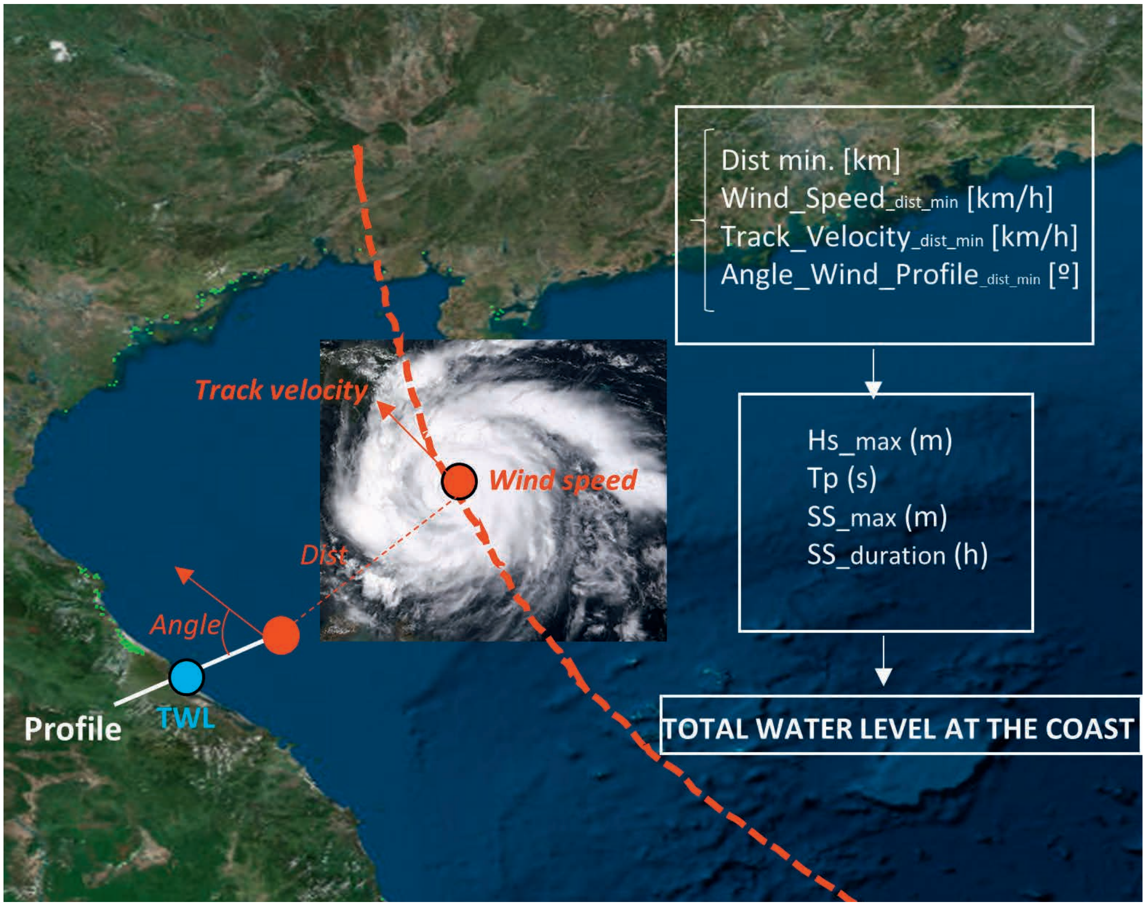


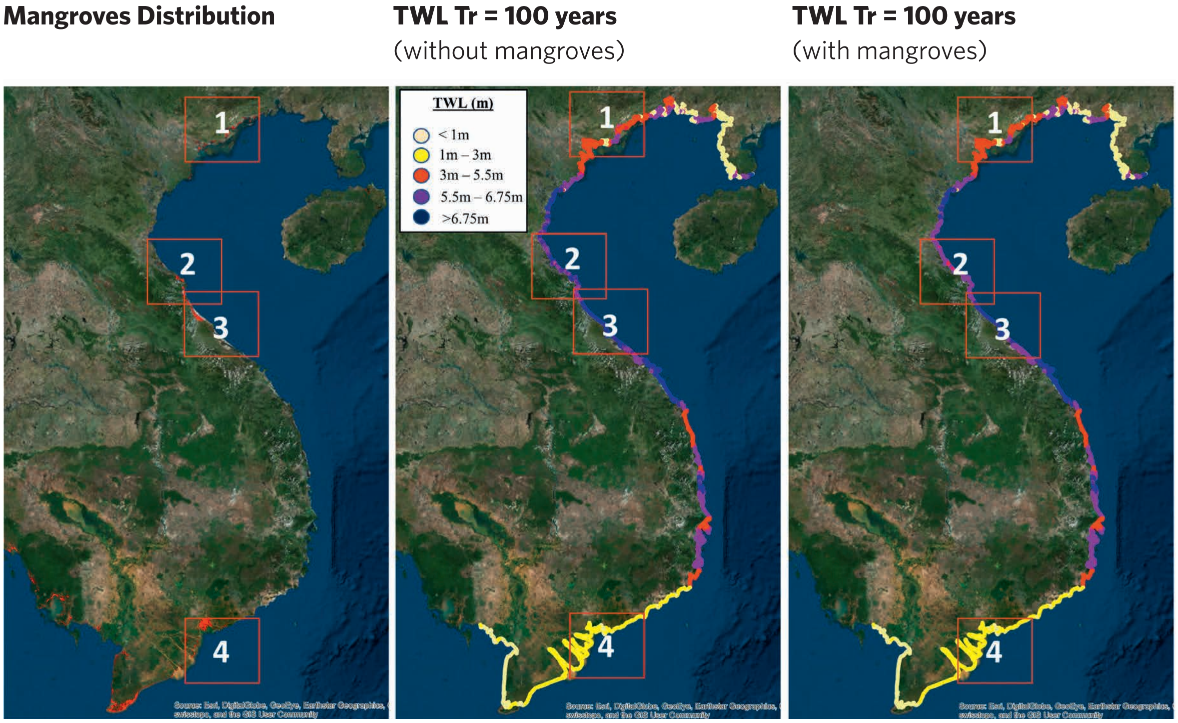
Figure 9: Methodology to obtain the flood height produced by a single tropical cyclone in a single profile. The three boxes, from top to bottom, list i) the offshore parameters; ii) the near-shore parameters, and iii) the final result, i. e. the Total Water Level (or flood height) at the coast.

unique combined time series datasets x 10 clusters per dataset x 1,173 profiles). These 44 million values are used to reconstruct the flood height along all of the world's coastlines. Each profile has been associated to one of the 1,173 families defining the ecosystem characteristics (mangrove length and depth) and one of the 3,787 combinations of waves + sea level. The final result is a time series (32 years = 32 data) indicating yearly maximum flood heights along the coast.

2.7 Step 4: Calculation of Flood Heights and Flooding Maps

2.7.1 Tropical Cyclones: Extreme Value Distribution of Flood Heights

The flood height has been calculated along the world's coastline for the 6,000 s contained in the IBtRACS database and with a spatial resolution of 1 km. In order to obtain annual expected damages, flooding maps for different return periods are required. Consequently, we must fit flood heights to an extreme value distribution. The two parametric distribution functions that have been historically used to fit extreme values are the GEV function (Generalized Extreme Value) and Pareto-Poisson. GEV model is the most used function to fit maximum values within a period. Pareto-Poisson works much better in case of using a Peak Over Threshold method, since it includes information on the magnitude and frequency. In this case we are interested in keeping this information and, thus, we apply the POT method and Pareto-Poisson distribution function at every coastal transect. In this case the POT method is applied over a variable threshold ensuring at least 1 event per year. An example of the flood height distribution in Vietnam, with and without mangroves, for a 100-year return period event is shown in Figure 10. Mangrove layer distribution is also shown in the figure to highlight the protection role of the ecosystem thanks to its capacity to reduce the flood height.



