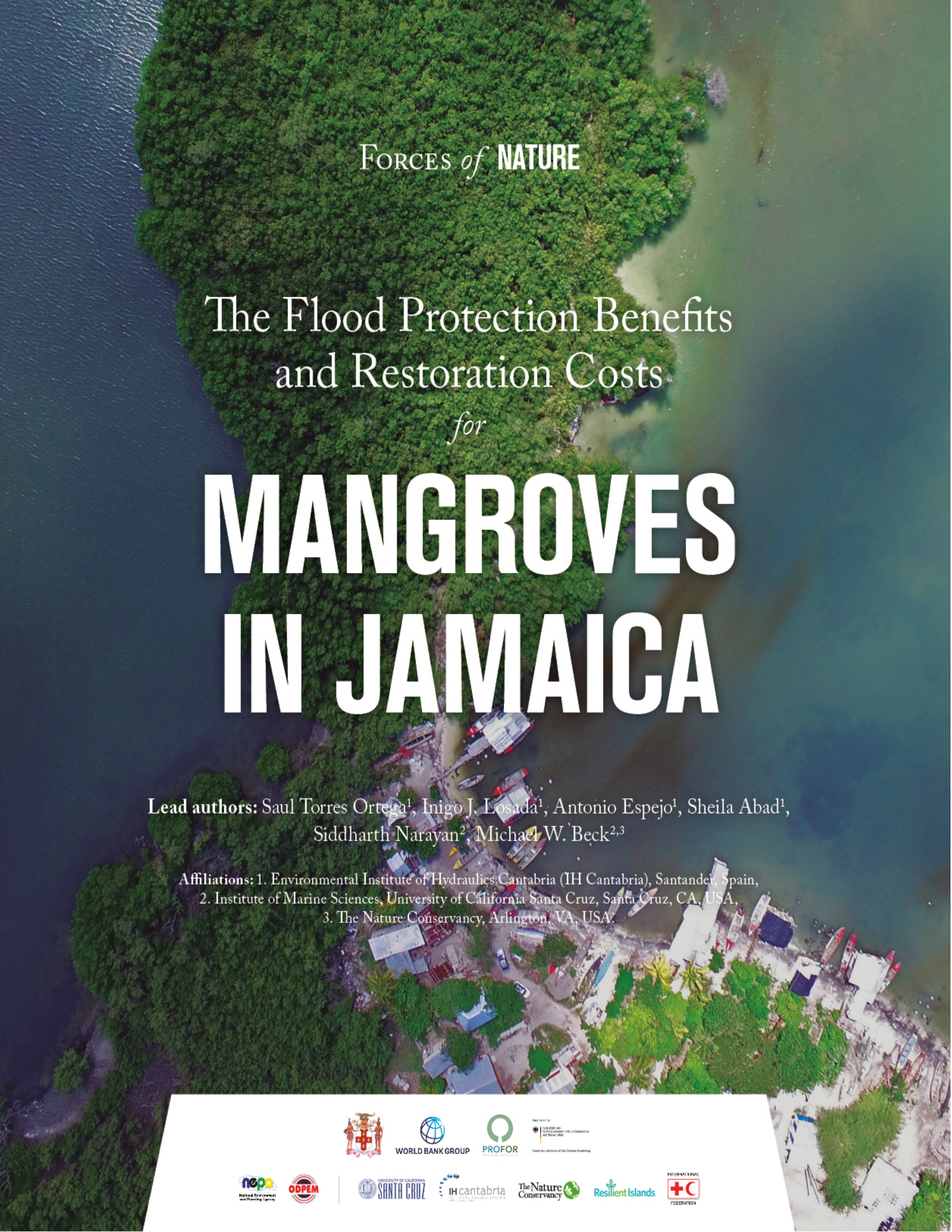

FORCES *of* NATURE

The Flood Protection Benefits and Restoration Costs *for* MANGROVES IN JAMAICA

Lead authors: Saul Torres Ortega[1], Inigo J. Losada[1], Antonio Espejo[1], Sheila Abad[1], Siddharth Narayan[2], Michael W. Beck[2,3]

Affiliations: 1. Environmental Institute of Hydraulics Cantabria (IH Cantabria), Santander, Spain, 2. Institute of Marine Sciences, University of California Santa Cruz, Santa Cruz, CA, USA, 3. The Nature Conservancy, Arlington, VA, USA.

WORLD BANK GROUP
PROFOR
UNIVERSITY OF CALIFORNIA SANTA CRUZ
IH cantabria
The Nature Conservancy
Resilient Islands
INTERNATIONAL FEDERATION

Acknowledgements

The *"The Flood Protection Benefits and Restoration Costs for Mangroves in Jamaica"* is one of the World Bank analytical products of the grant *"Assessment and Economic Valuation of Coastal Protection Services Provided by Mangroves in Jamaica"*, funded by the Program on Forests (PROFOR). This effort started in 2017 at the request of the Government of Jamaica through the National Environment and Planning Agency (NEPA), and the Office of Disaster Preparedness and Emergency Management (ODPEM). Numerous entities and professionals interested in the subject participated and an important group of collaborators made possible the materialization of this study. This analytical work is linked to the World Bank Jamaica Disaster Vulnerability Reduction Project (P146965).

The team especially wishes to thank the Program on Forests (PROFOR) for financing this product, and for the guidance and review provided by World Bank staff including Tahseen Sayed (Caribbean Country Director, LCC3C), Ozan Sevimli (Jamaica Country Manager, LCC3C), Sameh Naguib Wahba (Global Director, SURDR), Ming Zhang (Practice Manager, SLCUR), Valerie Hickey (Practice Manager, SLCEN), Werner Kornexl (Sr Natural Resources Mgmt. Spec, SEAE2), Garo Batmanian (Lead Environment Specialist, SENGL), Vanessa Velasco Bernal (co-Task Team Leader DVRP and Urban Development Specialist, SLCUR), Roland Bradshaw (Senior DRM Specialist, SLCUR), Eric Dickson (Senior Urban and DRM Specialist, SAF U2), Glenn-Marie Lange (Senior Environmental Economist, SENGL) , Alvina Elisabeth Erman (Economist, GFDRR), and Laura Ivers (Senior Communications Officer, SENGL).

Leading Authors and Editors

The *"The Flood Protection Benefits and Restoration Costs for Mangroves in Jamaica",* was supervised by a group of World Bank specialists in disaster risk management and natural resources comprised by Juliana Castaño-Isaza (Senior Consultant in Disaster Risk & Natural Resources Management, SLCUR) who provided overall leadership; and Simone Lee (Local Consultant, SLCUR), who coordinated this effort at the local level and provided invaluable technical inputs. Saurabh Dani (Task Team Leader DVRP, SLCUR) provided overall supervision and ensured alignment with the Jamaica Disaster Vulnerability Reduction Project.

The complete methodologies, data collection and analytics were led by a team of specialists from the University of California Santa Cruz (UCSC), the Environmental Hydraulics Institute (IH Cantabria), and The Nature Conservancy (TNC). These technical lead authors included:

Saul Torres Ortega[1], Inigo J. Losada[1], Antonio Espejo[1], Sheila Abad[1], Siddharth Narayan[2,] Michael W. Beck[2,3]

Government of Jamaica Leadership and Contribution

During the development of *"The Flood Protection Benefits and Restoration Costs for Mangroves in Jamaica",* invaluable support and leadership were provided by Andrea Donaldson, Anthony McKenzie, Ainsworth Carroll, Monique Curtis, Gabrielle-Jae Watson, and Kellie Gough, from the National Environment and Planning Agency (NEPA); and Anna-Kay Spaulding, and Michele Edwards from the Office of Disaster Preparedness and Emergency Management (ODPEM).

---

[1] Environmental Institute of Hydraulics Cantabria (IH Cantabria), Santander, Spain
[2] Institute of Marine Sciences, University of California Santa Cruz, CA, USA
[3] The Nature Conservancy, Arlington, VA, USA

Technical contributions were also provided by the Technical Working Group comprised of Stacey-Anne Preston (Jamaica Social Investment Fund), Johanna Richards (Water Resources Authority), and Howard Prendergast and Krystal Lyn (National Works Agency).

Additional Support:

The team would like to acknowledge additional support provided by the International Climate Initiative (IKI) and the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). In addition, it would like to recognize the contributions made by the IKI Resilient Island and Ecosystem-based Adaptation projects, and the Kingfisher Foundation.

The team would like to recognize the support provided by Cecilia De Santis (WB), Marcela Nandllely González (WB), Michelle Palmer (WB), Montserrat Acosta-Morel (TNC), and Natainia Lumen (TNC).

Finally, the team would like to express gratitude to Andrés Barragán, Mateo Zúñiga, Guillermo Torres, Diego Cobos, Felipe Caro y Sebastián Calderón from PuntoAparte., for translating complex scientific data into clear illustrations and infographics.

Rights and Permissions:

Suggested Citation: Ortega, S.T., Losada, I.J., Espejo, A., Abad, S., Narayan, S., Beck, M.W., 2019. The Flood Protection Benefits and Restoration Costs for Mangroves in Jamaica. Technical Report. World Bank, 2019.

Cover Photo: © Daniel Schwapp

Contents

List of Figures

List of Tables

Acronyms

ADCIRC	ADvanced CIRCulation
DVRP	Disaster Vulnerability Reduction Project
EDF	Expected Damage Function
FAO	Food and Agricultural Organization
FEMA	Federal Emergency Management Agency
GAR	Global Assessment Report
GMW	Global Mangrove Watch
GOJ	Government of Jamaica
GOW	Global Ocean Waves
IBTrACS	International Best Track Archive for Climate Stewardship
IH Cantabria	Hydraulics Institute, University of Cantabria
JMD	Jamaican Dollar
JRC-EU	Joint Research Commission – European Union
NEPA	National Environment and Planning Agency
POT	Peaks Over Threshold
RP	Return Period
RWC	Regular Waves Climate
TC	Tropical Cyclones
TCC	Tropical Cyclones Climate
TNC	The Nature Conservancy
TWL	Total Water Level
UCSC	University of California Santa Cruz
UNDRR	United Nations Office for Disaster Risk Reduction
UWI	University of West Indies
WB PROFOR	World Bank Program on Forests
WAVES	Wealth Accounting and Valuation of Ecosystem Services

Executive Summary

Jamaica, like other Caribbean and island nations is at high risk from coastal flooding and related hazards. Vulnerable coastal communities in Jamaica receive significant flood protection benefits from natural habitats like mangroves and coral reefs, even though these habitats are threatened by human development and activity and by natural stressors such as sea-level rise and climate change. As coastal flooding and habitat loss increase, there is great imperative among national disaster risk reduction agencies, conservation agencies and international aid institutions in Jamaica, to quantify the economic value of conserving and restoring mangrove habitats for risk reduction and to thereby inform national risk reduction, climate adaptation and conservation plans.

This Technical Report provides an ecological, economic and social assessment of the habitat status, risks, costs and flood protection benefits of mangroves in Jamaica with a focus on their role in coastal flood risk reduction. This work aims to support decisions for sustainable and cost-effective approaches for mangrove management and flood risk reduction. First, we assess the current status and recent trends in the distribution of mangroves in Jamaica. We then review the costs of restoration mangrove projects across Jamaica and the wider Caribbean. Using connected assessments, we consider the nationwide restoration potential for mangroves. We then focus on a rigorous nationwide assessment of flood risk and the risk reduction benefits of mangroves to people and property across Jamaica.

The core social and economic assessment in our report is on coastal flood risk and the value of mangroves for reducing this risk. The report follows approaches developed with the World Bank for assessing present flood risk and the benefits of mangroves for risk reduction. We combine probabilistic analysis of storm hazards across Jamaica with process-based modelling of coastal flooding and detailed exposure (people and built capital) datasets to provide some of the most comprehensive national flood risk assessments, with and without mangroves. We use state-of-art, high resolution hydrodynamic models, combined with the best available datasets of local storms, bathymetry, topography, land-use and mangroves, to quantify flood risk and annual expected benefits from mangroves. We estimate flood extents and annual expected flood damages by assessing flooding events of multiple return periods. We examine flooding and socio-economic exposure with and without mangroves across Jamaica using the 2005 mangrove map from the government of Jamaica as the habitat baseline ("current mangroves"). We also use satellite-imagery based mangrove data from 2013 developed by The Nature Conservancy and high resolution numerical modelling to assess the potential benefits of mangrove restoration at key sites where mangroves were lost.

We develop detailed and rigorous maps of present flood risk for Jamaica. These maps provide information on annual expected and catastrophic flood damages from tropical cyclones with and without mangroves nation-wide. These results are then augmented to assess the role of mangroves in reducing flooding for more frequent, non-cyclone flood events using more detailed hydrodynamic models in a few locations (Old Harbour Bay, Montego Bay).

Mangrove conservation and restoration can be an important part of the solution for reducing coastal risks. By valuing these coastal protection benefits in terms used by finance and development decision-makers, these results can be readily used to inform risk reduction, development and conservation decisions in Jamaica. Due to a recognition of the role of natural defenses in reduce these risks, the Government of Jamaica has committed to restoring mangroves as part of its risk reduction strategy and the World Bank's PROFOR program is helping the GoJ incorporate the value of mangroves into their disaster and risk management plans. Guidelines for including these

natural capital values within national accounting systems, specifically for flood risk reduction, have been piloted by the World Bank and others in the Philippines (Menendez et al., 2018). In Jamaica, the explicit valuation of natural defenses will allow the GoJ's agencies for disaster recovery, conservation and adaptation to identify and prioritize actions to restore and protect coastal ecosystems to reduce coastal risks to people and property.

Key Findings

- Mangroves currently cover approximately 9,800 hectares across Jamaica.
- More than 700 hectares of mangroves have been lost in recent decades
- More than two thirds of these lost mangroves are potentially restorable.
- Existing mangroves are threatened by a combination of human activity and climate change-related stressors such as sea-level rise and extreme high temperatures
- We assess and map (i) current flood risk and (ii) future flood risk if mangroves are lost across the storm frequency distribution (i.e., from small to large storms)
- In Jamaica, if the current mangroves were lost, over 10% more people, i.e. around 1,450 additional people, would be flooded annually many of whom live in poverty.
- If mangroves were lost damages to residential and industrial property would increase by nearly 24% by more than US $32.6 Million [JMD 4.38 Billion] annually.
- One hectare of mangroves in Jamaica provides on average more than US $2,500/year [JMD 336,000 / year] of direct flood reduction benefits from tropical cyclones; if considered over a 30-year period the average benefits per hectare for a mangrove conservation or restoration project would exceed $43,000 [JMD 5.78 Million] in coastal protection benefits alone.
- Of course, mangroves benefits are much higher than average in key populated areas. Some enumeration districts see benefits of exceeding US $10 Million [JMD 2.34 Billion] annually. In Hunts Bay, mangroves (200 ha) provide risk reduction benefits of over $1 Million annually; i.e., > $5,000/ha [JMD 672,000] annually or more than $86,000 [JMD 11/56 Million] over a 30-year period (with 4% discount).
- In Old Harbor Bay, mangroves lost between 2005 and 2013 have a flood protection value of nearly $1,000 /ha/yr. This value thus also represents the potential benefits from restoring mangroves that have recently been lost due to human activity.
- Based on a review of mangrove restoration projects, the costs of mangrove restoration in Jamaica are approximately $30,000 per hectare. This is a little higher than the average in other areas in the Caribbean. All of these values are based on a limited number of projects and costs can be expected to decline as projects and practice increases.
- The costs of hard infrastructure projects such as sea dykes and levees for coastal protection can exceed millions of dollars per km. Recent estimates of a sea dyke to protect Kingston Harbor exceed $10M/km.
- Mangroves provide the most protection for more intense storms of 100, 200 and 500 year return periods which cause significant flooding and damages. For example, during a 200-year storm, mangroves reduce the number of people flooded and avoid damages by nearly 50% throughout Jamaica.
- The results are presented in maps that show the spatial variation in national flood risk and mangrove benefits, which can inform (i) risk management and storm response and (ii) mangrove management, conservation and restoration.