Mangroves Distribution

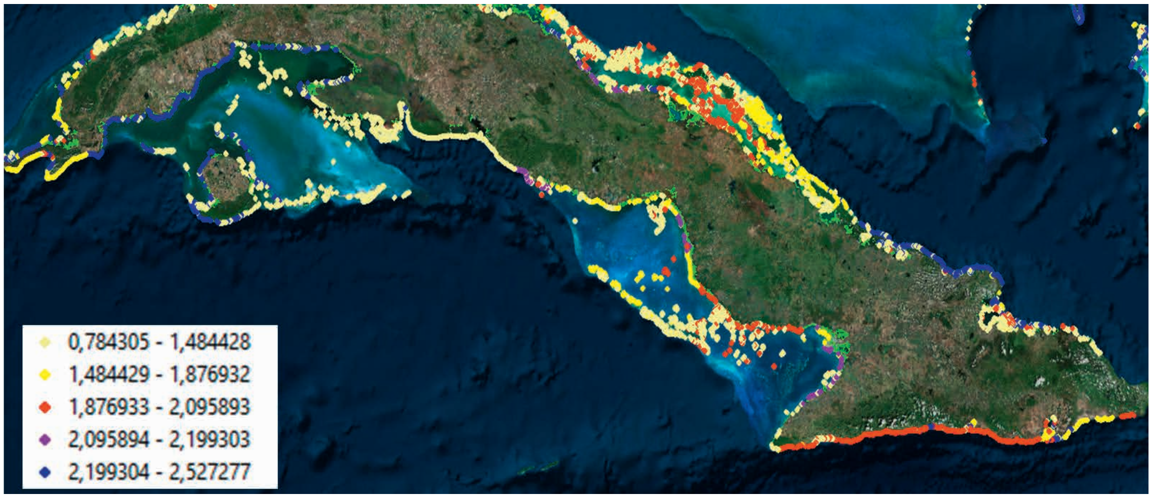
TWL Tr = 100 years
(without mangroves)

TWL Tr = 100 years
(with mangroves)

Figure 10: Example of the Total Water Level (TWL) at the coast produced by a tropical cyclone event of 100-year return period in Vietnam.

Mangroves Distribution

TWL Tr = 50 years (with mangroves)



TWL Tr = 50 years (without mangroves)

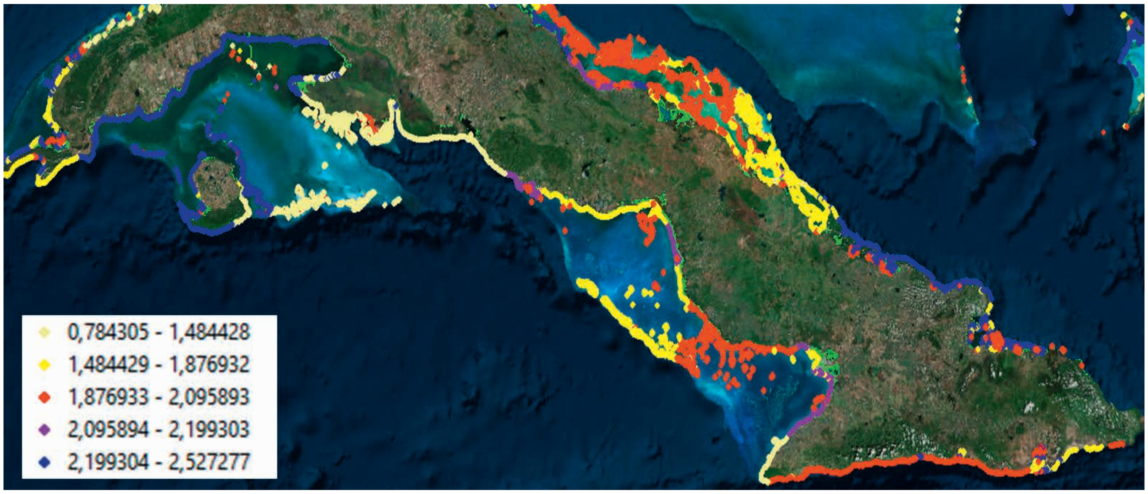


Figure 11: Example of the Total Water Level (TWL) in coast produced by regular climate event of 50-year return period in Cuba.

RFSM-EDA versus BATHTUB-GIS

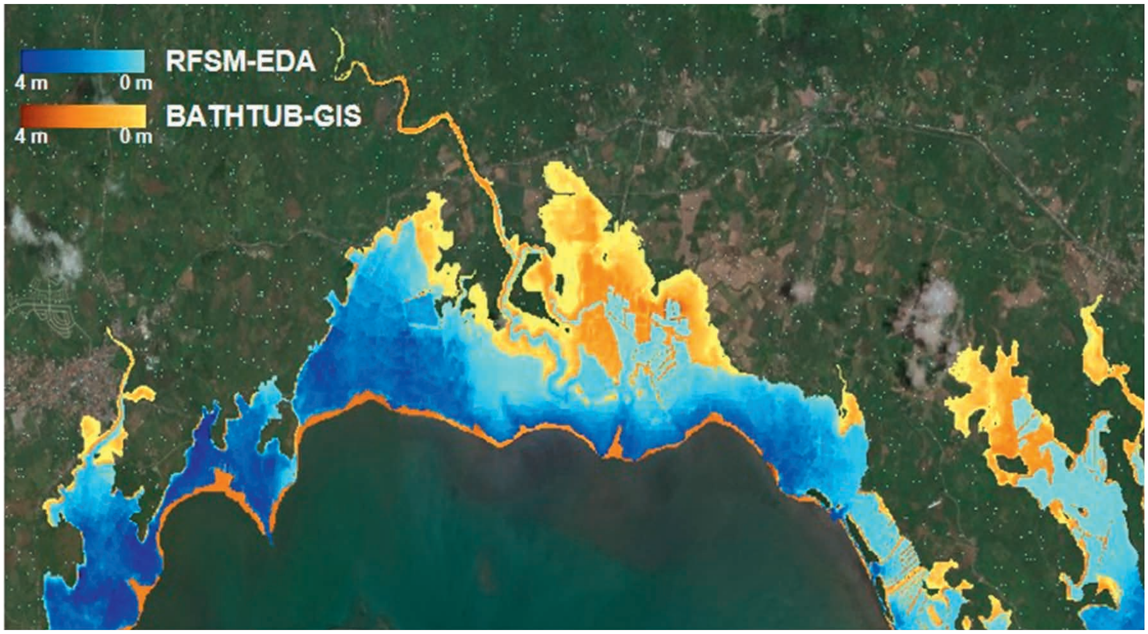


Figure 12: Flooding extents by two techniques: RFSM-EDA (blue) and Bathtub method (yellow). Both methods estimate similar flood extents for a 50-year return period tropical cyclone in Pagbilao, The Philippines.

2.7.2 Regular Climate: Extreme Value Distribution of Flood Heights

The extreme value distribution of flood height is usually obtained using a Peak-Over-Threshold method with the threshold set at 98% (i. e. the top 2% of all values are defined as extreme). To ensure time-independence of the selected data points, values that occur within 3 days of a previous value are excluded. A Pareto-Poisson distribution is then applied to the selected values to obtain a return period distribution for the extreme flood heights. However, since the collected data already correspond to the yearly maximum flood heights at the coastline, (32 data at each profile), the POT selection process is not required, and these maximum values are directly fitted to a GEV function. This is the most accurate method to obtain the extreme regime when using data from the maximum value within a period, as is the case here. The flood height is thus estimated every 1 km across the entire world's coastline for five return periods of 1, 10, 25, 50 and 100 years and two mangrove scenarios (with and without). An example of the flood height distribution with and without mangroves for a 50-year return period event in Cuba is shown in Figure 11.

2.7.3 Flooding Method: Hydraulic Connectivity

To calculate coastal flooding extents we start with a bathtub-type flooding approach. However, this initial approach is modified to only flood areas that are hydraulically connected in our high-resolution grid cells. More complex models are possible (see Losada et al. 2017). However, they require high resolution databases of bathymetry and topography, which were not available at global scale, and modified bathtub approaches work reasonably well (see Figure 12). Global scale projects with coarse DTM data and coastline extents of the order of thousands of kilometers require faster and simpler sophisticated techniques like the "Hydraulically-connected Bathtub" approach, which consists of connecting points of the DTM that are below the water level and are hydraulically connected, to obtain the flooding mask.