Introduction

The 2011 and 2015 Global Assessment Report on Disaster Risk Reduction highlight that the risk of economic loss due to tropical cyclones, storm surge and floods is growing as the exposure of economic assets increases and the health of coastal ecosystems degrades (UNISDR 2011, 2015). Erosion, flooding, and extreme weather events affect hundreds of millions of vulnerable people, important infrastructure, and economic activity, and cause significant losses to national economies. The impacts of coastal hazards can be devastating to coastal economies, particularly those of small island nations. In 2017, insured losses from coastal storms reached an all-time high with greatest impacts and damages across the Caribbean and southeast USA (Munich Re 2018). In 1998, Hurricane Gilbert caused damages in St. Lucia exceeding 365% of the island's GDP. In 2004, the losses caused by hurricane Ivan in Grenada were more than twice the nation's GDP.

Jamaica – like much of the Caribbean region – is at high risk from coastal hazards due to its exposure to tropical storms, high levels of coastal development, and vulnerable coastal communities. Approximately 70% of Jamaica's population lives in coastal areas, and over 50% of its economic assets such as airports, harbors and tourism infrastructure are located on the coast (Richards, 2008). Between 1988 and 2011, 11 major storms made landfall in Jamaica, causing significant damages to people and property. In terms of current value, Hurricane Ivan in 2004 caused over US$ 0.5 Billion in damages, i.e., nearly 6% of national GDP. Since 2004, Jamaica has experienced 10 major hurricanes, including Hurricanes Irma and Maria in 2017, that have caused over US$ 2 Billion (JMD 250 Billion) in losses (Planning Institute of Jamaica, 2004; The World Bank, 2018). Such natural disasters remain a main risk to the country's economy and economic outlook with significant challenges for disaster recovery and re-development. Meanwhile, human coastal development and economic activity continue to increase across the country. Due to a recognition of these increasing risks, and of the potential role of natural defenses to reduce these risks, the Government of Jamaica has committed to restoring mangroves as part of its risk reduction strategy and the WB PROFOR program is helping the GoJ incorporate the value of mangroves into their disaster and risk management plans.

Coastal ecosystems such as mangroves act as natural barriers to waves and storm surges and help mitigate flooding by reducing wave energy and slowing down storm surges. In addition, mangrove forests help purify water, cycle nutrients, prevent shoreline loss and soil erosion, provide high quality fisheries habitat, offer recreational and educational opportunities and sequester carbon (Millenium Ecosystem Assessment, 2005). Despite these benefits to coastal communities, coastal ecosystems including mangrove forests continue to be lost and degraded. Globally, mangrove forests have seen area losses of about 35% (Valiela et al., 2009) to 50% (Feller et al., 2012) since original global recordings in the early 1980s. Their annual loss rate is about 2.1% from natural forces such as hurricanes and associated winds, and anthropogenic forces such as coastal development and aquaculture (Valiela et al., 2009). The loss of mangroves and coral reefs will result in the loss of their ecosystem services, and specific to coastal flooding, will result in an increase in flood damages to communities that are otherwise protected by these ecosystems.

Mangrove forests help reduce coastal flooding by acting as physical obstacles to the flow of water and waves. The dense roots and stems of a mangrove forest provide a drag resistance that is strongly related to wave reduction (Mendez and Losada, 2004). Increasing the area of mangrove forests can lead to more drag on incoming waves and storm surges, thus reducing the flooding that these waves and surges will cause inland. On average, mangrove forests can attenuate incoming wave heights by more than 30% and in some cases, almost completely (Narayan et al., 2016). Mangrove forests can reduce storm surges by 26-76% (Sheng et al., 2012; Zhang et al., 2012). Peak water level height can be decreased by 4.2 to 9.4 cm on average across multiple mangrove forest patches (Krauss et al., 2009). These reductions in physical water levels are translated into benefits to people, in terms of reductions in coastal flooding during storms and hurricanes. Mangroves on Florida's coastline reduced inland flooding due to the storm surge from hurricane Wilma by up to 70% (Zhang et al., 2012). In addition to their direct effects on water levels, healthy mangrove forests have the capacity to build land elevation and keep pace with sea-level rise (McIvor et al., 2013). As ecosystem-based adaptation measures, healthy mangrove forests provide the unique advantage of self-maintenance in this respect, unlike traditional structures such as levees which will require costly upgrades to maintain current standards of protection (Hinkel et al., 2014).

The economic value of the flood reduction benefits of mangroves becomes evident in situations where coastal people and property sheltered by these ecosystems experience reduced flood damages during storms. These risk reduction benefits of mangrove forests have been demonstrated in several places around the world (Losada et al., 2018; Menéndez et al., 2018a). Importantly, the value of this risk mitigation service can be rigorously quantified to estimate the economic benefits of actions to conserve and/or restore coastal ecosystems that act as natural defenses, as shown in a comprehensive assessment of mangrove risk reduction values recently completed by our team for the Philippines. This report shows that across the Philippines mangroves protect over 613,000 people from flooding and avoid damages of US $1 billion annually (Losada et al., 2017).

Yet these vital habitats continue to be lost and degraded, with little consideration of their role as coastal protection alternatives, and with significant consequences for vulnerable coastal populations. Often, the loss of these habitats is greatest around large populations, i.e., the places were the impacts of coastal degradation are greatest, and where the most people stand to benefit from coastal ecosystems. Sixty percent of the world population is expected to live in urban areas by 2030, with greater concentration around coastal areas. This means that rates of coastal development will be increasing with heavy investments in coastal infrastructure and potential of loss of more coastal habitats. Despite their economic value for risk reduction and other ecosystem services, Jamaica's coastal ecosystems – including coral reefs, mangroves and seagrasses – are threatened and continue to be lost. Since the early 1970s, coral reefs off Jamaica's coastline have declined in coral cover from 52% to just 3% (Richards, 2008) and remain threatened (NEPA, 2013). While high quality national data on mangrove extents are scarce, surveys and imagery analyses by the Government of Jamaica (GoJ) show that mangrove extents increased from ~9700 hectares in 1997 to ~11,600 hectares in 2010 and then declined to ~9,800 hectares in 2013 due to human activity (FAO, 2005; NEPA, 2013).

To assist countries like Jamaica in valuing their mangrove risk reduction services, the WAVES Policy and Technical Experts Committee commissioned the development of guidelines for assessing and valuing coastal protection services of mangroves, seagrasses and coral reefs. The Nature Conservancy, UCSC and partners led this work with the World Bank and developed "Guidelines for measuring and valuing mangroves and coral reefs" (from now on referred to as Guidelines) (Beck and Lange, 2016). The Guidelines recommend using process-based approaches, and in particular the Expected Damage Function approach, for spatially explicit valuation of the coastal protection services from mangroves. The Expected Damage Function is adapted from approaches commonly used in engineering and insurance to assess risks and benefits.

To assess the coastal protection services of mangroves, this Report follows a five-step methodology recommended by the World Bank (Beck and Lange, 2016) (Figure 1). The five steps involve: estimation of offshore dynamics related with the regular and tropical cyclone climate; estimation of nearshore dynamics; analysis of the influence of habitats; estimation of coastal impacts with and without habitats; and estimation of the resulting flood damages to people and property. The methodology evaluates the protective services of the habitats – in this case, mangroves –in terms of avoided flood damages to people and property. These methods have been applied in two previous projects, to assess the value of coral reefs for coastal protection globally (Beck et al., 2018), and to assess the value of mangroves for coastal protection in the Philippines (Losada et al., 2017, Menendez et al. 2018). In this Report, we expand on these methods and apply more advanced process-based models at a smaller geographical scale.

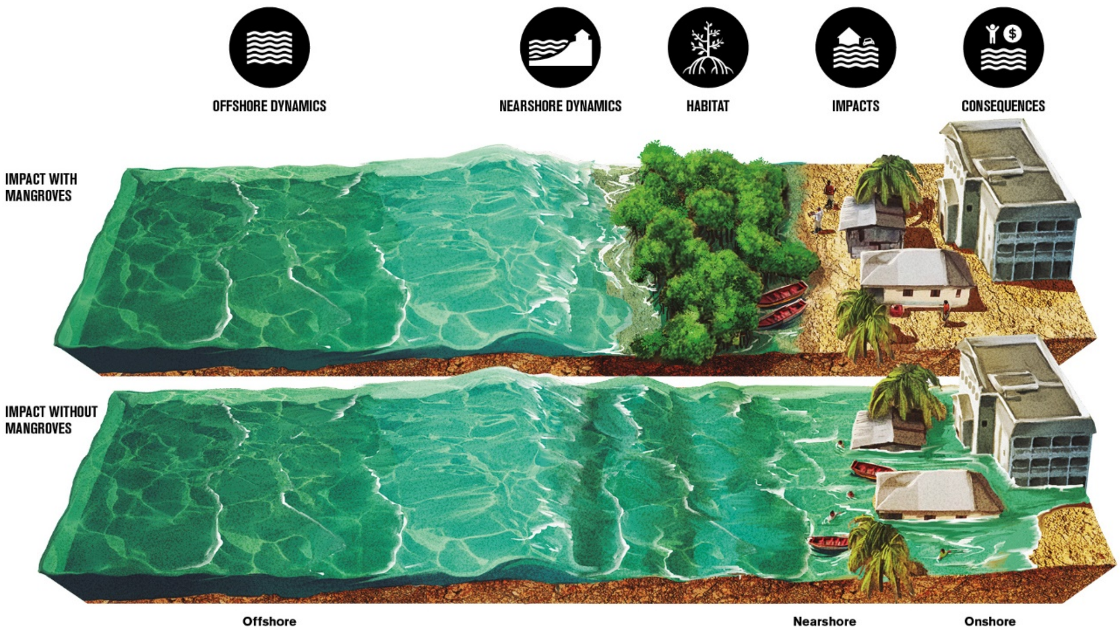

Figure 1: Mangroves prevent erosion and reduce the force of waves, storm surge and flooding.

Mangrove Habitat Status Assessment

Coastal mangroves in Jamaica today cover an area of around 9,800 hectares as per the latest estimate in 2013, 82% of which are found on the country's southern coastline. These mangroves are typified by a low diversity of species with *A. germinans* dominating. Mangroves are estimated to make up less than 3% of Jamaica's total forest cover (Government of Jamaica, 2017).

In general, there is very limited data on the spatial extents of mangroves since mangroves in Jamaica are typically classified and counted together with fresh-water 'swamp' forests and only recently have mangrove extents been recorded separately (NEPA, 2013). Though data on individual wetlands exist, there is little documentation of long-term trends in the extent, status and health of Jamaica's mangroves (Henry et al., 2018). FAO (2005) indicates, based on expert input, that in the 1970's that mangroves might have extended across more than 15,000 hectares in Jamaica. Estimates of mangrove extents since then vary a lot but it appears that by approximately 2000 mangrove extents fluctuated around 10,000 hectares based on multiple surveys and using different techniques (FAO, 2005; NEPA, 2013). These changes are however relatively recent and are built on a long history of mangrove loss and degradation nationally. Prior to 1997, mangroves in Jamaica were cleared or converted for other land-uses, often in irreversible ways (McDonald et al., 2003).

Mangrove losses and gains across Jamaica are however not spatially uniform, with some areas seeing significant losses and other coastlines witnessing gains (Figure 2). For example, Jamaica's southern coastline has seen some increases in mangrove cover in recent years for example, in the protected region of the Negril Great Morass. Mangrove extents however declined in two southern coastal parishes – St. Catherine and Clarendon – by over 40% (Mandal et al., 2019). Recently, Worthington and Spalding (2019) assessed the global change in mangrove distribution with satellite derived data from surveys in 1996 and 2016 and used these to assess the potential for mangrove restoration in areas of loss. This report estimates that more than 770 hectares of mangroves have been lost in Jamaica over the past two decades. While these analyses are conducted at a global scale, they nonetheless are very useful for showing the broad patterns of change across Jamaica (Figure 3). Not surprisingly, mangrove losses are highest in the southern parishes of St. Elizabeth, Clarendon and St. Catherine and in the parish of Trelawny in the north (Worthington and Spalding, 2019). Mangrove losses are lowest in the St. Thomas Morass in the east and in the mangrove forests of Westmoreland in the west.

Coastal development has been the main driver of mangrove loss across Jamaica. In the north of the country residential and tourism development have probably contributed the most to mangrove loss whereas in the south, port and industrial development has contributed substantially to losses (FAO, 2005; Spalding et al., 2010). Some mangroves have been lost to the expansion of agriculture. Pollution particularly in the greater Kingston area has also contributed to loss and more importantly degradation of mangrove habitats (McDonald et al., 2003). There have been additional impacts from more local activities such as the harvest of wood for charcoal. The losses of mangroves to development in Jamaica are in contrast to mangrove losses in other countries, which are often driven by expansion of shrimp aquaculture. These differences also have implications for mangrove restoration potential: areas lost to aquaculture are easier to restore than those lost to development such as airports.

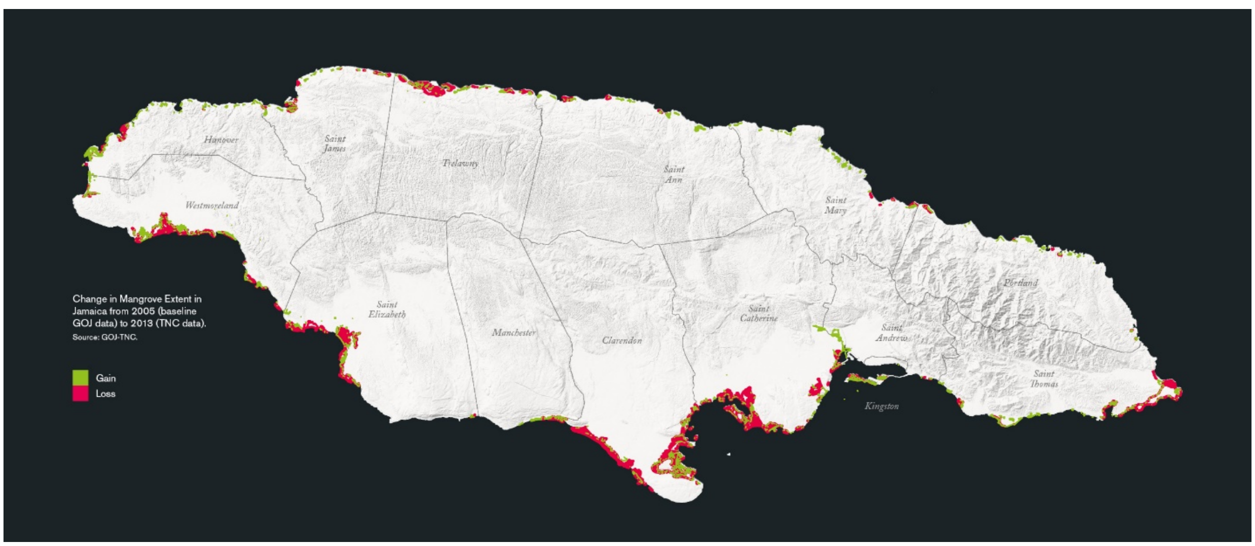

Figure 2: Change in Mangrove Extent in Jamaica from 2005 (baseline GOJ data) to 2013 (TNC Data).

Assessing historic mangrove loss and current mangrove extents are important for understanding where future restoration may be most feasible. Recently available data for multiple epochs between 1996 and 2016 from Global Mangrove Watch (https://www.globalmangrovewatch.org/; Bunting, 2019) show changes in global mangrove extents between 1996 and 2018. In the future these will allow for much wider consideration of changes in mangroves although they will not usually be as detailed as maps developed within and by specific countries.