We illustrate the final results with an example from Cancun, Mexico, using the tropical cyclones flooding estimates for 100-year return period events (Figure 13). The coastal protection role of mangroves is clearly observed. The

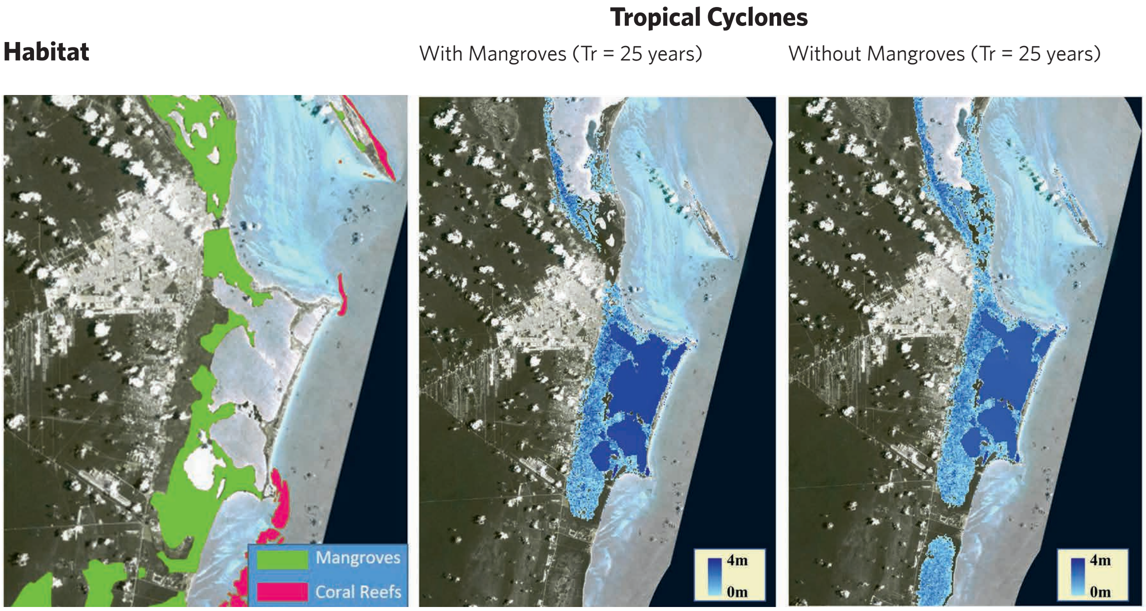


Figure 13: Coastal flooding in Cancun for 100-year return period tropical cyclones. Comparison between with (center) and without mangroves (right) scenarios. Left image represents habitat distribution in Cancun: mangroves (green) and coral reefs (red).

tropical cyclone which occurs, on average, once every 100 years would cause significant flood damages to the city of Cancun if all present mangrove cover were lost.

2.8 Step 5: Assessing Flooding Consequences

The expected benefits provided by mangroves are presented in social and economic terms. To calculate the exposure of assets (people and property), the consequences of flooding and benefits of mangroves for flood reduction are assessed across three key variables; population, residential and industrial stock. We followed established approaches for assessing the damages to people and property (residential + industrial stock) as a function of the level of flooding. We calculated the percentage of people and property that has been damaged (D) for a given flooding level and a certain coefficient that must be calibrated as $D(h) = h/(h + k)$. This curve indicates that as flooding level increases, the percent of damages also increases. These functions vary by people, property and even types of property. We used curves derived from the common database of damage functions in US HAZUS (Scawthorn et al. 2006) and from JRC (Joint Research Centre) (Huizinga et al. 2017).

In prior work, we tested the use of various damage curves (including complex damage functions) for population, residential and industrial stock from HAZUS in the Philippines (Losada et al. 2017), and we found that the results were not significantly different from approaches using simpler curves. To define case-specific semi-empiric damage functions across the countries protected by mangrove ecosystems, we used a different damage function for each category, i. e. population, residential and industrial stocks.

To calculate the risk probability, after calculating the flood height with 1 km resolution coastline, we extended the flood height inland by ensuring hydraulic connectivity between points at 30m resolution. From the flooding levels and flooding extent, we calculated the total area of land affected and damages. Flooding maps were also intersected with population data after resampling from the original 1 km resolution to 30 m of the digital elevation model. In addition to assessing risk and damages for specific events (e.g., 100-year storm event), we also examined average annual expected damages and benefits provided by mangroves. To estimate annual risk, we integrated the values under the curves that compare built capital damaged or people flooded, by storm return period, i.e., the integration of the expected damage with the probability of the storm events. We combine the flooding information for different return periods with the exposure and vulnerability of people and property to obtain the damage associated with different storm return probabilities in 1 x 1 km cells. That is, we used a raster based approach with 1 x 1 km cells and then averaged results into 100 km study units.

2.8.1 Population Data

Global exposure data for people was obtained from the Socioeconomic Data and Applications Center (SEDAC) fourth version of Gridded Population of the World at a 1 km spatial resolution (http://sedac.ciesin.columbia.edu/data/collection/gpw-v4). SEDAC is freely available, and includes a map viewer to see global distribution of different socio-economic assets (http://sedac.ciesin.columbia.edu/mapping/viewer/).

2.8.2 Residential and Industrial Property Data

This study uses data from GAR15 (Desai et al. 2015) on the economic value of the residential and industrial building stock. Throughout this report we use stock and property interchangeably to mean the physical buildings. The GAR15 provides a global exposure database with a standard 5 km spatial resolution and a 1 km detailed spatial resolution on coastal areas, estimating the economic value of the exposed assets, as well as their physical characteristics in urban and rural agglomerations. The variables included in the database are number of residents, and economic value of residential, commercial and industrial buildings (De Bono and Chatenoux 2015). The GAR15 database follows a top-down approach using geographic distribution of population and gross domestic product (GDP) as proxies to distribute the rest of socio-economic variables (population, income, education, health, building types) where statistical information including socio-economic, building type, and capital stock at a national level are transposed onto the grids of 5x5 km or 1x1 km using geographic distribution of population data and gross domestic product (GDP) as proxies (UNISDR 2015).

The study downscaled residential and industrial stock data from the GAR15 in the following manner:

1. For each point of GAR15 layer, the total population was calculated. Eight fields were added together: high, medium high, medium low and low income for both rural and urban population. GAR15 data is referenced to 2014, so an adjustment to 2015 WorldPop estimates was performed.

2. In each point of GAR15 layer, total residential building stock was calculated. Eight fields were added together: high, medium high, medium low and low income for both rural and urban residential stock.

3. In each point of GAR15 layer, residential stock per capita was calculated by dividing residential stock and adjusted population.

4. A raster layer was created for residential stock per capita. Inverse distance weighted interpolation was used for the creation of this raster.

5. Finally, using the population raster (from WorldPop, 100m resolution) the residential raster layer was calculated by multiplying residential stock per capita and population. A scale verification was done, checking that the sum of residential stock from GAR15 layer was the same that the sum of residential stock raster layer created. Industrial stock data were downscaled similarly.

2.8.3 Gross Domestic Product

World Development Indicators from the World Bank (https://datacatalog.worldbank.org/dataset/world-development-indicators) were used to obtain GDP data for each country involved in this study (World Bank 2017). GDP information is available from 1960 to 2016. Additionally, World Bank databases were used to validate other data-sources: population from SEDAC and residential and industrial stock from GAR15.

2.8.4 Damage Functions

Global Flood Depth-Damage functions are needed to evaluate the sensitivity of people and property to be damaged for different flood levels. A new report from the EU Joint Research Centre (JRC) collected data from Africa, Asia, Oceania, North America, South America and Central America and proposed damage functions for residential and industrial stock, commerce, transport, infrastructure and agriculture at each location (Huizinga et al. 2017). We refer to these hereafter as JRC damage functions. These damage functions are a new alternative to damage curves from HAZUS databases (Scawthorn et al. 2006), which were based only on US collected data but frequently extrapolated for use in other geographies. JRC damage functions were born with the aim of addressing flooding effects on property globally, developing a consistent database of depth-damage curves.

To demonstrate the level of detail of JRC damage functions, an example of the sensitivity of different residential buildings (Africa and Europe) is shown in Figure 14.

Damage functions for residential buildings

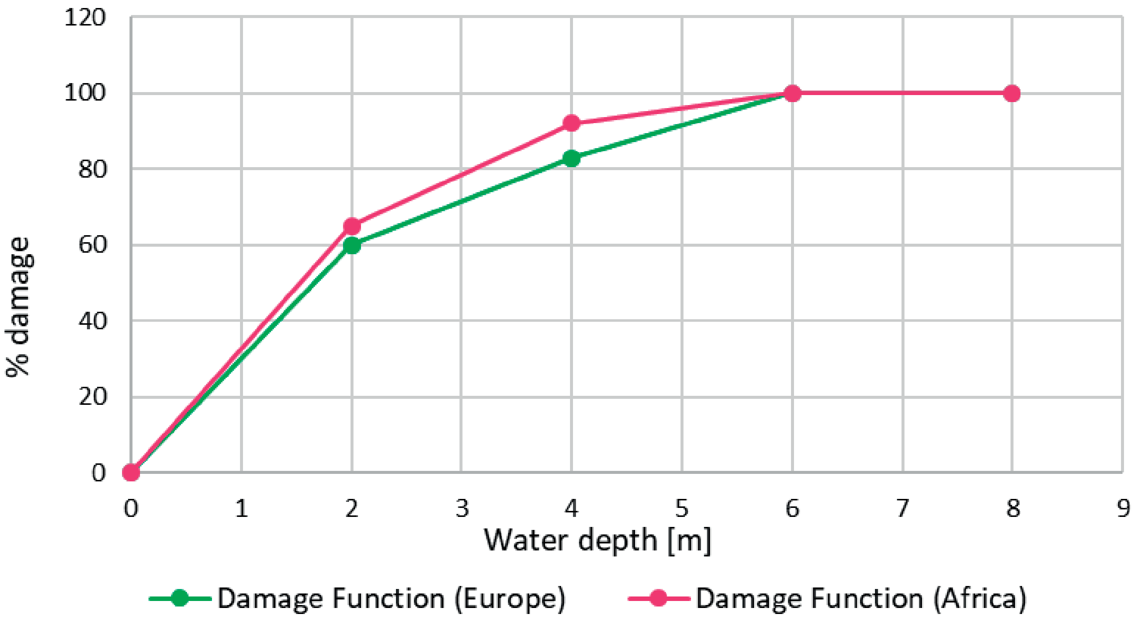


Figure 14: Example of Damage functions for different residential buildings in Africa and Europe.