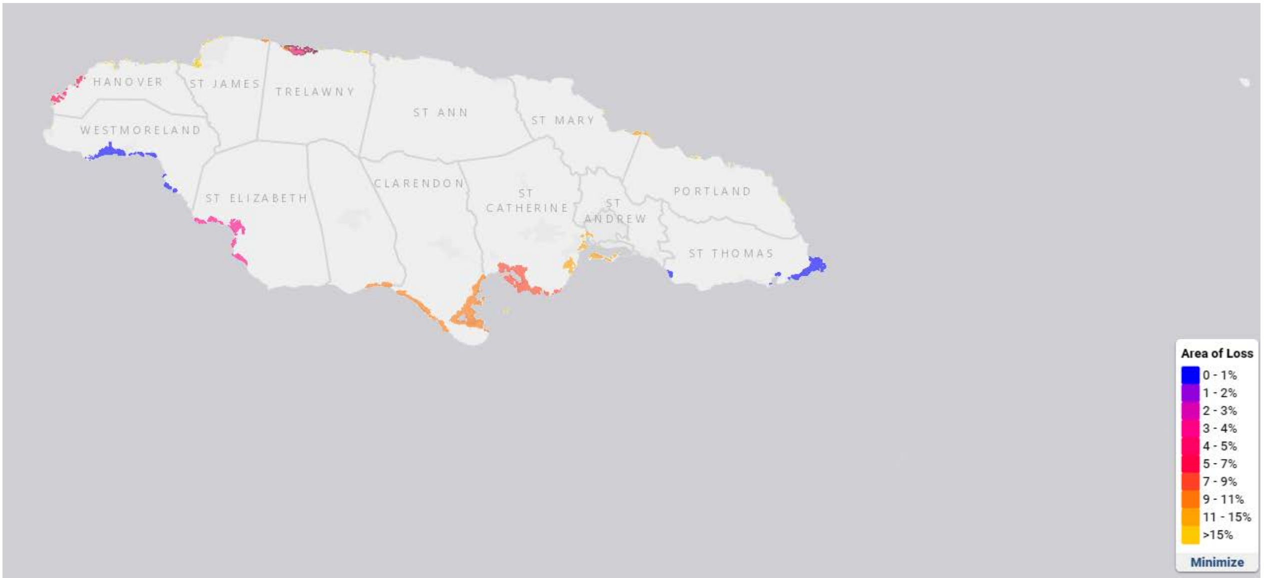

Figure 3: Change in Mangrove Extent in Jamaica from 1996 to 2016 from Worthington and Spalding (2019).

Mangrove Habitat Risk Assessment

The reasons for the loss and degradation of Jamaica's mangrove forests are multiple. In addition to coastal protection, which has not been valued rigorously so far, Jamaica's mangroves also provide other ecosystem services that are critical to local communities. These services include timber supplies for construction and daily-use and artisanal products, small-scale farming, and firewood. As a result, these forests are threatened in some areas due to over-exploitation of resources. Other, more extreme, threats to mangrove forests, particularly on the northern coastlines, include mangrove clearing for private and commercial housing and hotels. The government of Jamaica includes mangroves together with other wetlands as "swamp forests" which have experienced a 95% loss since 1998, primarily due to clearing for agriculture, buildings and infrastructure, and shifts to herbaceous wetlands (GoJ, 2017). In addition to direct human impacts, mangrove forests in Jamaica are expected to be affected by climate change. In general, adverse impacts to mangroves from climate change include increases in sea-level, frequency and/or intensity of storms, temperature and aridity (Gilman et al., 2008; Jennerjahn et al., 2017). The combination of current stressors means that there are present losses of mangroves in Jamaica and in other regions of the Caribbean and reduces their resilience and ability to manage and recover from the combined effect of future stressors particularly from changes in sea-level, storminess, rainfall and drought (e.g., Cortés et al., 2019).

The future health of mangroves in Jamaica, in the absence of targeted action to conserve or restore these forests, depends to a large extent on how easily accessible the forest is to human use and activities (McDonald et al., 2003). One example is the St. Thomas Great Morass in eastern Jamaica that covers around 1660 Ha (Henry et al., 2018). This area of mangrove forests has remained relatively undisturbed due to its remoteness from urban regions. Yet, even in this region a variety of human uses potentially threaten the mangrove forests particularly if they are not well managed. Common human activities of mangrove forests in the region include grazing of cattle and other livestock, subsistence agriculture, charcoal production and construction from mangrove wood and timber, and subsistence fishing in the canals and rivers (Henry et al., 2018).

The risk to mangrove forests from humans also extends to indirect impacts that can occur in the absence of direct activities like extraction or deforestation. For example, shoreline hardening using artificial structures and developing coastlines with hard barriers can increase the vulnerability of mangroves to sea-level rise by preventing landward mangrove migration – a process commonly known as 'coastal squeeze' (Doyle et al., 2010; Krauss et al., 2011). Increases in the frequency of droughts and reduced rainfall, related to extreme El Nino events in the Caribbean, can further impact mangroves by limiting sediment supplies (Galeano et al., 2017). Another indirect human impact is pollution from human activity, such as outfalls from waste-water treatment plant or waste from construction activities that can cause already stressed mangrove habitats to either degrade or be completely lost, and negatively impact their ability to recover after natural stressors such as a hurricane or drought (Mott McDonald, 2007).

Mangrove forests in Jamaica and in rest of the Caribbean are also likely to be impacted by three major factors in addition to coastal squeeze: higher storms, increases in temperatures and reductions in rainfall during the wet season (Ward et al., 2016). While mangroves in the Caribbean appear to be keeping pace with current sea-level rise rates of 1 to 2.5 mm/year this may not remain the case with accelerated sea-level rise in the future (McKee et al., 2007).

Mangrove forests in Jamaica and elsewhere have been observed to be damaged by hurricane events and this damage is likely to increase in the event of hurricanes of higher intensity or frequency (e.g., Doyle et al., 1995). Yet, recent evidence from hurricane-impacted mangroves in the Philippines and elsewhere, indicates that these mangroves can equally recover from hurricanes over time-spans of few years to a couple of decades (Baldwin et al., 2001; Imbert, 2018; Sherman et al., 2001).

As the value of these habitats to humans, in terms of coastal protection and other critical ecosystem services is recognized, the GoJ is moving towards active plans and measures to conserve and protect Jamaica's remaining mangroves. Since 2005, the GoJ has protected multiple mangrove sites, mostly in the southern parishes. The recent National Forest Management and Conservation Plan (Government of Jamaica, 2017) explicitly recognizes mangrove restoration as a priority for national climate adaptation plans. The GoJ and the World Bank Program on Forests (PROFOR) are now working to assess and evaluate the economic value of coastal protection provided by mangroves in Jamaica, linked to their ongoing Disaster Vulnerability Reduction Project (DVRP).

As part of their global assessment on mangrove change, (Worthington and Spalding, 2019) have developed with our assistance a restoration potential score for mangroves globally including for those in Jamaica (Figure 4). The analysis considers factors such as land use, sea level rise and sediment availability and identifies the likelihood that mangroves lost over the past two decades could be restored. With the caveat that this is a general and global analysis, this report estimates that more than 770 hectares of mangroves have been lost in Jamaica over the past two decades but more than 70% of these mangroves could be potentially restorable.

Habitat restoration is not necessarily simple, but of all marine ecosystems, mangroves are the most restorable. Mangroves are opportunistic and given the right settings, they can thrive. Hundreds of thousands of hectares of mangroves have been successfully restored around the world and best practices are now well known. What is critical is to ensure that the location is restored in terms of elevation and water flows and that the social and political framework is secure against those impacts that caused their original loss, with clear ownership and regulations for the restoration locations.

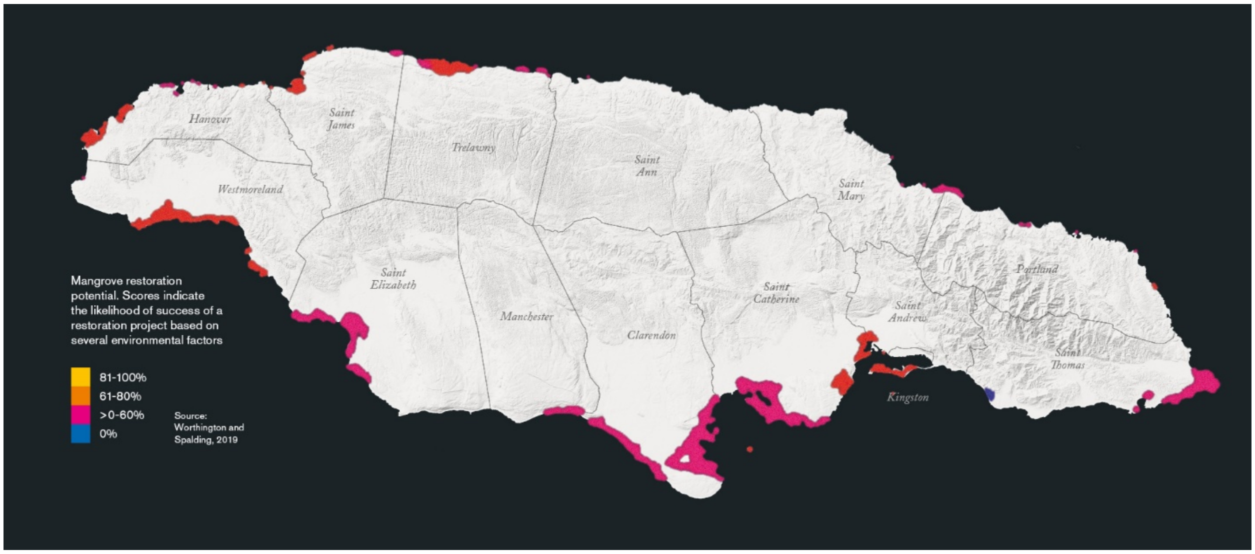

Figure 4: Mangrove restoration potential. Scores indicate the likelihood of success of a restoration project based on several environmental factors (Worthington and Spalding, 2019)

Mangrove Habitat Cost-effectiveness Assessment

Mangrove habitats, along with coral reefs and other coastal habitats provide significant economic value to nations and coastal communities in Jamaica, the Caribbean, and globally in terms of coastal protection, carbon sequestration, tourism and fisheries benefits (Beck et al., 2018; Kauffman et al., 2014; Menéndez et al., 2018b; Schuhmann and Mahon, 2015). Jamaica's mangrove forests provide US $32.6 Million [JMD 4.38 Billion] in flood risk reduction benefits every year. These are in addition to the billions of dollars in other ecosystem services such as tourism, carbon sequestration, fisheries, timber and firewood that are critical for enhancing the resilience of coastal communities (Heck et al., 2019; Edwards, 2019).

The coastal resilience benefits of mangroves are well recognized though less is known about how the cost-effectiveness of these habitats, i.e., how the benefits of restoration compare to the costs. This lack of knowledge can hinder investments in restoration for coastal resilience and risk reduction. Today, the Government of Jamaica, like several other national, regional and global institutions including the Caribbean Biodiversity Fund (CBF), the World Bank and the International Federation of the Red Cross and Red Crescent Societies explicitly recognize the economic payoffs of investing in restoring mangrove forests for disaster recovery, climate adaptation and conservation (Barbier et al., 2011; Daily, 1997; Hagger et al., 2017; Menz et al., 2013). These institutions are increasingly focusing on the returns on investment of a project as a means to inform where to prioritize investments in restoration efforts (Barbier et al., 2018). As a result, mangrove restoration projects are often focused on specific ecosystem service benefits such as carbon sequestration or coastal protection (Narayan et al., 2016; Wylie et al., 2016). Yet, poor understanding of the costs of mangrove restoration can limit investments in mangrove restoration for coastal resilience. Meanwhile, the continued loss and degradation of these habitats (cf. Section Habitat Status/Risk) has a direct impact on coastal populations in Jamaica due to a loss in coastal protection and other vital ecosystem service benefits.

Globally, hundreds of thousands of hectares of mangroves have been restored over the last several decades, though information on their costs or the factors driving their costs is limited. In Jamaica, mangrove restoration projects totaling a few hundred hectares have been implemented, or are being implemented, over the last decade. These projects are however not as large in scale as restoration efforts in countries like Vietnam, Bangladesh, the Philippines or Guyana (Beck and Lange, 2015). Typically, these restoration projects involve either active planting of mangrove saplings in areas with degraded or lost mangroves, or hydrological restoration to establish the right conditions for mangrove establishment (Lewis, 2001; Primavera et al., 2012).

In this report, we describe the costs of mangrove restoration in Jamaica and across the wider Caribbean region. We also identify factors that are particularly important in determining the costs of mangrove restoration projects. We additionally compare mangrove restoration costs in Jamaica to the costs of reef restoration and of other coastal protection alternatives like sea dikes and levees. In total we assess data from 137 mangrove restoration projects world-wide, including 72 projects from the Caribbean (Narayan et al., 2019). We also assess data from 58 coral reef restoration projects and 28 artificial coastal structures. These data are obtained through a systematic literature review of the reported costs of mangrove restoration projects in Jamaica and the Caribbean region, and the costs of coastal protection structures in Jamaica, using the Google Scholar, Web of Science, Scopus, and Google search engines. For mangrove restoration costs we extend and build on the data provided by the comprehensive review conducted by Bayraktarov et al., (2016). In addition to the literature review we reached out to relevant government and other institutions in Jamaica and the Caribbean for data on project areas, locations and costs, and any site-specific factors that would influence these costs. All cost data were combined with information on project area to obtain a cost per hectare. For linear coastal protection structures and coral reefs, these cost data were combined with information on the length of the structures to obtain a cost per linear kilometer (i.e., a cost per hectare for an assumed structure width of 10 meters).

Mangrove restoration costs less than $50,000 per hectare [JMD 6.7 Million] across the Caribbean region though data on costs are limited. In Jamaica two such projects report costs of $32,000 per hectare [JMD 4.3 Million], and over 70% of these costs are attributable to fencing needed to protect the restoration site. Restoration costs across the wider Caribbean are generally comparable and vary from around $23,000 per hectare [JMD 3.1 Million] in countries like Guyana to around $14,000 [JMD 1.88 Million] in Grenada. The costliest location in the Caribbean region for mangrove restoration is Florida, with median costs being as high as $45,000 [JMD 6 Million] and extremely variable.

Mangrove restoration in Jamaica, and globally, is multiple orders of magnitude cheaper than coastal protection structures. In Jamaica, limited data indicate that sea-dykes and levees to protect the Kingston Harbor can cost over $11 Million [JMD 1.48 Billion] per linear kilometer (Nakka, 2010). Generally, across the Caribbean, seawalls and levees can cost up to ~$6 Million per kilometer [JMD 806 Million], whereas offshore breakwaters are much costlier at ~$20 Million per kilometer [JMD 2.6 Billion], though typically, these projects are smaller than a few hundred meters. Mangrove restoration is also typically cheaper per hectare than coral reef restoration. Reef restoration costs $640,000 per hectare [JMD 86 Million] in Jamaica and more than $1 Million per hectare (median) [JMD 134 Million] in other areas across the Caribbean region is over. Similar to offshore breakwaters, typical cost data for reef restoration projects are from projects smaller than a few hundred meters.

In general, the factors influencing the costs of mangrove restoration projects are four-fold: i) the costs of land and permitting; ii) the costs of obtaining and transporting the material; ii) the costs of designing and constructing the project, and; iv) the costs of monitoring and maintaining the project post-construction (Narayan et al., 2019). Since mangrove restoration typically happens in the inter-tidal zone, the availability and price of land and the necessary permits. Another factor that influences costs is the restoration technique. Restoration by planting mangrove saplings manually can be cheap if these projects make use of local, voluntary labor. Projects involving hydrological restoration can be more expensive due to the need for specialized equipment, labor and the purchase and transportation of sediment. Maintenance and monitoring is also an important cost component, though often not reported in restoration projects.

The factors influencing the costs of coastal protection structures are broadly similar to the factors for mangrove restoration projects. Typically, coastal structures like seawalls and levees take up less space than a mangrove restoration project, though the taller a structure, the more space it generally requires, and the costlier it becomes (Aerts, 2018; Ward et al., 2017). Coastal protection structures can also be costly to build in terms of material, labor and expertise; and costly to maintain in terms of repairing damage or upgrading in response to changes in sea-level. Offshore structures such as sea dykes or breakwaters are typically costlier due to more difficult working environments.

Coastal Protection Ecosystem Services Assessment: Methods

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 (Beck & Lange, 2016). Coastal flooding is the result of the interaction of a hazard represented by a flood height or Total Water Level (TWL) at the shoreline with coastal and inland topography and features. The spatial extent of this flooding is represented using flood maps and is used to estimate the extent and severity of damage to people and property. Producing these maps first requires information on the total water level at the coastline, which is therefore one of the most relevant components of this work. In this study, the TWL at the shoreline is estimated as the combination of multiple water level components including the mean water level, tides, storm surge and water level contributions from wind-driven waves (run-up/setup) (Figure 5).