3. Results

This section describes the global flood reduction benefits of mangroves in terms of the additional people and property that would be flooded and damaged if mangroves were lost. Globally, mangroves provide significant annual expected benefits and avert significant damages from catastrophic events. These results are presented in terms of the number of people flooded and the value of residential and industrial property damaged. The results identify where mangroves provide the greatest benefits to people and property.

Mangroves reduce annual flooding to people globally by more than 39%, providing benefits to more than 18 million people every year. Mangroves reduce annual property damages by more than 16%, with an annual value of more than US$ 82 billion (see Figure 15). If we examine the spatial distribution of where mangroves provide the greatest annual expected benefits to people and property, we can identify hotspots of benefits around the world. The protection benefits to people are highest in key areas in the Indian Ocean and East Pacific. However, annual averted damages (i.e., benefits of mangroves) to residential and industrial building stock are more evenly distributed globally (Figure 20).

The annual benefits are higher for regular climate conditions than for tropical cyclones. This is because events in regular climate conditions, though low in intensity of damage, are more frequent. Mangroves provide the greatest benefits for more frequent, lower intensity storm events, because they have a proportionally greater effect on reducing flood extents for smaller flooding events. Mangroves reduce flooding to 32% of people for 1 in 10 year events, whereas they only reduce flooding to 16% more people for 1 in 100 year events.

While we generally show the combined results of flooding from tropical cyclones and regular climatic events (Figure 15) it is useful to identify the benefits of mangroves to these separate types of events (Figure 16 and Figure 17). Under regular climate conditions, the % benefits provided by mangroves decreases somewhat for larger events.

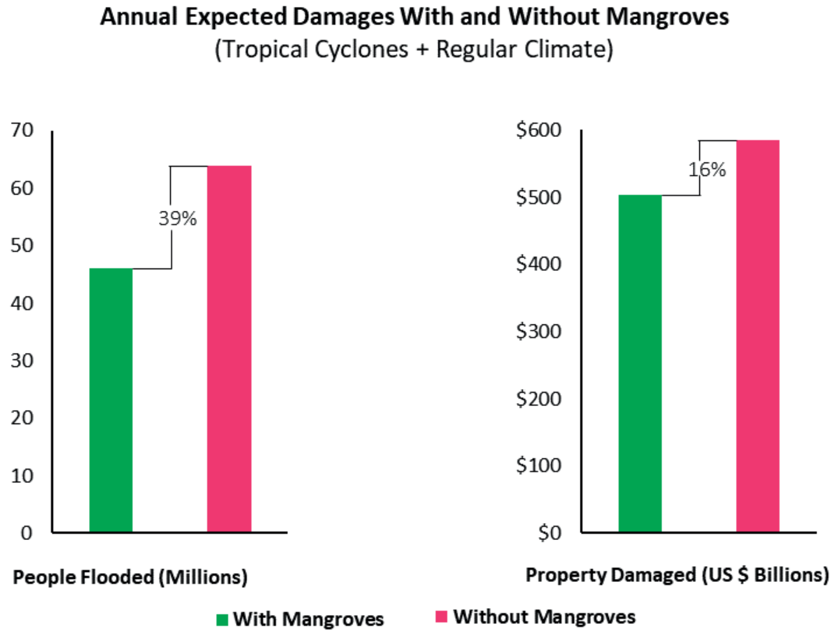


Figure 15: Total value (i.e. tropical cyclones + regular climate) of Annual Expected Damages to people and stock globally, with and without mangroves.