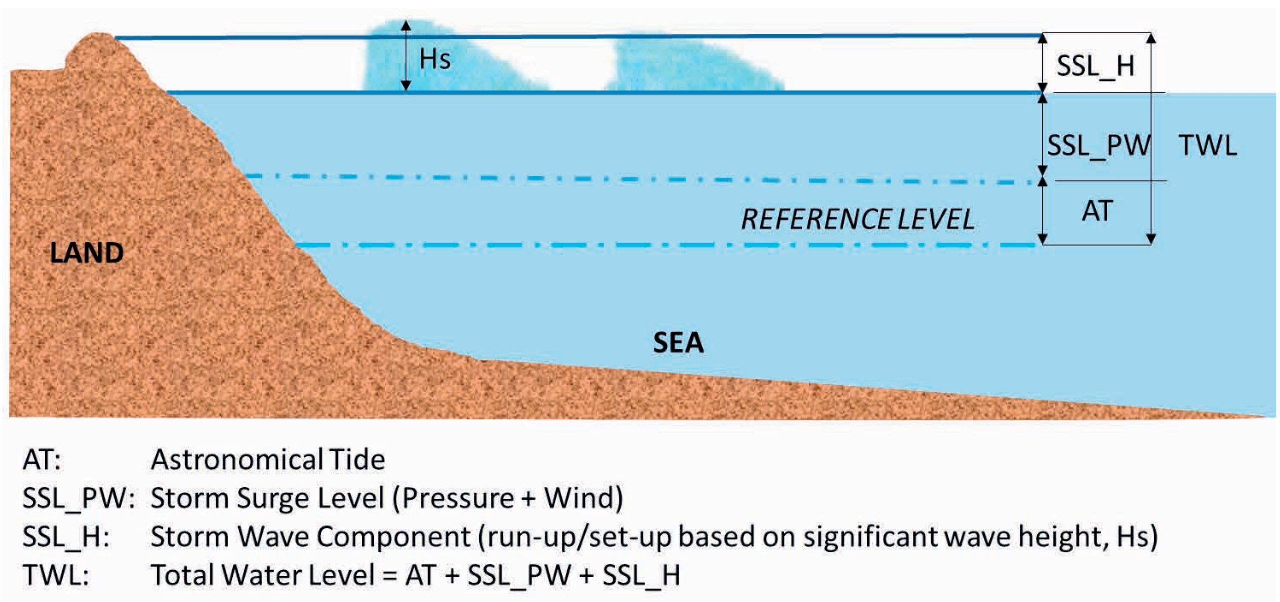

Figure 5: Definition of flood height or total water level as the combined effect of mean water level, astronomical tide, storm surge (tropical cyclones) and waves (set-up/run-up)

In this work, the flood risk reduction benefits of mangroves are evaluated at the national scale for Jamaica and using improved, higher resolution models in two local sites. The national analysis is addressed by performing numerical simulations of a number of historical and synthetic hurricanes (hereafter referred to as Tropical Cyclone Climate or TCC) based on a highly accurate topo-bathymetric model. Coupled wave-hydrodynamics are resolved in a 2D finite element mesh where the effect of the mangroves on the flow is introduced as a resistance of the water flow by means of the Manning coefficient. This resolves the processes that contribute mostly to the storm surge (i.e. atmospheric set up due to wind and pressure deficit and steady wave set up). At the local scale, there are still processes such as the surf beat and infra-gravity wave resonance that may be relevant in tropical coastal environments (Pearson et al., 2018). Also, wave-driven flooding hazards on coral reef-lined coasts is commonly the result of extreme water level events that are not related meteorologically to tropical cyclones, and commonly known as "sunny-day" events (Hoeke et al., 2013) (hereafter referred to as Regular Wave Climate or RWC). In either case (i.e. TCC or RWC), when these waves encounter an obstacle in the form of a coral reef or mangrove forest, they usually undergo significant transformation due to vertical variations in bathymetry or forest structure. Thus, at the local level, the study uses a model that is able to account for different groups of waves and for vertical variations in the structure of a mangrove forest. This model is nested within the national model to examine localized water level and flooding effects at the two sites.

We examine flooding and socio-economic exposure with and without mangroves across Jamaica using the 2005 mangrove map from the government of Jamaica as the habitat baseline ("current mangroves"). We also use satellite-imagery based mangrove data from 2013 developed by The Nature Conservancy to inform further analyses on the potential benefits of mangrove restoration at key sites where mangroves were lost compared to the baseline.

The national scale analyses of mangrove benefits for TCC is analyzed using state-of-the-art numerical models ADCIRC+SWAN (Dietrich et al., 2012). The ADCIRC (ADvanced CIRCulation) model solves the depth averaged barotropic form of the shallow water equations. SWAN computes the wind generated waves, the radiation stresses and their gradients in the same unstructured mesh, and then passes those gradients as a forcing function to ADCIRC. One of the main strengths of the ADCIRC+SWAN model is the ability to work with unstructured meshes, with very fine resolution near the coast and much coarser resolution in open waters. Such a high resolution allows a realistic representation of the coastline and hence a better estimation of the storm surge and waves. Due to their efficiency working in large domains (hundreds to thousand km's) these models are the most appropriate to model long lasting tropical cyclones (days to weeks). The assessment of tropical cyclones for the TCC analyses is approached from a probabilistic perspective at the national scale, consisting of 6 steps:

- Step 1: Collection from the International Best Track Archive for Climate Stewardship IBTrACS database of the historical tropical cyclones that have affected Jamaica, and statistical characterization of their tracks and intensities. These data are used to generate a large number of synthetic tropical cyclone events via Monte Carlo simulations, which is a technique used to understand the impact of risk and uncertainty in prediction and forecasting models. By means of this technique the historical record is extended toward 5000 years, what allows studying the protective function of the mangroves at national scale from with a probabilistic approach. From the large number of generated TCs, and due to computational efficiency, a comprehensive selection of the tropical cyclones to be simulated with the hydrodynamical and wave model is carried out. In this study, the analysis has focused on those tropical cyclones exceeding Category 1 (i.e. maximum winds ≥ 64 kt).
- Step 2: Generation of the wind and sea level pressure associated to each tropical cyclone as forcing of the hydrodynamic and wave model.
- Step 3: Modeling the selected tropical cyclones using the ADCIRC+SWAN modeling suite with and without mangroves.
- Step 4: Extreme value analysis of the flood height along all emerged points of the computational mesh for both scenarios and calculation of the flood height maps associated to different return periods.
- Step 5: Calculation of flooding consequences on population and built stock or property using an expected damage function approach for both scenarios.

The local scale analyses for RWC are conducted at two sites in Jamaica using an advanced numerical model, XBeach. The XBeach model can take into account the effect of wave and flow damping due to vegetation (Roelvink et al., 2015). It is mostly applied for relatively short (hours to days) and medium-scale (few km's) applications. XBeach computes the propagation of wind-generated waves by itself and computes these waves on the scale of wave groups. Furthermore, XBeach computes the infragravity wave component which is important in reef-lined coasts (Pearson et al., 2018). The RWC analyses at the local scale is tackled following a four steps approach:

- Step 1: Statistical characterization of the offshore dynamics from the GOW II wave reanalysis (Perez et al., 2018). The extreme value distribution of the significant wave height (Hs) is determined on the closest point in front of the local sites.
- Step 2: Modeling the selected return periods using the surfbeat mode of XBeach with and without mangroves.
- Step 3: Calculation of flood heights and corresponding flood maps at mangrove protected areas.
- Step 4: Calculation of flooding consequences on population and built stock or property using an expected damage function approach for both scenarios.

Figure 6 summarizes the methodological approaches for the two analyses. To allow model comparison across the two scales, the local XBeach model also simulates storm conditions associated with different return periods of the TCC. This additional analysis can shed light on the validity of the assumed simplifications for the national scale and will help validate the national scale results.

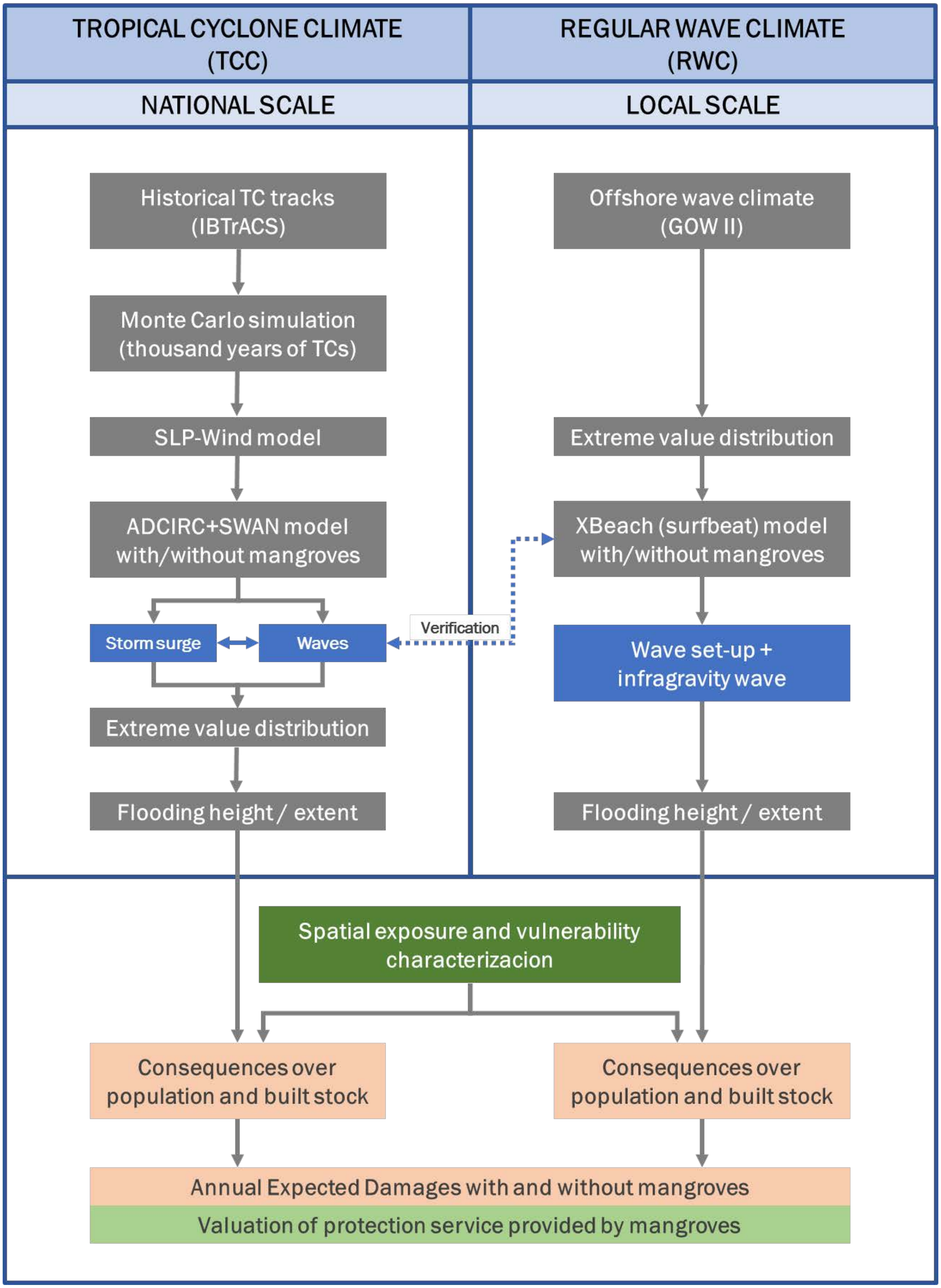

Figure 6: General scheme of the methodology.

For these analyses, we use the highest resolution datasets available at the national scale for storm and wave climate, coastline, topography, bathymetry, mangroves, asset exposure and damage functions (Table 1). Due to the paramount importance of the topo-bathymetry for simulation storm surges, a topo-bathymetric model has been built based on the best available sources, Figure 7. The bathymetry is built by the integration of ETOPO1 (1km x 1km resolution) from deep water to 500 m water depth, NAVIONIC nautical charts from 500 m to 25 m water depth and satellite information derived from LANDSAT images (10 m x 10 m resolution) from 25 m to 0 m water depth.

Topography comes from stereoscopic images acquired by IKONOS, with 6 x 6 m resolution and provided by the Government of Jamaica. Finally, the coastline is defined with a 10 m resolution from OpenStreetMapData, http://openstreetmapdata.com/data/coastlines. The bathymetry and topography are then merged at the coastline (Figure 7). As can be seen in Figure 7 there is no interruption between the under-water bathymetry and the topography above water. The Landsat derived bathymetry also allows an improved representation of the coral reef cover with a 10 m x 10 m spatial resolution.

Information on socio-economic exposure is obtained from different sources, combining 250m resolution population spatial distribution from GHSL-JRC and Jamaica National Census, and 1km resolution GAR17-UNISDR for the characterization of built capital. Vulnerability functions are based on functions provided by the European Union's Joint Research Commission (JRC; Huizinga 2017).

Table 1: Datasets used to estimate mangrove coastal protection benefits in Jamaica

Component	Databases	Variables	Spatial Resolution	Temporal Resolution	Time Length
Coastline	OpenStreetMap	Global coastline shapefile	10 m	--	--
Bathymetry	1. LANDSAT-derived (IHC) (0 to 25 m depth) 2. NAVIONIC nautical charts (25 to 100 m depth) 3. ETOPO1 (>500 m depth)	Bathymetry derived from various sources and combined	10 x 10 m 1 x 1 km	--	--
Topography	IKONOS images (Govt. of Jamaica)	Elevation raster	6 x 6 m	--	--
Mangroves (baseline)	Government and Jamaica	National mangrove extent shapefile	--	2005	2005
Mangroves (for local degradation analyses)	The Nature Conservancy	National mangrove extent shapefile	--	2013	2013

Tides	TPX0.8 Database	Global tidal model ensemble	--	--	--
Storm Tracks	International Best Tracks Archive for Climate Stewardship	Storm tracks	6-hourly	1851	2016
Mean Sea Level	Port Royal Tide Gauge	Hourly water level time series	--	Hourly	19654-73
Population	JRC-EU Global Human Settlement Layer	Global spatial layer of population	250 m	2015	2015
Population below Poverty	Jamaica National Census	Persons below poverty line	Communities	--	2011
Stock/ Property	GAR17 (UNISDR) – Total, Residential, Industrial Stock	Global property distribution layers	1 km downscaled to 250 m	2017	2017
Damage Functions	EU JRC	% damage / flood level	Per country	--	2017

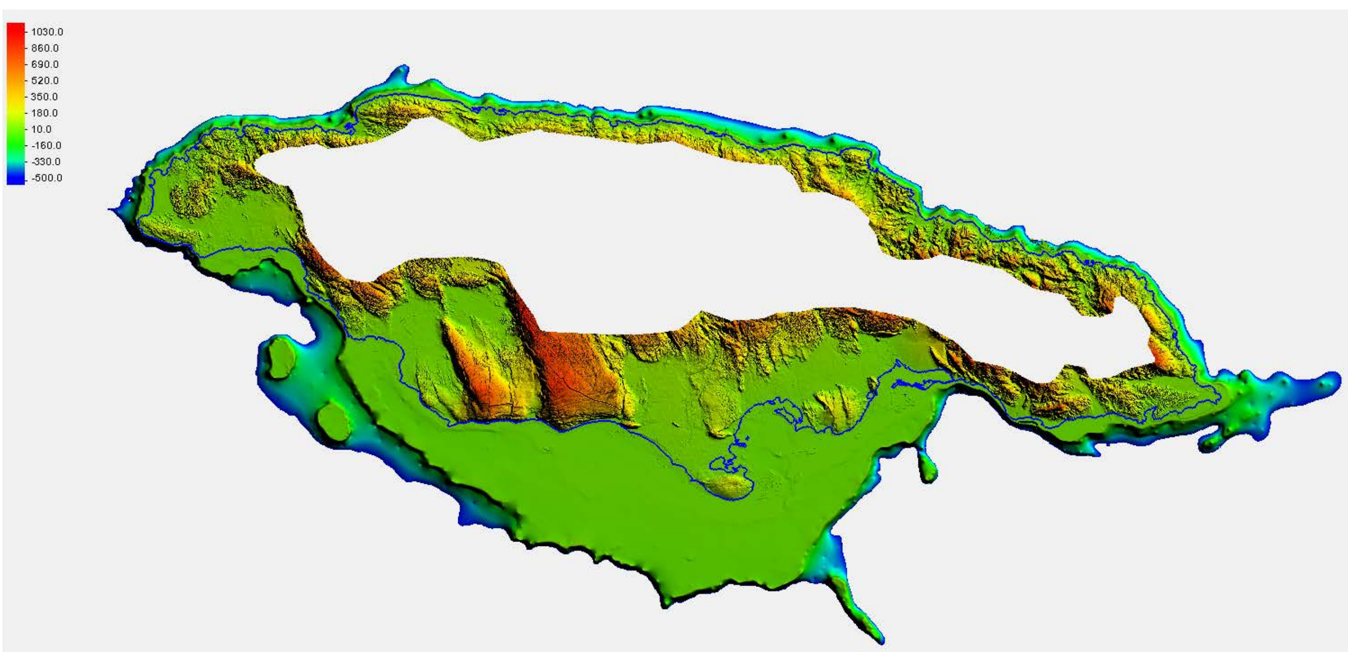

Figure 7: Topo-bathymetric model constructed for the simulation of sea levels, currents and waves, coastline is represented by the solid blue line (Produced by IHCantabria based on the combination of various sources).

Tropical Cyclone Climate (National scale)

Offshore Climate

Information about historical tropical cyclones comes from the International Best Track Archive for Climate Stewardship (IBTrACS) v03r10 (Knapp et al., 2010) provided by NOAA. This file contains ensemble mean data from observations performed by different institutions using various methods. Data contains 6-hourly information of tropical cyclone center 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 1851 to date. Despite global satellite-based observations started in 1970, the IBTrACS database covers from 1851 to 2016, thereby including some uncertainties and non-homogeneities before the 60s. According to IBTrACS, 46 tropical cyclones have passed within less than 500 Km from Jamaica during the last 46 years (Figure 8). Figure 9 shows the tracks of three of the most intense hurricanes that have affected the southeastern part of Jamaica: Hurricanes Gilbert (1988), Dean (2004) and Ivan (2007).

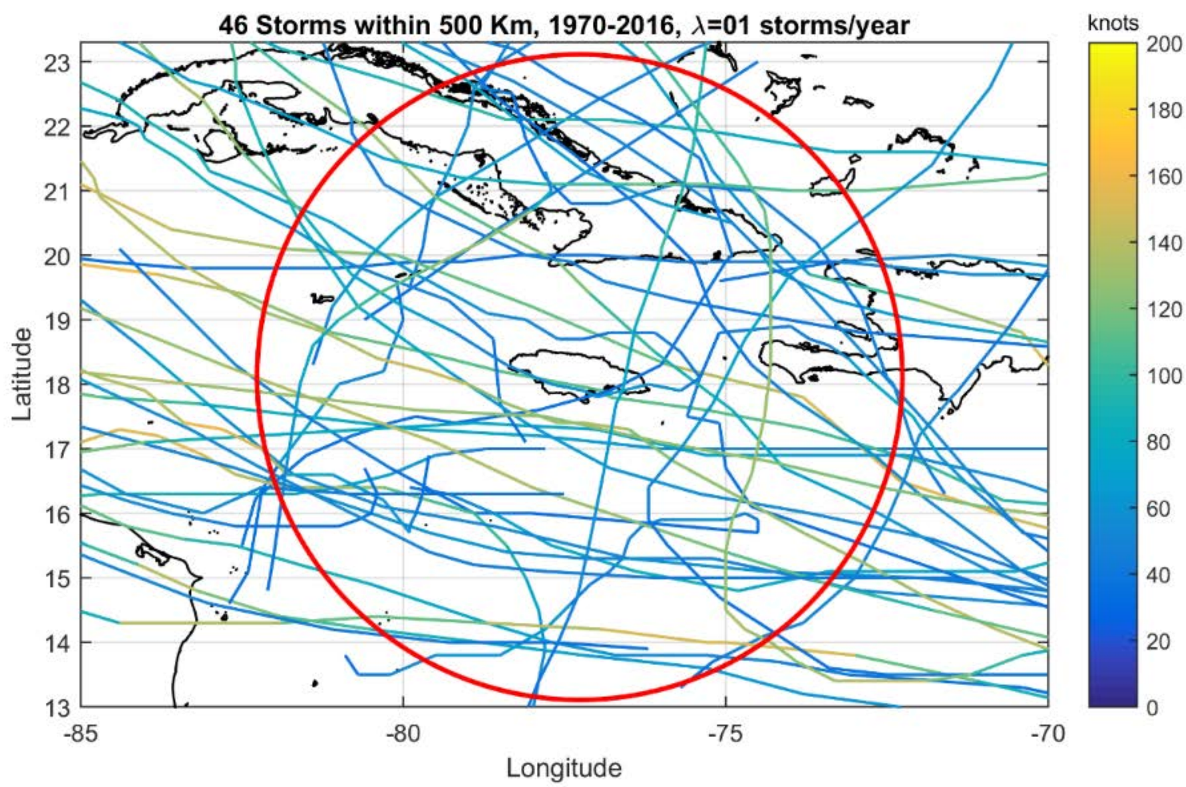

Figure 8: Historical TC tracks affecting Jamaica from 1970 to 2016. The red 500 km radii circle represents the selection area to perform TC statistics. Wind speeds are 1 min sustained as provided by IBTrACS.

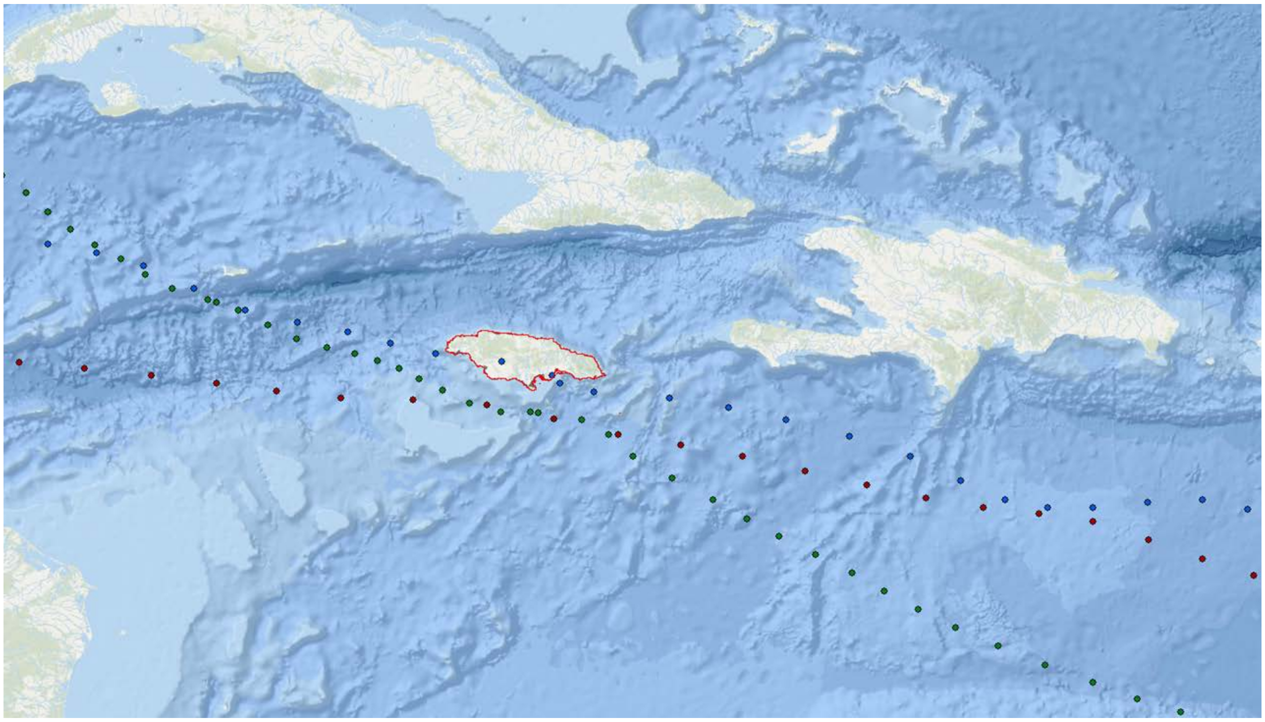

Figure 9: Hurricane Gilbert in September 1988 (blue), Hurricane Ivan in September 2004 (green) and Hurricane Dean in August 2007 (red)

This study uses a statistical Monte Carlo simulation to extend the historical record of tropical cyclone (TC) events to facilitate robust analyses of annual flood probabilities. Due to the very low probability of highly intense hurricane events and the relatively short length of available records, historical data on tropical cyclone tracks is typically not enough to estimate the annual occurrence probabilities of different extreme water levels. The Monte Carlo method, which uses numerous simulations, is commonly employed to overcome this problem. The Monte Carlo method, by means of weighted statistical bootstrapping of the relevant TC parameters, provides long records of TC activity (i.e. up to 5000 years) in which the mean values and distribution patterns of TC parameters are in agreement with observational data. This method, described in Nakajo et al. (2014), has been widely used and validated in numerous applications. In this manner a stochastic model based on the joint probability functions of the TC parameters and temporal correlations is used to extend the historical record of TCs that made landfall in Jamaica from 46 to around 5000 years. Figure 10 shows the increased population of TCs in the area: from 46 events in the historical record to 3792 in the 5000 simulated years.

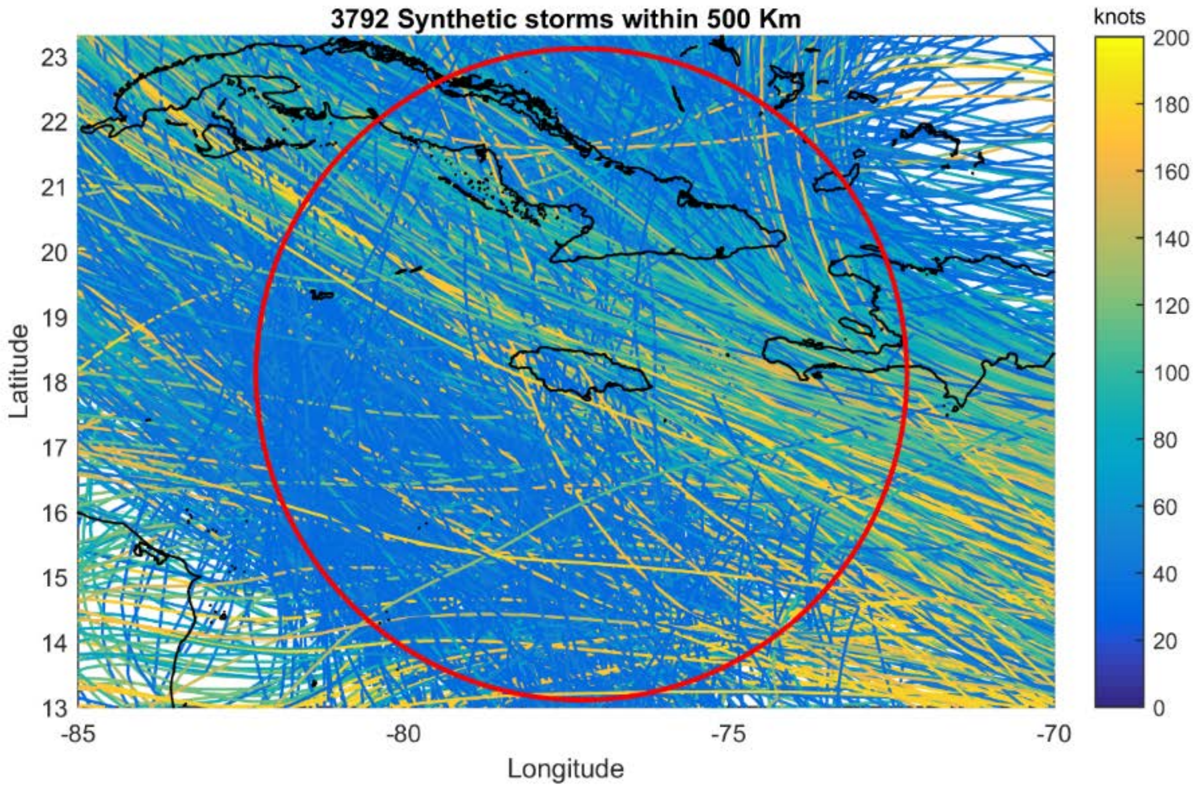

Figure 10: Synthetic Tropical Cyclone tracks produced by Nakajo et al. (2014) for a 5000 years period.

The synthetic tropical cyclone dataset produced using the Monte Carlo method is compared to the historically observed data. Figure 11 shows the relationships between different TC parameters: storm frequency, minimum pressure, maximum winds, longitude and latitude displacements and translation speeds. The distribution of extreme events in the statistical model is similar to the historical data. The statistical model tends towards a more idealized distribution due to the longer length of the synthetic dataset.

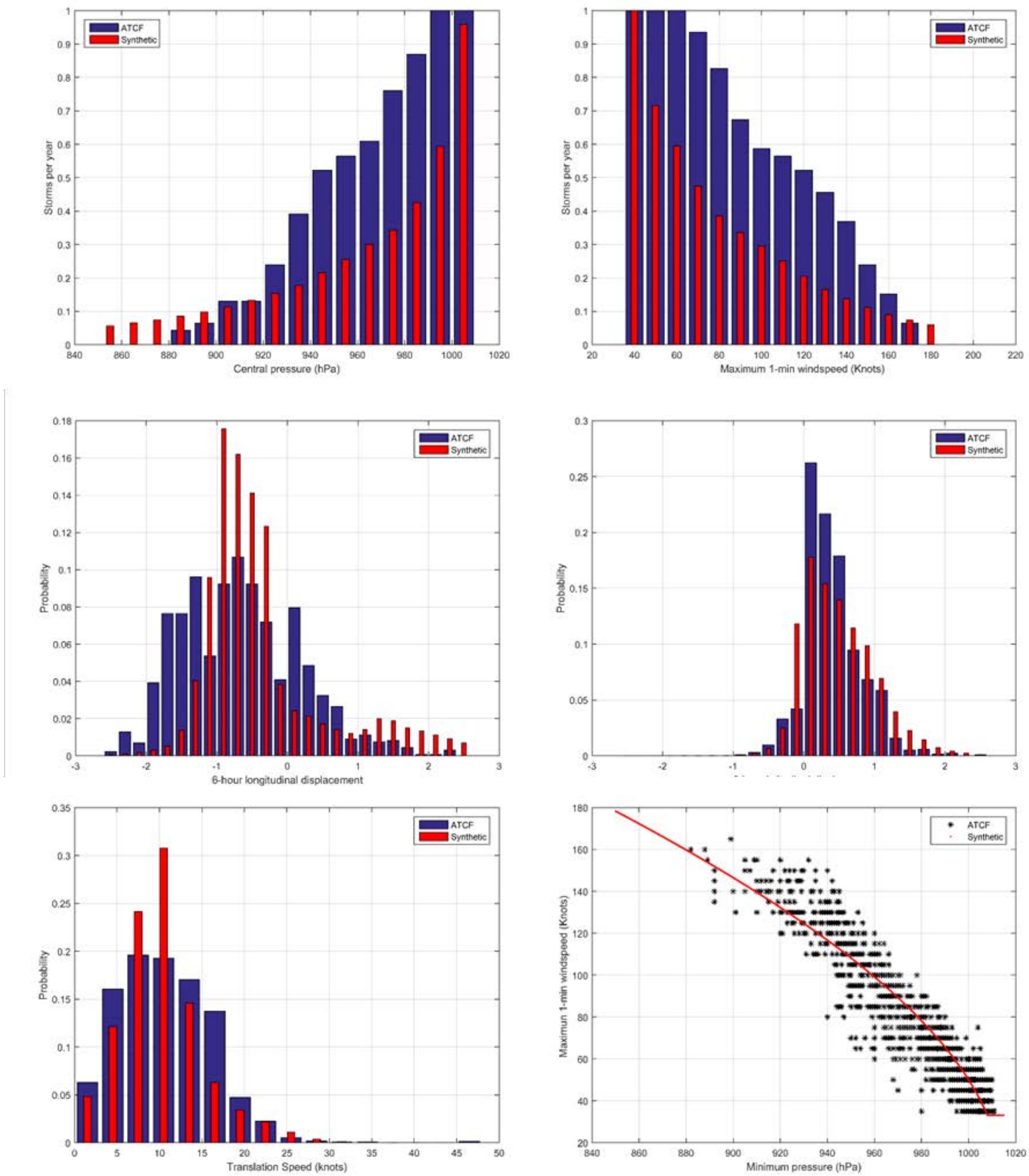

Figure 11: Comparison of the probability density functions of the TC parameters (IBTrACS in blue; Synthetic in red).