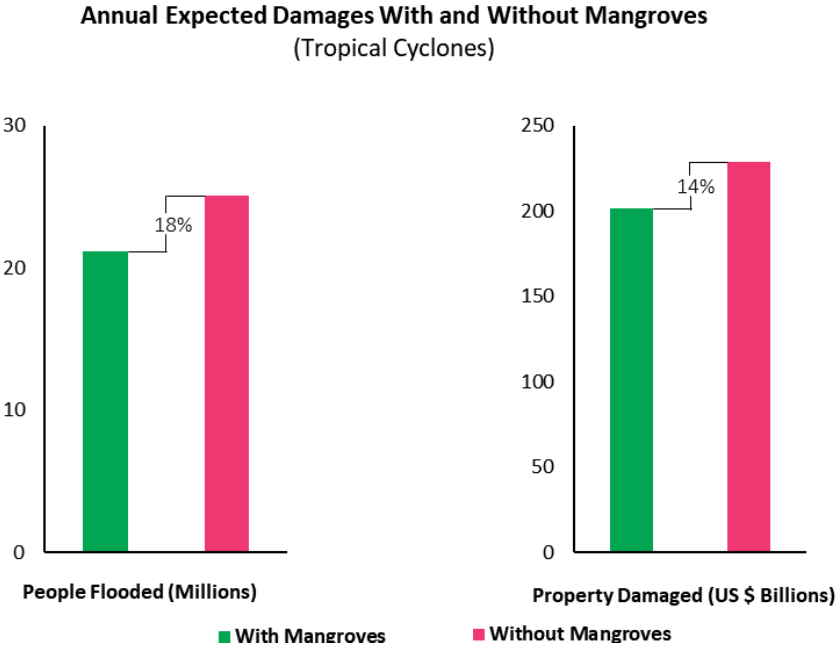


Figure 16: Annual Expected Damages to people and stock for tropical cyclones

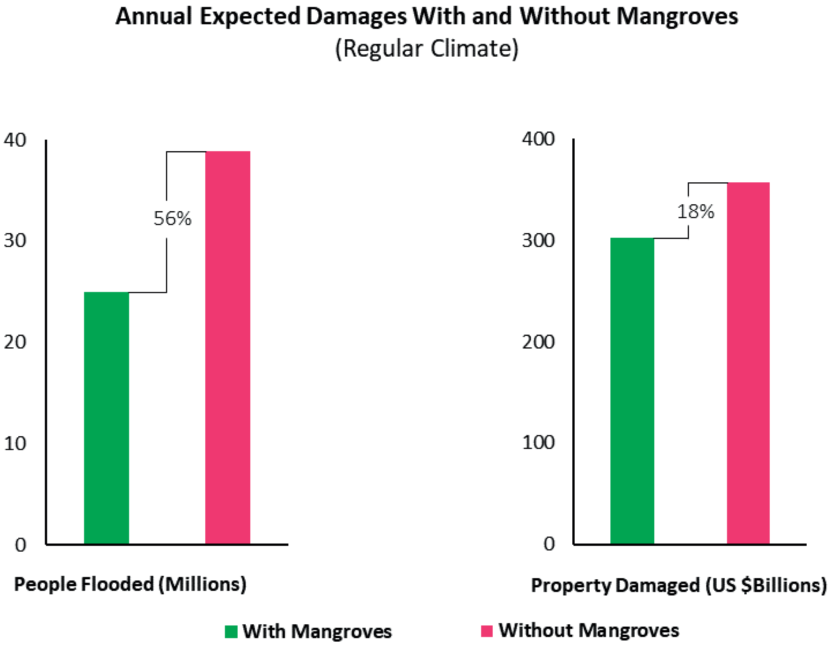


Figure 17: Annual Expected Damages to people and stock for regular climate

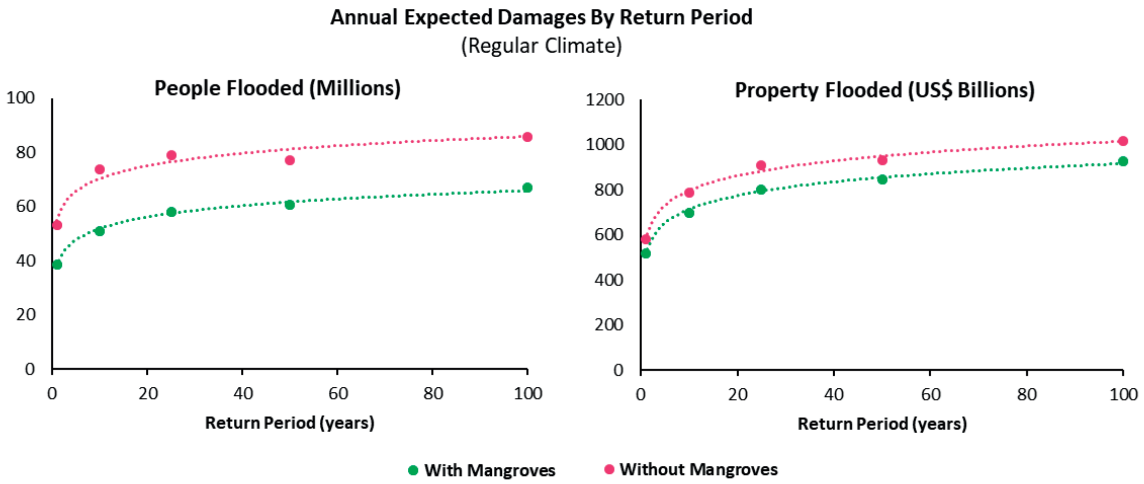


Figure 18: Damage per return period to people and stock for regular climate

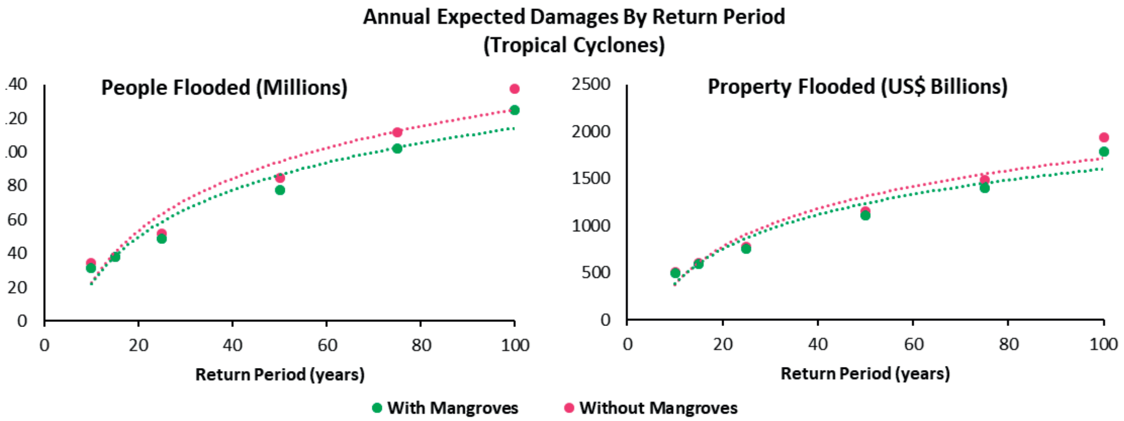


Figure 19: Damage per return period to people and stock for tropical cyclones

For example, in a 10-year event without mangroves there would be 13% more property damaged; whereas this level of benefit drops to 10% for a 100-year event (see Figure 18). During tropical cyclones, the percentage benefits provided by mangroves increases slightly for more extreme cyclones. For example, in a 10-year cyclone without mangroves there would be 2% more property damaged; whereas this level of benefit increases to 8% for a 100-year event (Figure 19).

We also looked at where mangroves may provide the greatest overall risk reduction benefits by taking information on exposure reduction and socio-economic vulnerability. The WorldRiskIndex includes a vulnerability index that considers social, economic, and governance indicators (Bündnis Entwicklung Hilft 2017). For all coastal nations that receive benefits from mangroves, we combine our estimates of flood exposure reduction with the vulnerability scores of the WorldRiskIndex to produce a ranking of countries that are estimated to receive the greatest overall risk reduction benefits from mangroves. The countries estimated to receive the greatest risk reduction benefits from mangroves are Guinea, Mozambique, Guinea-Bissau, Sierra Leone and Madagascar (Figure 21 and Table 2).

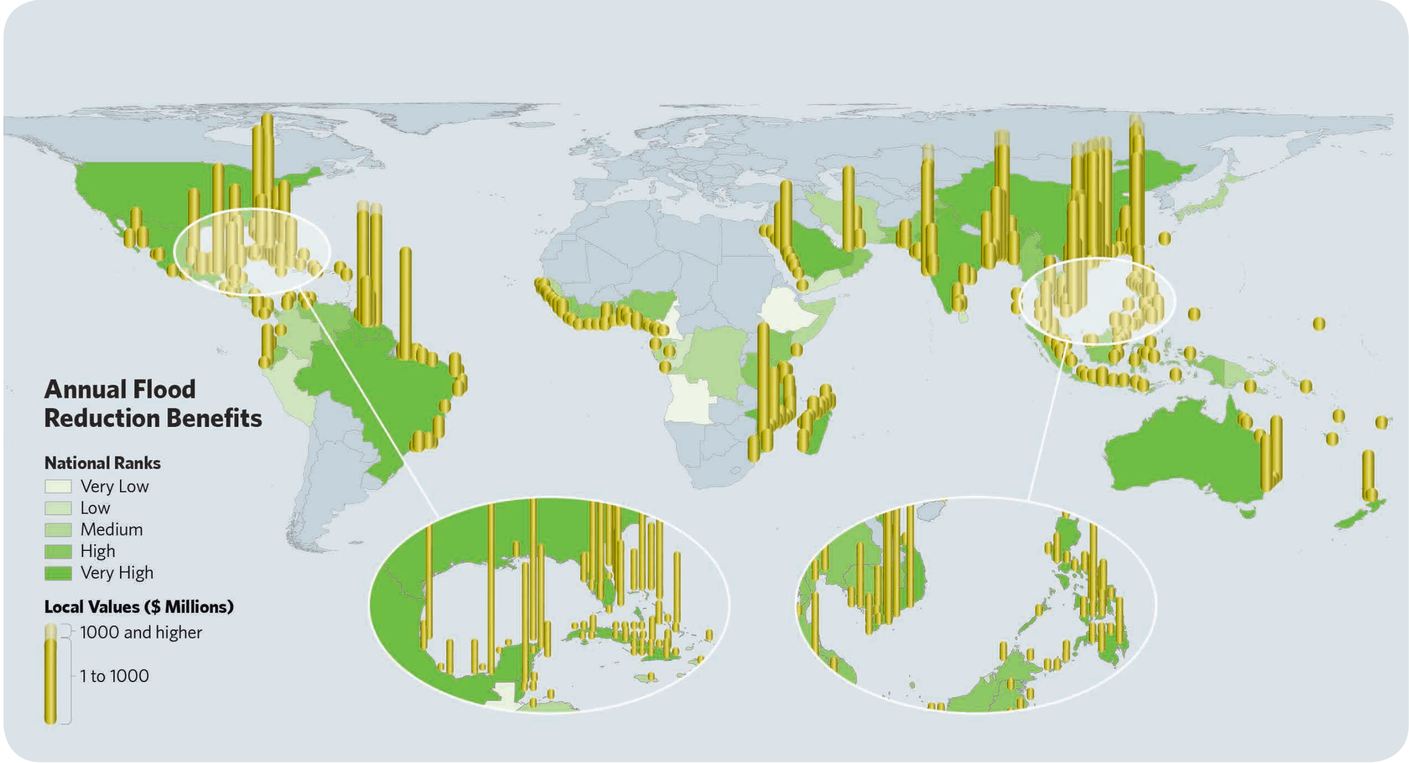


Figure 20: The map shows where mangroves provide the greatest flood reduction benefits for property. The values represent the difference in annual expected damages in US $ millions with and without mangroves per 100 km of coast.