From the synthetic tropical cyclone dataset comprising 3792 events, a smaller set (i.e. 462) of representative TC events are selected for the simulation of coastal flooding and damages (Figure 12). Since the simulation of such a large amount of TCs is practically unaffordable, a comprehensive selection of a number of representative TCs is needed to quantify flooding probabilities associated with a Tropical Cyclone Climate. From the synthetic dataset, Category 1 or higher hurricanes (maximum sustained 1-min winds up to 64 knots) passing within a 100 km buffer from the Jamaican coastline are selected. These selection criteria ensure that flooding probabilities for the region are representative of the events most likely to cause coastal flooding: strong hurricanes that are close to the coastline. Figure 12 displays the final selection of tropical cyclones to be simulated, which includes 9 historical (see Table 2) and 453 synthetic tropical cyclones.

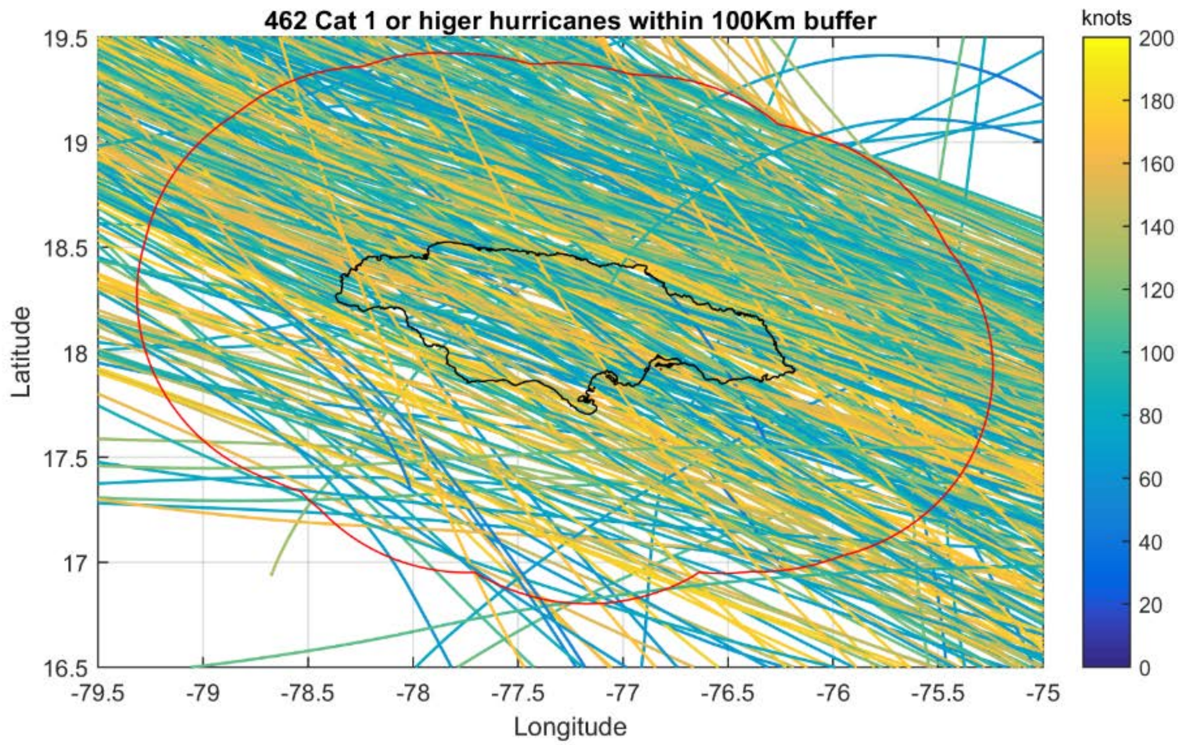

Figure 12: Category 1 or higher tropical cyclones within a 100 km buffer from the Jamaican coastline.

Table 2: Selected historical events to be simulated, Wmax is maximum 1-minute sustained wind.

Name	Date	Wmax (knots)
Carmen	30-Aug-1974	76.1416
Allen	02-Aug-1980	118.2088
Gilbert	09-Sept-1988	117.4809
Iris	05-Oct-2001	75.0290
Charley	10-Aug-2004	148.3572
Ivan	03-Sept-2004	117.8865
Dennis	05-Jul-2005	127.5986
Dean	14-Aug-2007	124
Sandy	22-Oct-2012	85.000

Boundary Conditions for Coastal Flood Model

Once the Tropical Cyclone (TC) events have been selected, the coastal flooding associated with each event is simulated using the coupled ADCIRC+SWAN Model (described in 5.2.3 below). The first step in estimating coastal flooding from a TC event is to simulate its wind and pressure fields that form the boundary input conditions for the coastal flood model. A parametric wind model – the Dynamic Holland model - was used to generate the wind and atmospheric pressure fields for each of the 462 selected TCs Hurricane best track or forecast data contains some

basic 6-hourly information, including eye location and time, maximum wind speed and radius, and central pressure. Parametric wind models offer distinct advantages for modelling TC induced winds such as the simple input requirements and the low computational cost. The Dynamic Holland model (Holland, 1980) calculates some parameters from those data to apply in empirical equations to calculate the atmospheric pressure and gradient wind velocity, from which wind velocity at 10 m height is calculated. However, Holland's original model was parameterized to fit an instantaneous snapshot of a TC at the gradient wind level, rather than the surface level winds of a dynamically developing TC in motion. Therefore, modifications and additions were made to the published model to account for the dynamic changes in the TC parameters along the TC track.
Figure 13 shows the wind swath produced by the Dynamic Holland model for hurricane Dean in August, 2007, where wind speeds in Kingston reached as high as 180 km/h. This model is capable of reproducing key TC characteristics such as the asymmetries induced by the translation of the system, with higher wind intensities on the right side of the track of the TC.

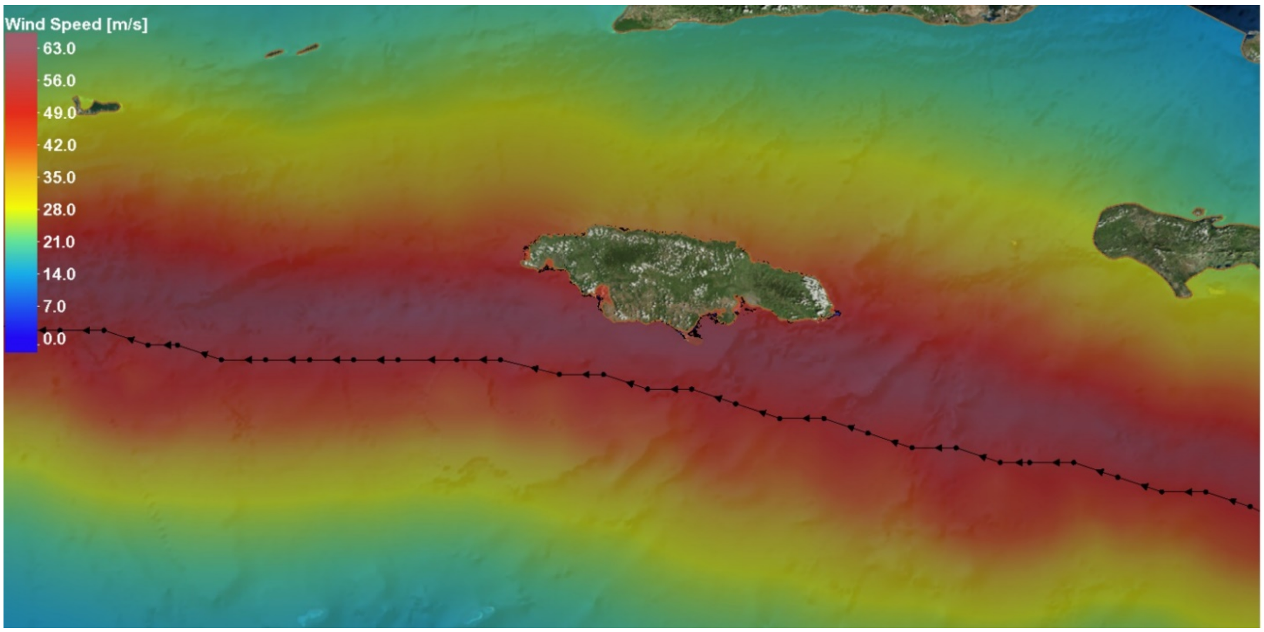

Figure 13: Wind swath as produced by the Dynamic Holland model for Hurricane Dean in August, 2007.

Coastal Flood model

To predict coastal flooding we use the coupled ADCIRC+SWAN numerical model to estimate total water levels at the coastline from waves and storm surges for each of the 462 TC events. The ADCIRC (ADvanced CIRCulation; Luettich and Westerink, 2004) numerical model computes water levels via solution of the generalized wave continuity equation, and currents from the vertically integrated momentum equations. To estimate the contribution of waves to total water level, ADCIRC is coupled with a wave model SWAN (Simulating Waves Nearshore, Booij, 1999). SWAN receives inputs from ADCIRC on wind velocities, water levels, bottom friction and other parameters, to compute wind-generated waves, and the associated radiation stresses and stress gradients, which are then returned to the ADCIRC model as a forcing function. ADCIRC+SWAN has been validated against measured waves and storm surges during several historical storms (Dietrich et al., 2012). One of the main strengths of the ADCIRC+SWAN model is the ability to work with unstructured meshes, with very fine resolution near the coast and much coarser resolution in open waters.

For Jamaica's coastline, we develop a variable resolution mesh representing more than 136,000 points. The mesh resolution ranges from 200 m at the shoreline to up to 25 km in open waters (Figure 14). The development of the mesh was based on the Localized Truncated Error Analysis (Hagen et al., 2001), which optimizes the placement of nodes to properly incorporate the physics underlying tidal flow and circulation to the mesh generation process.

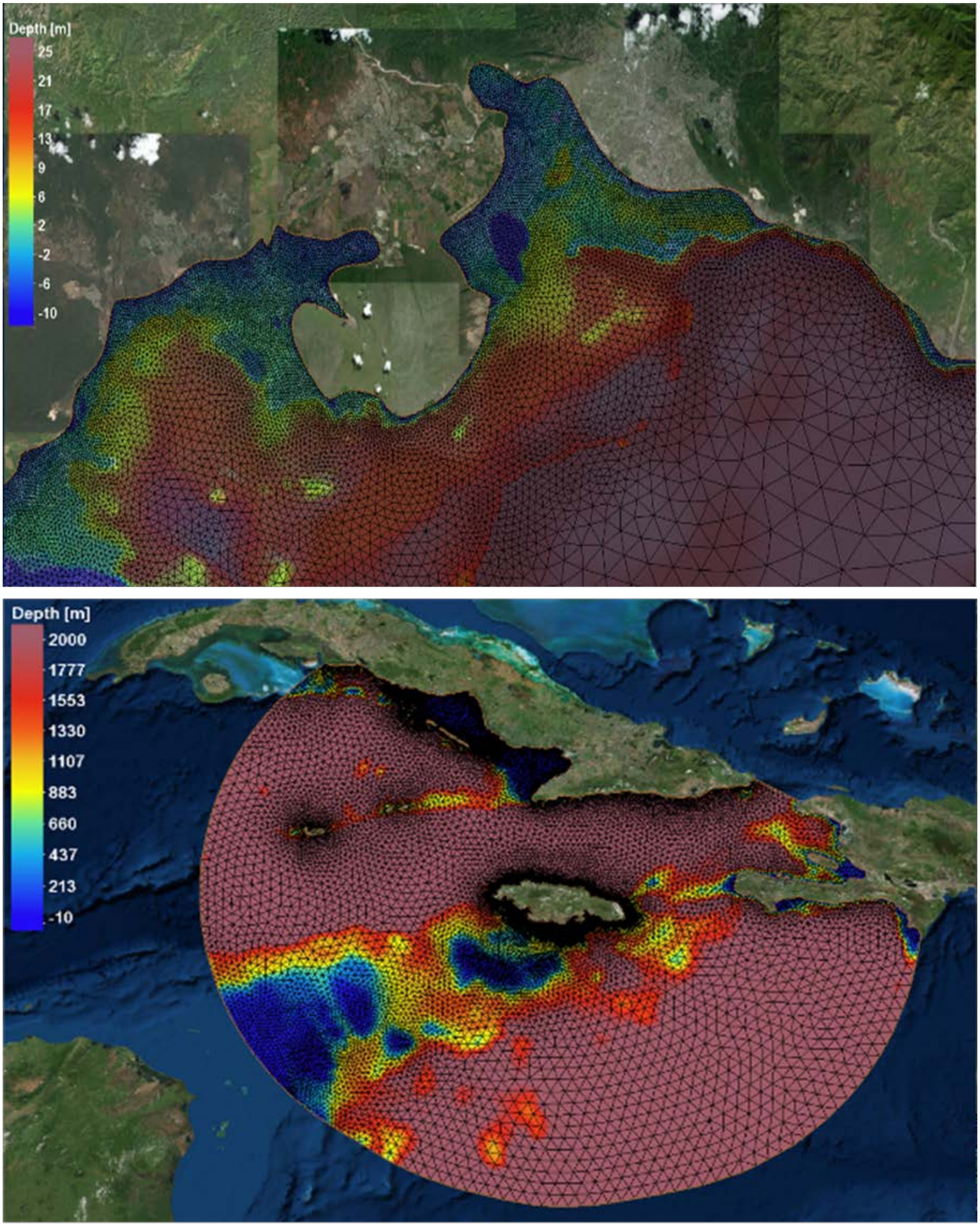

Figure 14: Top) computational domain and bathymetry used to perform the storm surge and wave modelling, (Bottom) zoom over Kingston area. Depths are in meters (referred to the MSL).

The propagation of water levels and waves from the open ocean to the shoreline – and its interactions with intervening features such as coastal habitats or bathymetry – are characterized in the models by estimating a terrain (i.e. land-cover) specific shear stress. The coefficient of bottom friction is a critical parameter to incorporate the effects of terrain-specific bottom shear stress on total water levels and wave heights. Here, we use the friction coefficient to characterize the effect of mangroves, coral reefs and other coastal habitat and land-cover features on the propagation of storm surges and waves. In ADCIRC, bottom friction is computed using a Manning's coefficient (n). In this study we assign coefficient values of 0.02, 0.05 and 0.15 for the open ocean, coral reefs and mangroves, respectively (Figure 15).

Figure 15: Manning's n used in ADCIRC+SWAN.

ADCIRC converts the specified Manning coefficient (*n*) to an equivalent quadratic bottom friction, Cd, according to following formula (1):

$$Cd = \frac{gn^2}{H^{1/3}} \quad (1)$$

where H is the bathymetric depth plus the water surface elevation and g the gravitational acceleration constant.

As ADCIRC computes terrain-specific bottom friction, SWAN is configured to use variable bottom friction instead using a constant approach as defined by the default JONSWAP formulation. SWAN bottom friction is formulated as a dissipation term and included as part of the source/sink term in the spectral action balance equation (2):

$$S_{bot}(\sigma,\theta) = -C_b \frac{\sigma^2}{g^2 sinh^2(kH)} E(\sigma,\theta) \quad (2)$$

where σ and θ are the spectral wave frequency and direction, respectively, C_b is a bottom friction coefficient, g is the gravitational acceleration, $k$is the wave number and E the spectral energy density. The coefficient C_b (3) depends on the bottom orbital motion, U_{rms} that according to Madsen et al. (1988):

$$C_b = f_w \frac{g}{\sqrt{2}} U_{rms} \quad (3)$$

where f_w is a non-dimensional friction factor that depends on the bottom roughness length scale, that is given by the Bretschneider et al. (1986) relation where the roughness length depends on the Manning's coefficient and depth.

Regarding the surface stresses, ADCIRC can use a spatial attribute called canopy coefficient that allows the user to turn off wind stress in heavily forested areas that have been flooded, like a swamp, thus shielding the water from the effect of the wind.

The mesh has been configured with 2 open boundaries (one in open water and other in the Windward Passage, between the islands of Cuba and Hispaniola, see Figure 14) that are forced with the amplitude and phase of the following tidal constituents: M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, MN4, MM and MC, to characterize tide variability and to calibrate-validate the model. Tidal harmonics has been obtained from the TPX0 8 database (http://volkov.oce.orst.edu/tides/global.html). Validations of the model's astronomical tide predictions were performed using the Port Royal gauge (Figure 16). The predicted phase and the amplitude agree almost perfectly with the observed water levels reconstructed from the tidal gauge data. The short length of the instrumental record does not contain the signal of any relevant hurricane and thus cannot be used to validate the model's storm surge predictions.