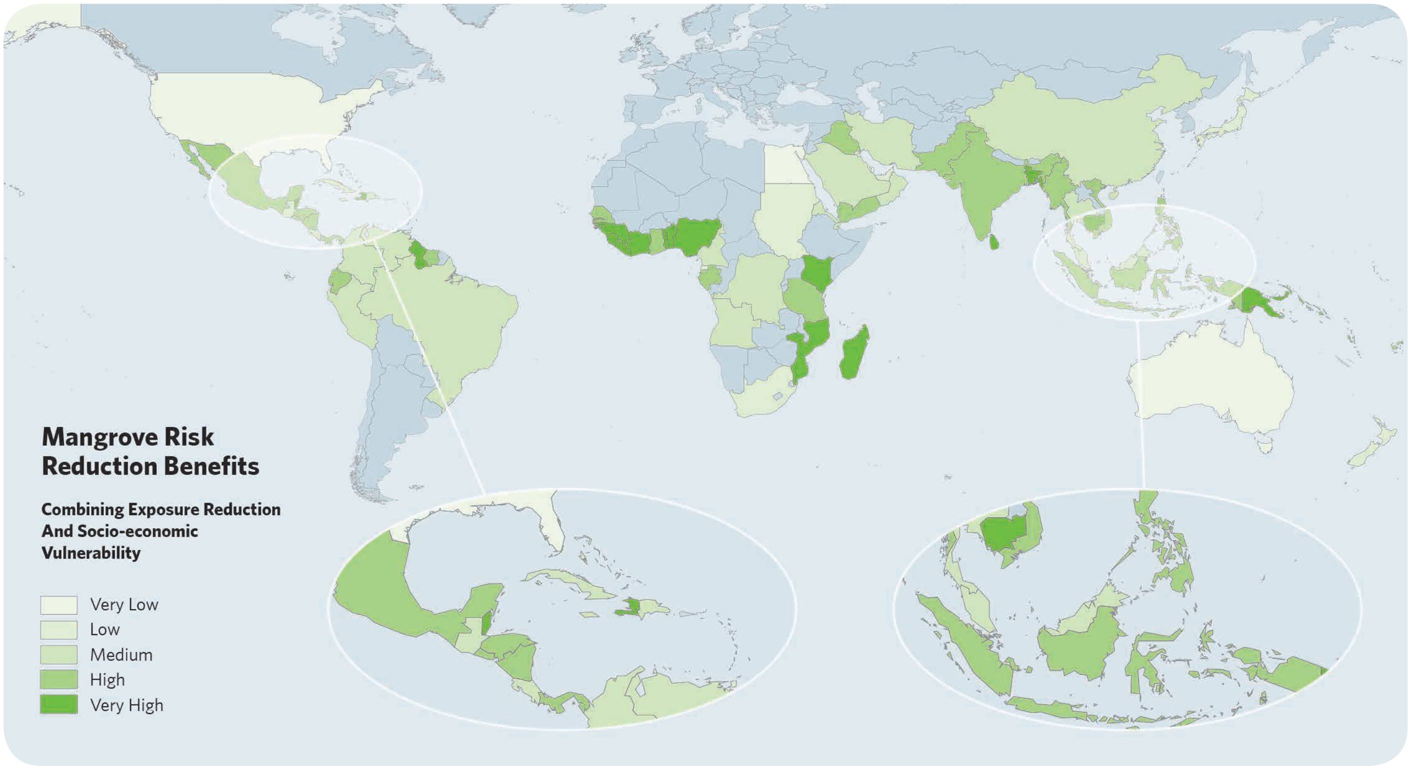


Figure 21: The map combines data on socio-economic vulnerability from the WorldRiskIndex (Bündnis Entwicklung Hilft 2017) with property flood reduction benefits from mangroves (Figure 20) to rank the countries that likely receive the greatest risk reduction benefits from mangroves. Higher scores (in darker green) indicate likely greater overall risk reduction benefits from mangroves. Countries in gray do not have mangroves and are excluded from the analysis.

Countries Where Mangroves Provide the Greatest Annual Flood Exposure Reduction				
People Protected (millions)		Property Protected (US $ Billions)		Property Protected per GDP
Vietnam	8,1	China	19	Guyana
India	3,3	United States	13	Belize
Bangladesh	1,3	India	9	Bahamas
China	0,8	Mexico	9	Suriname
Philippines	0,7	Vietnam	7	Mozambique
Brazil	0,4	Guyana	7	Vietnam
Nigeria	0,4	Mozambique	2	Guinea-Bissau
Indonesia	0,3	Saudi Arabia	2	Madagascar
Mozambique	0,3	Bangladesh	2	Benin
Mexico	0,3	Bahamas	2	Sierra Leone

Countries Receiving the Greatest Risk Reduction Benefits from Mangroves	
Vulnerability (WorldRiskIndex)	Overall Risk Benefits
Haiti	Guinea
Liberia	Mozambique
Sierra Leone	Guinea-Bissau
Mozambique	Sierra Leone
Guinea	Madagascar
Madagascar	Benin
Guinea-Bissau	Guyana
Nigeria	Solomon Islands
Comoros	Liberia
Togo	Cote d'Ivoire

Table 2: On the left, countries receiving greatest benefits in flood exposure reduction from mangroves. On the right we combine informantion on vulnerability from the WorldRiskIndex with our flood exposure reduction data to estimate the countries that receive the greatest overall risk reduction benefits from mangroves. The countries in the vulnerability column are the top 10 most vulnerable countries from the WorldRiskIndex that have mangroves.

4. Discussion and Recommendations

Mangroves can play a major role in coastal risk reduction to people and property by 39% and 16% respectively. The national benefits provided by mangroves vary depending on whether they are considered in absolute or relative terms (Table 2). While the greatest absolute benefits, in terms of total people and assets protected, occur in large, populous countries, the relative importance of mangroves for countries varies per capita or per GDP. Very large countries with highly developed coastlines, including China, United States, India, Mexico and Vietnam, receive the greatest total annual benefits from avoided damages to property. However, when considering benefits on a per capita basis, Guyana, Belize, Bahamas, Suriname, and Mozambique rank highest in avoided property damages. In these latter countries, mangroves gain importance as a risk reduction asset because these countries have less resources to spend on disaster recovery.

These spatially explicit results identify critical hotspots at sub-national scales where mangrove benefits are particularly high. For example, mangroves provide significant benefits throughout the Philippines, but these values are greatest in the central and northern regions of the country that are the most heavily impacted by annual typhoon and high wave events (Figure 20). Also, mangroves have particularly high risk reduction benefits in highly populated and vulnerable delta regions, which are low lying and with extensive mangroves. For example, mangrove benefits are especially high in the Ganges-Brahmaputra delta in India and Bangladesh, the Mekong delta in Vietnam, and parts of the Amazon delta in northern Brazil (Figure 20). These are among the poorest regions in these respective countries, highly vulnerable and in need of disaster risk reduction strategies (e.g., UNDP 2004). It is here where mangroves play a particularly important role in reducing risk, by reducing both flood exposure and socio-economic vulnerability.

4.1 Mangroves and Socio-Economic Vulnerability

Mangroves first reduce risks by protecting coastlines against flooding, erosion and storm surge and thus reducing exposure. At the same time, mangroves can also provide benefits to lives and livelihoods and thus reduce socio-economic vulnerability. The reduction of both exposure and vulnerability are highly relevant within the UN frameworks of disaster risk reduction (UNISDR) and climate change (UNFCCC). UNISDR aims to help vulnerable countries and people by avoiding or reducing losses (UNISDR 2005), complementing sustainable development, and damping the negative cycle of hazards and poverty (Barnett et al. 2008, Dercon 2005). Poor people suffer disproportionately from natural hazards because they are exposed to floods and droughts more often, lose more as a share of their wealth when hit, and receive less support for recovery. In fact, disasters in the aftermath of extreme natural events can keep people in poverty and move them into poverty (Hallegatte et al. 2016).

Mangrove ecosystems contribute most to countries with high exposure to hazards and high socio-economic vulnerability. By combining the results of the expected flood damage reduction benefits of mangroves with data from the WorldRiskIndex 2017 (Bündnis Entwicklung Hilft 2017) on national vulnerability, we find that these mangrove benefits are most important for countries in West and East Africa.

Recent initiatives by the G7 and the G20 to help reducing risk in vulnerable communities focus on people living on less than US$ 15 purchasing power parity (PPP) per day. PPP is one proxy for social vulnerability. A study conducted by the Munich Climate Insurance Initiative (MCII) defines the extreme poor as people living on less than US$ 1.9 PPP per day, the moderate poor as those living on US$ 1.9-3.1 PPP per day, and vulnerable people as those living on US$ 3.1-15 PPP per day. According to the UN Millennium

Case Study

Enabling Sustainable Management of Mangroves

Siargao is the most eastern island of the Philippines. Due to its location it is highly exposed to extreme natural hazards and climate change. It is also surrounded by the largest mangrove forest in the Philippines, which provides both flood defense and the main source of livelihood for local communities. Increasing storms leading to fewer fishing days at sea and unsustainable fishing practices have reduced fish harvests by 30% during the last ten years. Local communities fishing using traditional methods could no longer generate sufficient income. As a result, local fishermen have been pushed towards destructive fishing practices and illegal mangrove logging. In combination with weak economic and environmental governance and poor law enforcement, the rate of mangrove degradation and extraction was high. The unsustainable use of Siargao's natural resources exposed local families to hazards and increased their vulnerability.

To protect Siargao's mangroves forests and support sustainable resource management, the Center for the Development of Indigenous Science and Technology (SIKAT), in partnership with Misereor (a member organization of Bündnis Entwicklung Hilft), began a project in 2013. SIKAT contributed to the formation of a network of community organizations and local authorities that would improve natural resource management and decrease the vulnerability of the coastal communities. With the support of SIKAT, the community established and maintains mangrove protectorates and mangrove nurseries, guarded by local fishermen. Working with churches and schools, SIKAT engages diverse community members to participate in mangrove plantings. To improve law enforcement teams, marine protection officers are empowered with equipment and training. Furthermore, SIKAT promotes alternative income opportunities, including drying fish, and mangrove crab fattening, which has been particularly successful: 18 families make a living by harvesting crabs, fattening them with fish waste, and selling them to hotels and other businesses (Mously 2015).

As a result, more than 5,000 hectares of mangroves are now co-managed by community organizations and local governments, and more than 25 hectares of mangroves have been reforested. Illegal mangrove logging has declined significantly; no cases were reported in 2017. Increased community awareness and participation in mangrove management has influenced the public perception that communities, particularly those living near mangroves, are now safer from flooding, storm surge and sea level rise. The engagement of local government has improved law enforcement, and has also raised political attention, influencing decisions on disaster risk reduction and environmental protection in the region. In 2017 the Del Carmen municipality in east Siargao approved new disaster risk reduction and resource management plans. The case of Siargao shows that effective management of mangroves for multiple ecosystem services is possible.

Development Goals database some of the countries that we have identified where mangroves provide the most risk reduction benefits are also countries where a high percentage of people live in extreme poverty including Guinea (35%), Mozambique (69%), Guinea-Bissau (67%), Sierra Leone (52%) and Madagascar (78%).

4.2 Gaps & Constraints

The results of our global mangrove models depend on the resolution of data available, including hydrodynamic (e.g., storms and waves), ecological (mangrove) and socio-economic (e.g., population, stock and GDP) parameters. We used the best available global datasets, including the highest possible resolution datasets of bathymetry and topography. These flood models can be improved with higher resolution data on bathymetry and topography. Better bathymetry data will enhance the calculation of surge and wave propagation to nearshore regions, and better topography will improve estimates of inland flooding (Losada et al. 2017). Improving the quality and coverage of these datasets will also help improve all public and private risk models, very few of which currently exist in regions with mangroves.

These results likely underestimate the full coastal protection benefits of mangroves. Given the geographic scale of this global exercise to estimate flood protection benefits from mangroves, we had to use a simplified combination of 1-D and 2-D hydrodynamic models to calculate flooding. In these models, mangrove flood reduction benefits are estimated via a bottom roughness coefficient as per standard practice in coastal engineering. This can result in some underestimation of the actual physical effect of mangrove vegetation in slowing down waves and water levels. While the effects of mangrove vegetation can be better represented by more computationally expensive 2-D and 3-D hydrodynamic models (Sheng et al. 2012), this more precise and intensive analysis is more appropriate for specific sites, and quickly becomes impractical at larger spatial scales. In addition, this study only considers wave and surge reduction processes and does not estimate the effect of mangroves on reducing wind speed and preventing subsequent damages. The ability of mangroves to reduce wind speeds is particularly significant during tropical cyclone and hurricane events. Finally, mangroves can often play a key role in reducing coastal erosion by reducing wave energy as well as by trapping and building sediment (McIvor et al. 2013), all of which complement their coastal protection benefits.

4.3 Implications & Recommendations

These social and economic valuations of mangroves can inform the policy and practice of development, risk reduction and conservation sectors as they seek to identify sustainable and cost-effective approaches for risk reduction. By showing the spatial variation of the flood reduction benefits provided by mangroves, these results can identify the places where mangrove management may yield the greatest returns. By valuing these coastal protection benefits in terms used by financial institutions and government decision-makers (e.g., annual expected benefits), these results can be readily used alongside common metrics of national economic accounting, and can inform risk reduction, development and environmental conservation decisions globally.

These results also inform climate adaptation and financing. Preventing and minimizing losses is the bedrock of effective risk management and adaptation. When current risks are reduced, future risks are reduced as well, and the ability of countries to devote resources to other adaptation activities increases (UNISDR 2005, Warner 2010). The Bali Action Plan calls for "consideration of risk sharing and transfer mechanisms, such as insurance" to address loss and damage in countries particularly vulnerable to climate change (UNFCCC 2007). Insurance activities must be viewed as part of a climate risk management strategy of vulnerable nations that includes, first and foremost, activities that prevent human and economic losses from climate variability and extremes. To harmonize climate insurance with adaptation, it is essential to align adaptation incentives with prevention and risk reduction. Nature-based defenses such as mangroves and reefs can play an important role but have yet a largely uncaptured contribution to such risk reduction and adaptation strategies.

There are many actions that we can take now to advance and incentivize mangrove conservation in policy, practice and finance, given the clear value of mangroves' natural coastal protection benefits. Our recommendations are summarized here and explained below:

Summary of Recommendations

+ **Governments and NGOs should scale up existing mangrove restoration for risk reduction projects.**
+ **Planners should include mangrove defenses in national adaptation, land use, risk management and development plans.**
+ **Engineers and insurers should include mangrove natural defenses in cost-benefit analyses and their government and private clients should demand that they are included.**
+ **Economists should include mangrove defenses in national and regional accounts.**
+ **National and multi-national funders should support mangrove restoration for risk reduction.**
+ **Disaster managers, insurers and risk modelers should include the benefits for mangrove defenses in their assessments.**
+ **Financiers, insurers, NGOs and governments should use these risk reduction benefits to develop new financial tools that support restoration for risk reduction.**

+ **Mangrove restoration projects for risk reduction should continue to be scaled up.** Mangrove restoration for risk reduction has been done at large scales over hundreds of thousands of hectares in places such as Vietnam, Philippines and Guyana. While best practices are still evolving, current approaches are well advanced. The practice is well beyond the testing phase and ready for large scale implementation. We believe that many of the key countries that we have identified could develop large-scale mangrove restoration plans, which could get supported by the Green Climate Fund, the Adaptation Fund, and other sources.
+ **The risk reduction benefits of mangroves can be more widely incorporated in National Adaptation Plans of Action.** Under the UNFCCC framework, national adaptation plans prioritize mangrove management (e.g., Sierra Leone, Guyana, Myanmar), but primarily for the benefits of their extractive resources. Full recognition of the risk reduction benefits of mangroves would provide a more realistic representation of their true value to climate adaptation and hence funding for their protection and restoration.

- **Land use and development plans should include the benefits of mangroves as natural defenses.** Overall there should be a greater alignment between land use planning and risk management. This would help local government and communities to understand their exposure to a wide variety of risks and to develop plans to manage their risks. Mangrove restoration can become an integral part of planning for resilience in cities along tropical coastlines risk models can play an important role here, in assessing the value of infrastructure projects, and demonstrating the risk reduction provided by mangroves.

- **The use of mangroves as natural solutions for risk reduction may be mainstreamed in development policies particularly through the international risk reduction agenda.** Mangrove conservation and restoration can be an important part of the solution for reducing the vulnerability of coastal communities to risks, especially as those risks increase with climate change. Mangroves are just beginning to be incorporated into the international risk reduction agenda. Natural defenses are included for the first time in the UNISDR Sendai Framework for DRR (SFDRR), but they are not yet fully mainstreamed for example in national development policies and programmes. The SFDRR should articulate more clearly the rationale for promoting and investing in natural defenses to support mainstreaming in countries.

- **Mangroves in particular should be better recognized in these policies for the multiple benefits that they provide for reducing vulnerability of coastal communities.** Indeed where these mangrove benefits are recognized and enhanced, it makes it easier for communities to contribute towards and benefit from their sustainable management. These benefits could be better mainstreamed in local education and restoration programs, which can support livelihoods.

- **Mangrove risk reduction benefits can now be included in national accounts.** At present, national accounts and associated statistics (e.g., GDP) only consider the extractive benefits of habitats, but do not account for the benefits provided by leaving ecosystems in place. Recognition of the full suite of benefits, from risk reduction to fisheries to carbon mitigation, will enable funding for their management commensurate with the multiple societal and economic benefits they provide.