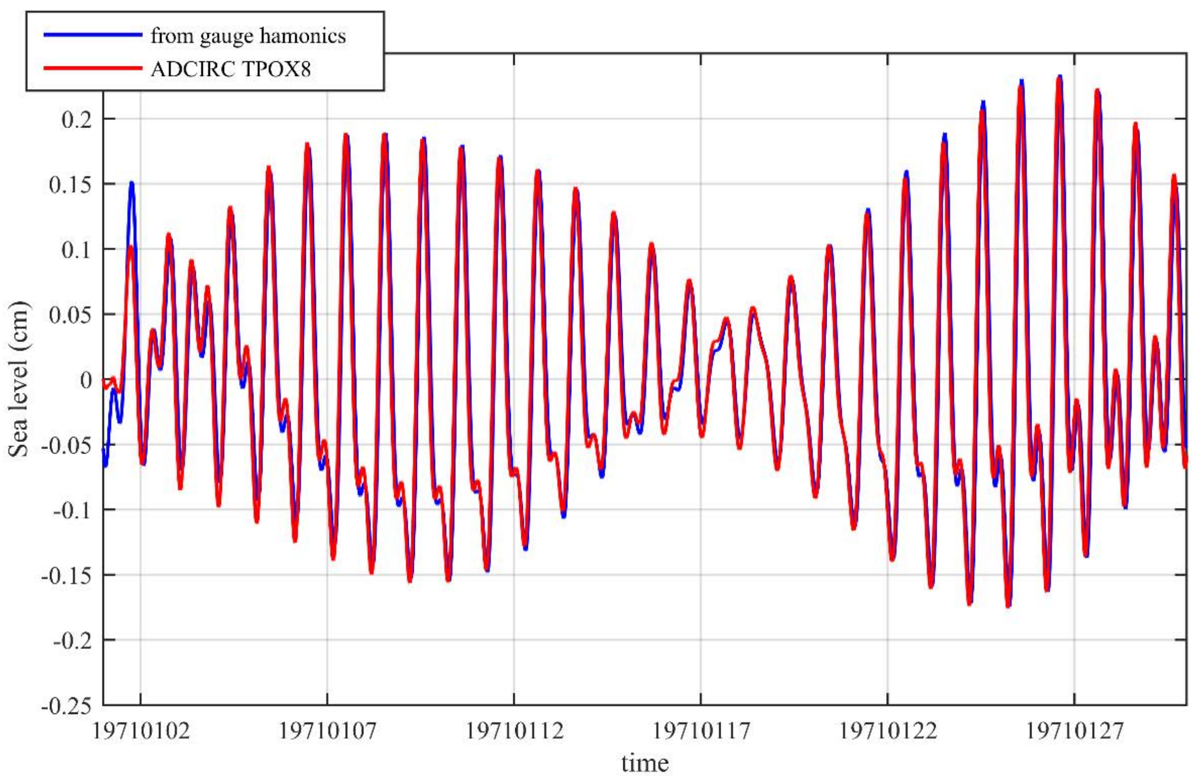

Figure 16: Comparison of tide amplitude and phase as reconstructed from the gauge harmonics with sea levels simulated with ADCIRC.

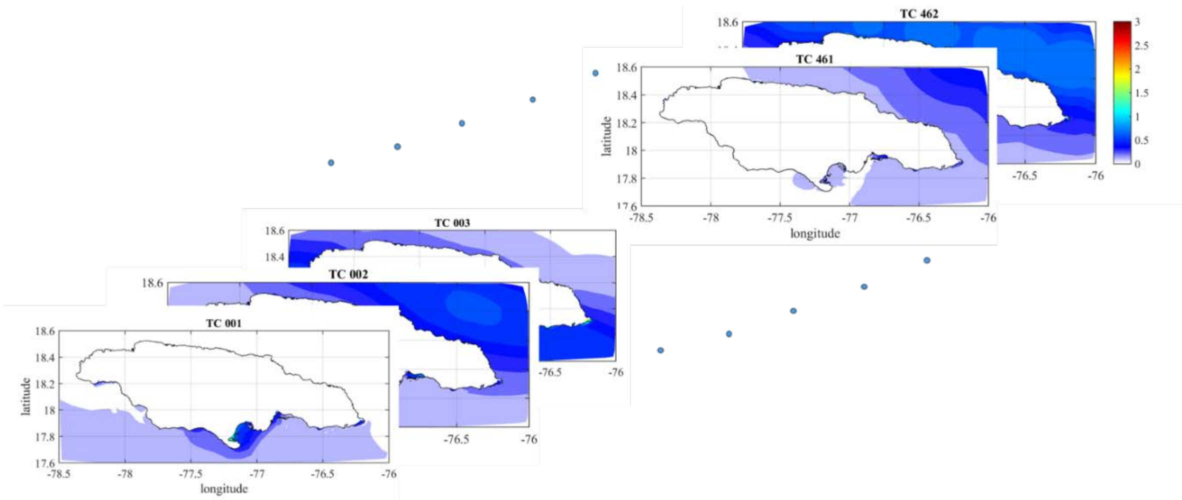

Figure 17: Produced flood database consisting of 462 simulated TCs for mangrove and non-mangrove scenarios.

Exceedance Curve of Total Water Levels

The simulated flooding from the 462 events for the with mangrove and without mangrove scenarios are converted into probabilistic distributions of storm surge levels. These distributions allow the estimated flooding (i.e. total water levels) from the 462 events to be cumulatively characterized as an annual probability of exceeding a certain total water level for each mangrove scenario (Figure 17). First, at any given location, we assume the arrival of the storms to be a stationary Poisson process, with the TC rate as the frequency for which a storm exceeds a defined threshold (i.e. the 90% percentile). In practice, we determine the return period values that satisfy the condition expressed in (4):

$$1 - F(x) = {}^{1}/_{T} \quad (4)$$

where T is the return period in years and F(x) the number of years for which the maximum value is lower than x, divided by the total number of years in the chosen data set. We apply a peaks-over-threshold (POT) method to model this tail with a generalized Pareto distribution. It is important to mention that TCs have been simulated considering a constant sea level (mean sea level, MSL) and thus they do not incorporate tidal variability.

Figure 18 displays two examples of how the computed coastal flood heights at any given coastal point are converted to the probabilistic, Generalized Pareto Distribution. In Figure 18, the dots are the flood heights corresponding to TCs that inundated this location and the solid lines are the corresponding fits to the GPD for scenarios with mangroves (green) and without mangroves (red). Here, Point #730, elevated 0.48 m above the mean sea level is flooded once each 60 – 70 years depending on the presence or absence of mangroves. The effect of mangroves is much more apparent in Point #1885, elevated 1 m, where return periods associated to 1 m flood height go from once each 300 years, with mangroves, to once each 170 years without mangroves. This analysis has been conducted for all coastal areas below 10 m elevation.

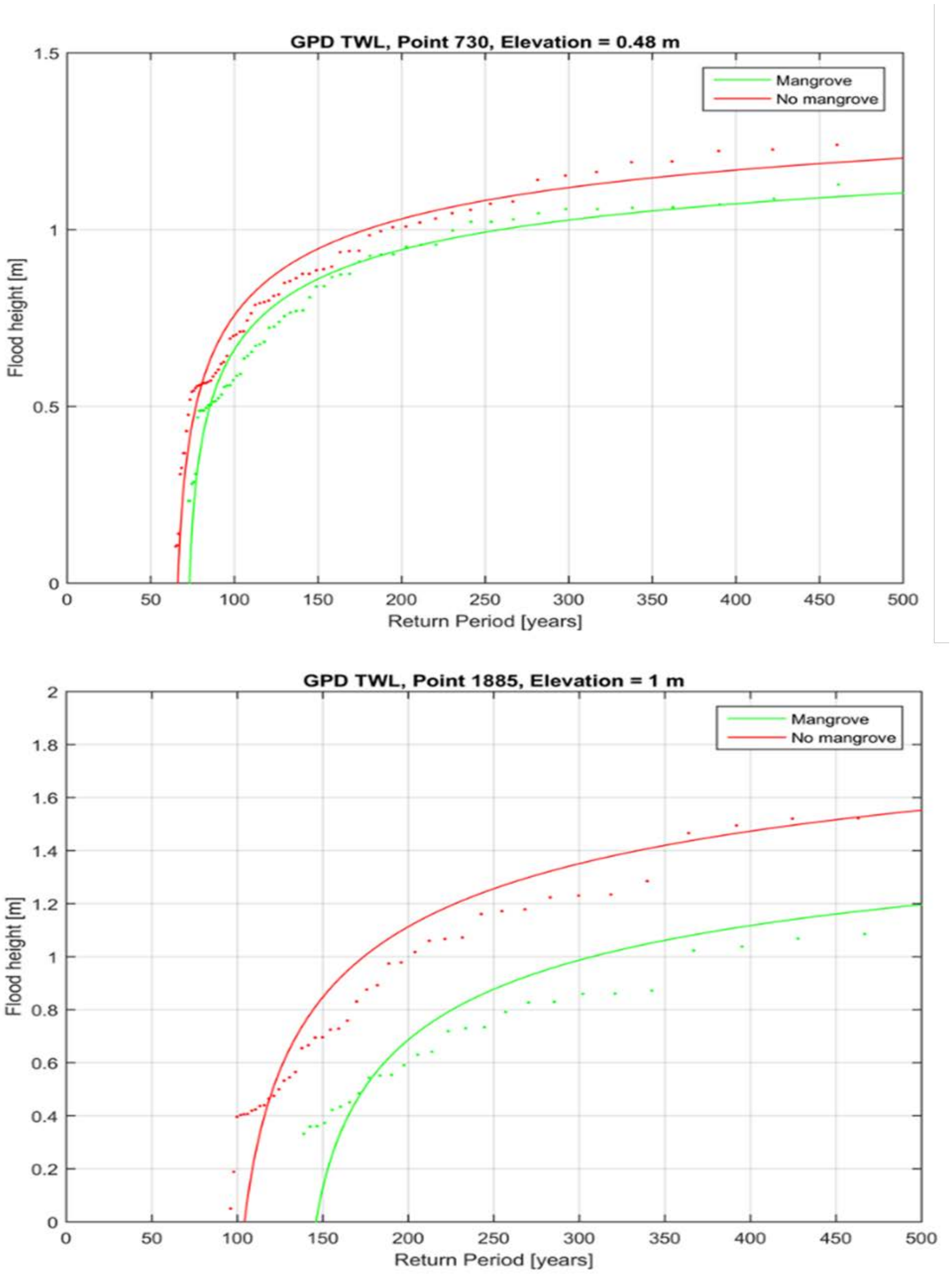

Figure 18: Example of the generalized Pareto distribution fits to the flood heights at two points with different elevations. Red and green lines and points correspond to the mangrove and non-mangrove scenarios respectively. Top: Point 730; Bottom: Point 1885

Regular wave climate (Local scale)

Offshore Climate

In addition to the flooding from extreme tropical cyclone (TC) events, we also simulate flooding from "daily" regular wave-driven flooding at a high resolution at two local sites. Figure 19 shows the available mesh nodes from GOW2 and the selected offshore points to analyze the regular wave climate at the two local sites (Figure 19, top panel). Offshore day to day waves have been obtained from the GOW2 global wave hindcast (Perez et al., 2017) produced by IHCantabria. This Regular Wave Climate (RWC) analysis uses global wave data to drive a high-resolution numerical model, XBeach, that estimates total water levels at the shoreline due to wave-driven processes. To avoid double-counting the flooding from tropical cyclones, wave events corresponding to the passage of nearby TCs are removed from this analysis (Figure 19, bottom panel).

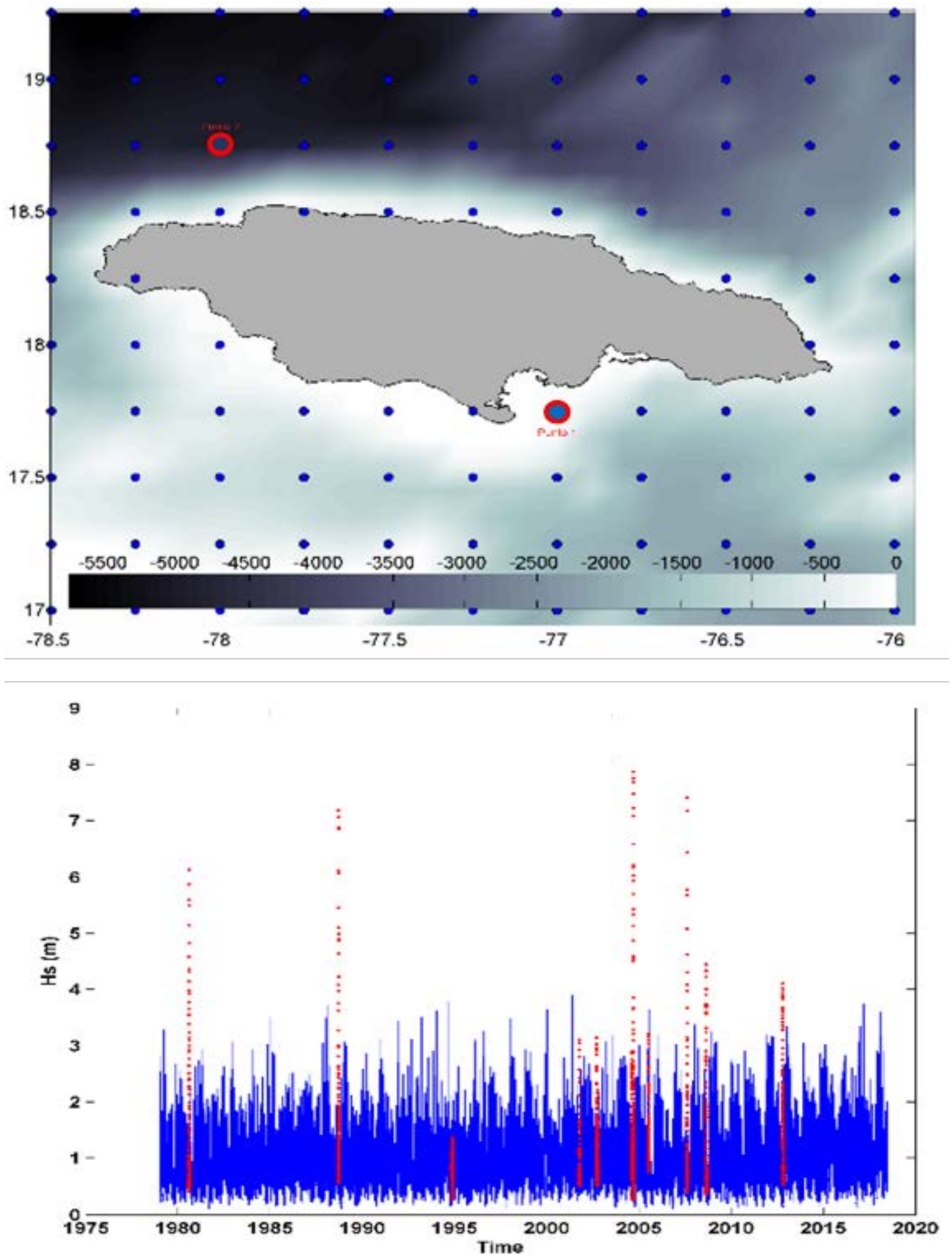

Figure 19: TOP: GOW2 mesh around Jamaica and selected nodes to analyze the protective function of the mangroves against wave generated flooding in Old Harbor and Montego bays; BOTTOM: Hs time series (blue lines) and Tropical Cyclones removed (red dots) for the shoreline in front of Montego Bay.

The scalar and directional generalized extreme value (GEV) distributions obtained for the two analyzed offshore points are displayed in Figure 20. As can be seen, Old Harbor Bay, located on the southern coast of Jamaica is dominated by a more intense wave climate as a result of the persistent trade winds over the Caribbean Sea. On the northern part of Jamaica, the wave climate is slightly more gentle, due to the shadow effect imposed by the land-contours. The directional extreme value distributions demonstrate the dominance of the waves from the 2nd quadrant (i.e. east to south-southeast), while the prevailing direction of the extreme waves in Old Harbor Bay is from the southeast, in Montego Bay those extremes come from the east and northeast.