- **Mangroves should be included in public and private insurance (risk) models, maps, and data.** Our results show that flood risk models can measure the benefits of mangroves. These models are used by governments and businesses to price risk (e.g., insurance, bonds). By incorporating ecosystems, risk models not only accurately portray existing risk, including the risk reduction benefits of existing habitats, but also help identify the most cost-effective risk reduction solutions. In contrast to typical models of ecosystem services, which are often ecological models that must be adapted for use by businesses, this work fits ecosystems into existing business models. The risk industry should explicitly identify the inclusion of mangroves and other natural capital in their models (e.g., RMS, AIR) and their global maps for risk data.

- **Cost-benefit analyses for flood reduction solutions should consider natural defenses.** Mangroves and other natural coastal defenses are rarely considered as alternatives in traditional cost benefit analyses for flood protection. However, many studies have demonstrated that mangroves and other natural solutions for risk reduction may be as or more cost effective than grey solutions for risk reduction (e.g., Narayan et al. 2016, Reguero et al 2018). Government and private clients should ensure that coastal engineers and risk modelers assess the cost effectiveness of natural defenses when considering coastal protection alternatives. The results and models presented here show how those benefits can be examined rigorously and create a direct basis to change that paradigm.

- **These rigorous valuations of coastal protection benefits can support financing**

opportunities for mangrove restoration for risk reduction. Local, regional and national governments support the development of artificial coastal defenses from a variety of sources, from special purpose tax districts to bonds and loans funded by risk reduction benefits. As natural defenses are included in the risk and cost effectiveness models of insurers and engineers, these same 'standard' financing tools can also be used to support (re)building of natural defenses based on their risk reduction benefits. For example, the value of the protection services offered by mangroves can be considered in insurance industry models to lower premiums.

- **There are opportunities to develop new financing tools to support mangrove restoration.** Valuations of the risk reduction services of mangroves can support the development of catastrophic hazard bonds and blue bonds that could use the risk reduction benefits of mangroves to support habitat conservation and restoration. Resilience and catastrophe bonds are financial instruments designed to help manage the financial risks associated with natural disasters. Catastrophe bonds become more valuable investments when the probability of a triggering event and/or the estimate of its total financial loss to investors goes down; these incentives create the basis for resilience bonds (Vajjhala and Rhodes 2016). A resilience project designed to divert floodwater, such as the restoration of mangroves, could create both social value and environmental benefits. The result of an effectively integrated insurance and resilience project finance strategy is that a community is physically protected from the worst on-the-ground outcomes, while potential financial losses are reduced and investors' bond holdings improve in value over time.

- **Mangroves should be included in post-disaster recovery financing.** While pre-disaster efforts for risk reduction are particularly cost effective, it is a fact that most funding for risk reduction comes after disasters. Mangroves and other coastal habitats need to be better included in these restoration and recovery efforts to rebuild these natural defenses, especially because they are cost-effective solutions for coastal protection. Typical government budget mechanisms for post disaster financing (e.g., increasing loans, credit lines and taxes) can be complemented by a contingent line of credit such as the World Bank Development Policy Loans with Catastrophe Deferred Drawdown Option (World Bank 2013). We recommend that investment in risk reduction measures such as mangrove protection and restoration are built into such loan agreements to reduce future risk exposure.

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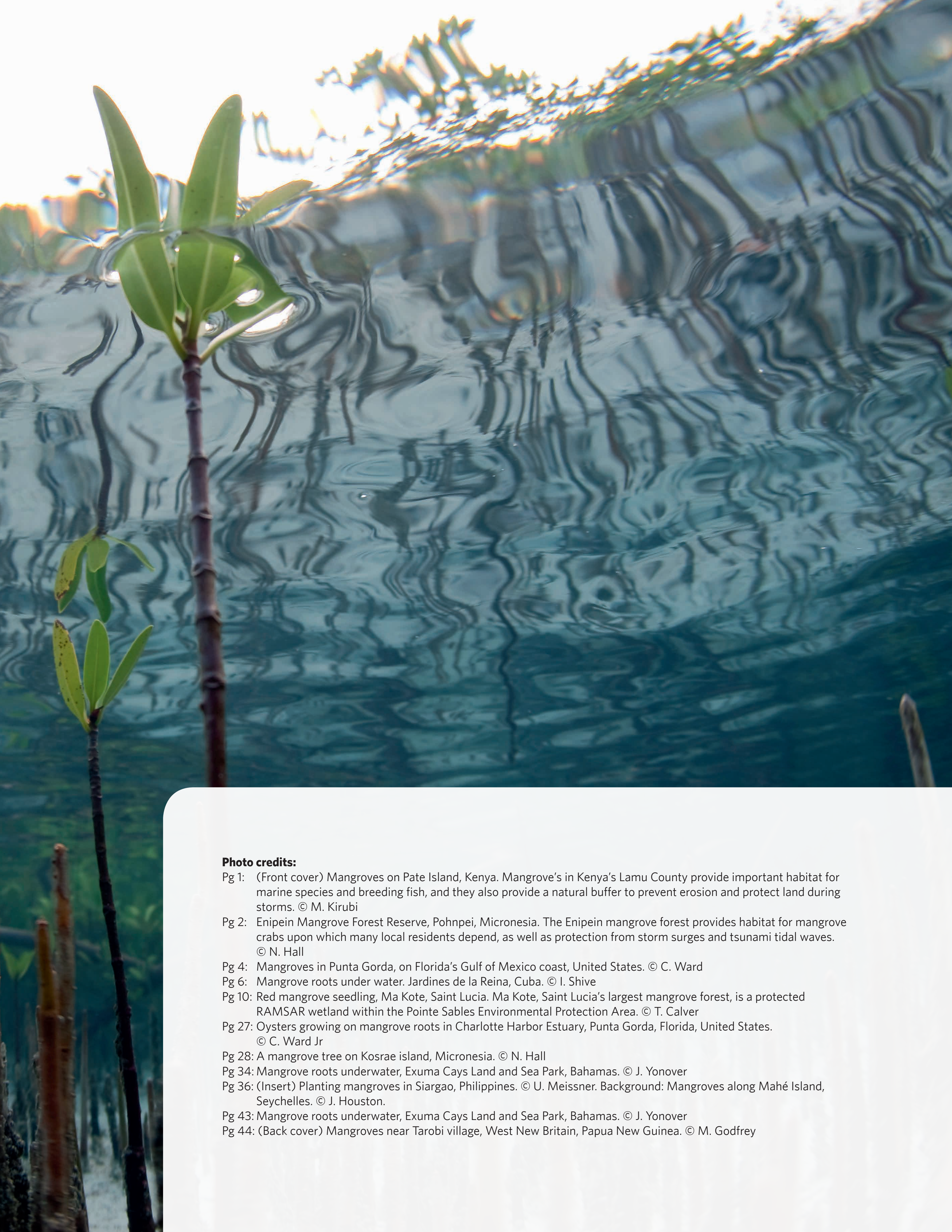

Photo credits:

Pg 1: (Front cover) Mangroves on Pate Island, Kenya. Mangrove's in Kenya's Lamu County provide important habitat for marine species and breeding fish, and they also provide a natural buffer to prevent erosion and protect land during storms. © M. Kirubi

Pg 2: Enipein Mangrove Forest Reserve, Pohnpei, Micronesia. The Enipein mangrove forest provides habitat for mangrove crabs upon which many local residents depend, as well as protection from storm surges and tsunami tidal waves. © N. Hall

Pg 4: Mangroves in Punta Gorda, on Florida's Gulf of Mexico coast, United States. © C. Ward

Pg 6: Mangrove roots under water. Jardines de la Reina, Cuba. © I. Shive

Pg 10: Red mangrove seedling, Ma Kote, Saint Lucia. Ma Kote, Saint Lucia's largest mangrove forest, is a protected RAMSAR wetland within the Pointe Sables Environmental Protection Area. © T. Calver

Pg 27: Oysters growing on mangrove roots in Charlotte Harbor Estuary, Punta Gorda, Florida, United States. © C. Ward Jr

Pg 28: A mangrove tree on Kosrae island, Micronesia. © N. Hall

Pg 34: Mangrove roots underwater, Exuma Cays Land and Sea Park, Bahamas. © J. Yonover

Pg 36: (Insert) Planting mangroves in Siargao, Philippines. © U. Meissner. Background: Mangroves along Mahé Island, Seychelles. © J. Houston.

Pg 43: Mangrove roots underwater, Exuma Cays Land and Sea Park, Bahamas. © J. Yonover

Pg 44: (Back cover) Mangroves near Tarobi village, West New Britain, Papua New Guinea. © M. Godfrey

This Technical Report, and its accompanying Summary Report, may be found at:
nature.org/GlobalMangrovesRiskReductionSummaryReport and **nature.org/GlobalMangrovesRiskReductionTechnicalReport**

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