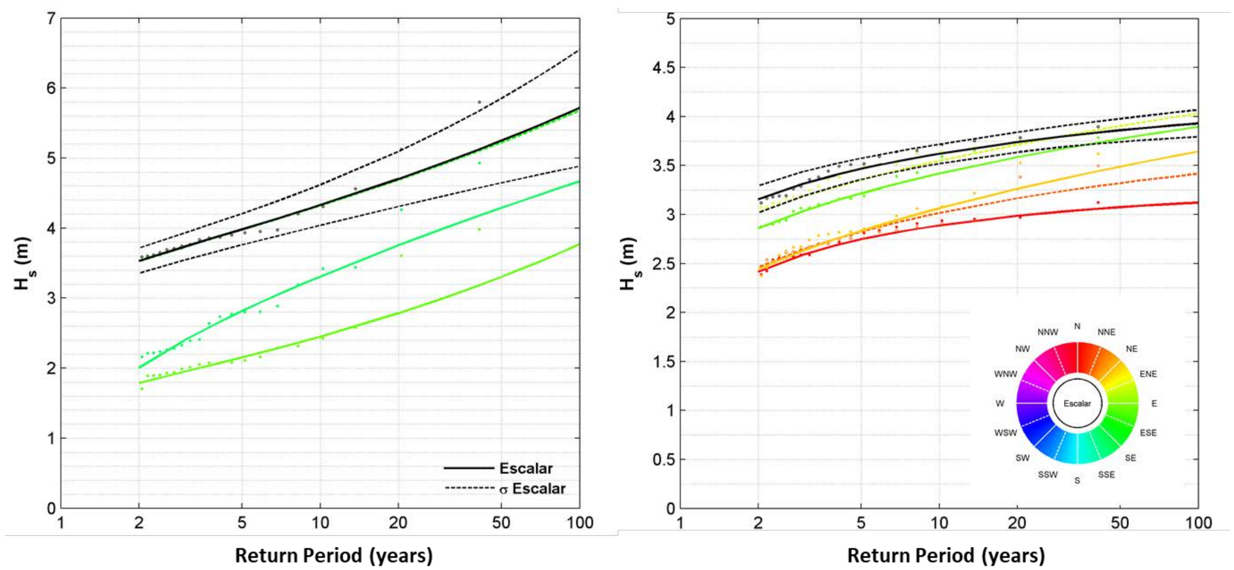

Figure 20: Scalar (black lines) and directional (colored according to the directional scale) GEV distributions of Hs at the offshore points front of Old Harbor Bay (left) and Montego Bay (right)

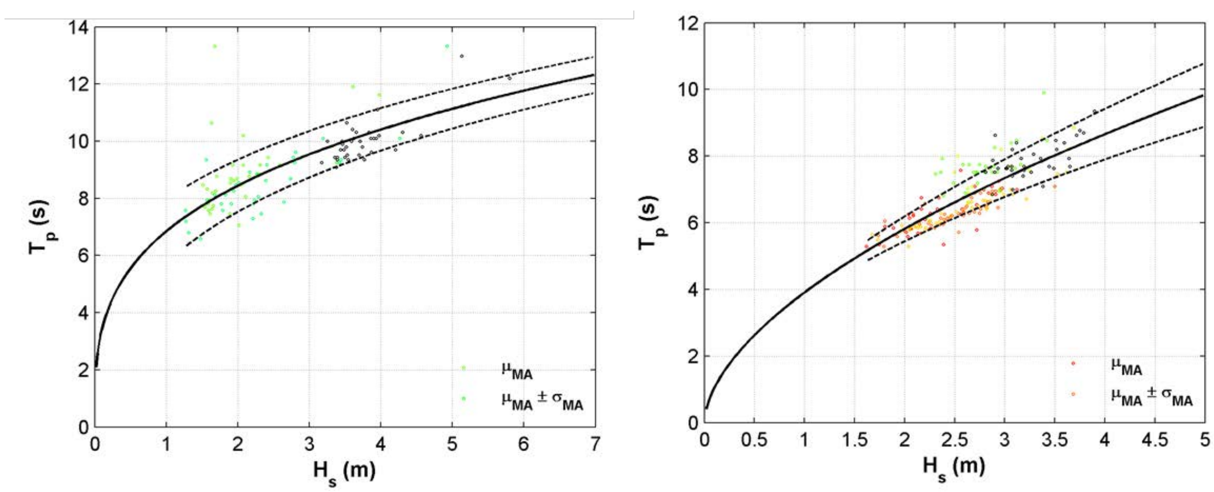

Figure 21: Hs-Tp scatter plots at the offshore points front of Old Harbor Bay (left) and Montego Bay (right)

The significant wave height - peak wave period (Hs-Tp) relations (Figure 21) indicate larger wave periods in the southern coast of Jamaica. As can be seen, Hs-Tp of annual maxima present low dispersion, what facilitates the selection of a peak period and direction for each Hs return period to be simulated.

Boundary Conditions for Coastal Flood Model

The statistical analysis of offshore wave climate is used to produce the wave parameter boundary conditions for the coastal flood model described below in Section 5.3.2. According to the statistical analysis of the offshore wave climate in Old Harbor and Montego bays, Table 3 shows the cases that have been selected to be simulated in order to characterize the protective function of the mangroves against the waves-driven flooding. Despite the small tidal range in Jamaica (less than 40 cm according to the Port Royal tide gauge), the reference level for the simulation has been set to 0.6 respect the mean sea level (MSL) to incorporate possible sea level anomalies associated with those rough wave conditions (i.e. simulations has been done adding ~40 cm to the mean high tide, including possible wind set-up, sea level seasonality, interannual variability, etc.). As those conditions mainly correspond to distant generated swells or locally generated seas, wind speed has been set to 0 in the simulations.

Table 3: Representative extreme sea states from the RWC to be simulated with XBeach at the two local sites.

	Old Harbor Bay				Montego Bay			
RP (Years)	5	25	50	100	5	25	50	100
Hs (m)	4	4.8	5.1	5.9	3.5	3.7	3.8	4
Tp (s)	10	10.7	11.3	12	8	8.5	8.6	9
Wave Dir	SE	SE	SE	SE	ENE	ENE	ENE	ENE
Wind (m/s)	0	0	0	0	0	0	0	0
Wind Dir	--	--	--	--	--	--	--	--
Eta0 (m)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6

Coastal Flood Model

To consider the effect of both, incident waves and infragravity waves, the XBeach model (surfbeat mode) was used in this study to assess wave attenuation in mangrove forests and to evaluate the protective value of mangroves in Jamaica.

XBeach is a two-dimensional model for wave propagation, long waves, and mean flow. The model consists of formulations for short-wave envelope propagation, nonstationary shallow-water equations, sediment transport, and bed update. Innovations include a newly developed time-dependent wave action balance solver, which solves the wave refraction and allows variation of wave action in x, y, time, and over the directional space, and can be used to simulate the propagation and dissipation of wave groups (Roelvink et al., 2009). Recently, the development team has been working on a very new application: "wave attenuation by vegetation on XBeach". Wave attenuation by vegetation is successfully implemented in the simulating waves nearshore (SWAN) model for short waves by Suzuki et al., (2012). The implementation is based on an energy attenuation equation (6), first provided by (Dalrymple et al., 1984) which was further developed and validated by (Mendez and Losada, 2004):

$$D_v = \frac{1}{2\sqrt{\pi}}\rho C_D b_v N_v \left(\frac{k}{2\sigma}\right)^3 \frac{sinh^3 kah + 3 sinh\, kah}{3k cosh^3 kh} H_{rms}^3 \quad (6)$$

where D_v is the time-averaged rate of energy dissipation per unit area; C_D, b_v, and N_v are the vegetation drag coefficient, diameter, and spatial density; k is the average wave number; σ is the average wave frequency; αh is the mean vegetation height; h is the water depth (m); and Hrms is the root mean-square wave height at that point.

In the XBeach model, the short-wave attenuation by vegetation is implemented in a comparable way, where k and σ are respectively the wave number and wave frequency associated with the peak period of the incident waves. The long-wave attenuation by vegetation is modeled with a Morison-type equation defined as (7):

$$F_v = 0.5 C_D b_v N_v \frac{ah}{h} u|u| \tag{7}$$

where u is the orbital velocity.

The vegetation properties can be specified for multiple species and can vary per species over the vertical to mimic a mangrove tree (Figure 22). In XBeach a vegetation-file can be specified that contains a file list with vegetation properties including number of vertical sections, the height of a section (h), drag coefficient (C_D), number of plants per unit area (N_v), and plant area per unit height (b_v).

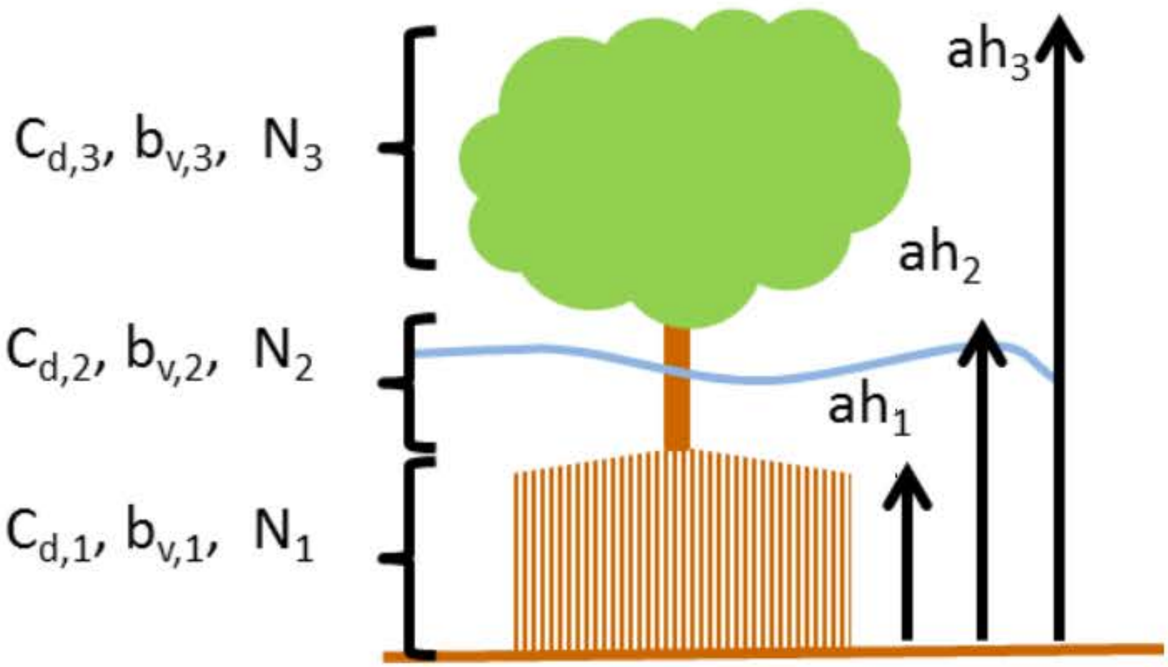

Figure 22: Scheme of the parametrization of the mangrove wave attenuation model.

Two high resolution meshes of 10 m x 10 m spatial resolution have been designed to propagate the waves and determine wave-driven floods in the two study sites (Figure 23). All simulations have been done with version 1.23.5493 of the XBeachX BETA release, surfbeat mode using default settings wherever applicable. The nine vegetation parameters—three for each of the three layers that had to be estimated or measured on the basis of the requirements of the XBeach model—are the diameters (b_v), densities (N_v) and heights (ah) of the roots, stem, and canopy.

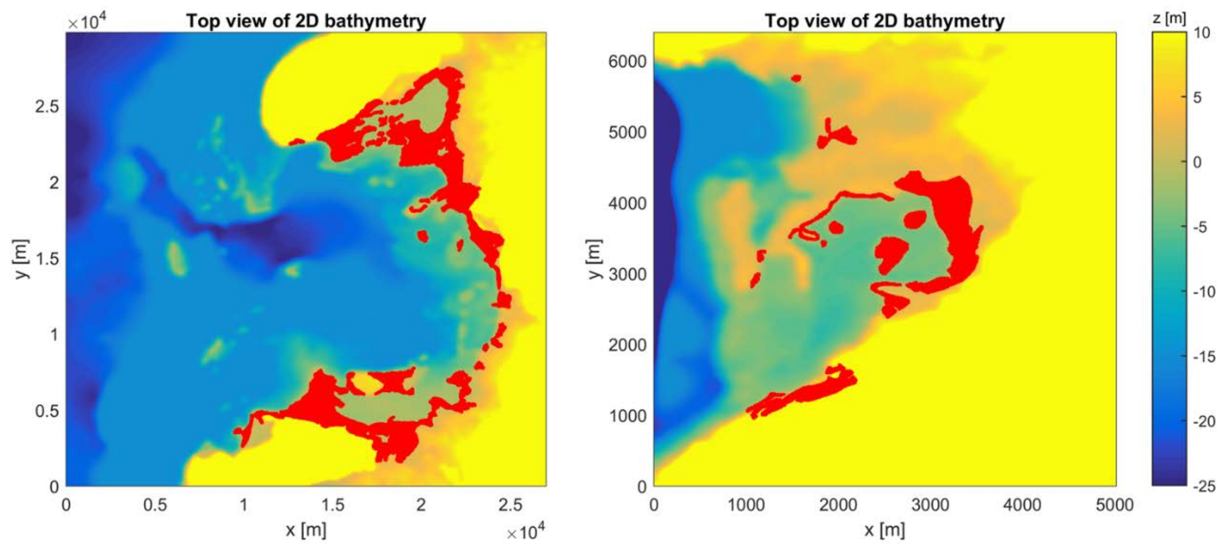

Figure 23: Old Harbor Bay XBeach mesh (left) and Montego Bay (right), the mangrove forest extent is represented by a red patch.

X-Beach requires critical input parameters to define key flood reduction characteristics of mangroves. Rhizophora mangle is dominant mangrove in Jamaica though there are also extensive areas *of Avicennia germinans*, and some small stands of *Laguncularia racemosa* and *Conocarpus erectus*. The characteristics of Rhizophora sp. are fully described by Narayan et al., (2011) for mangrove in India, which, in the absence of better data, we have adopted here. Note that the drag coefficient has been set to 1 for all the sections, according to Suzuki et al., (2012). These values are all within the range of field measurements by UWI for mangroves in Bogue Lagoon (Table 5), except for the number of prop roots assumed in this study which are higher than measured at the two sites. However minor differences in one variable have very little overall impact on the model results because this is only one of several variables that are merged together in to one parameter estimate of the "bulk drag coefficient".

Table 4: Vegetation parameters used in the XBeach simulations obtained from Narayan et al., (2011).

Rhizophora sp.			
Number of sections	3		
	Root	Stem	Canopy
ah	0.8	6	2
bv	0.075	0.25	0.5
N	130	1.7	100
Cd	1	1	1

Table 5: Comparison of Parameters from Bogue Lagoon mangroves and parameters used in flood models

Property	Range – Field Measurement	Values (Root, Stem, Canopy) – This Study
Diameter / Width	0.007 – 0.22 (Roots & Stem); 0.01 – 13 (Canopy)	0.075 (Roots); 0.25 (Stem); 0.5 (Canopy)
Number, N	1 – 76 (Roots)	130 (Roots)
Height	6 – 16 (Total)	8.8 (Total)

Assessing flood damages: Consequences for property and people

The expected benefits provided by mangroves are assessed 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 two key variables: population and built stock (divided into residential, industrial and services stock). We followed well-established approaches for assessing the damages to people and property (built stock) as a function of the level of flooding. We calculate the percentage of people and property that has been damaged (D) for a given flooding level and a given coefficient that must be calibrated as (8).

$$D(h) = \frac{h}{(h+k)} \tag{8}$$

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 and built stocks.

To estimate inland flood damages, we first estimate inland flood extents. We translate the total water levels at the shoreline for events of specific return periods from the statistical distribution of total water levels described in Section 5.2.4 into inland flooding. Total water levels at the coastline for specific return periods, calculated at a 250 meters resolution, are used to estimate inland flood extents and heights. To estimate flooding, we use a bathtub flooding model which we modify to include a hydraulic connectivity requirement. In this model the total volume of water at the shoreline for every 250 meters stretch of coastline is distributed inland via hydraulically connected points using detailed, high-resolution topographic data. From the flooding levels and flooding extent, we calculate the total area of land affected and damages.

We intersect the flooding maps with population and built stock data after resampling exposure from the original 250 meters (population) and 1 kilometer resolution (property) to 250 meters of the flooding model. Assets (population and built stock) are only considered in coastal zones with an elevation lower than 10 meters assuming that areas at higher elevation are not flooded.

In addition to assessing risk and damages for specific events (e.g., 100-year storm event), we also examine average annual expected damages and benefits provided by mangroves. To estimate annual risk, we integrate the values under the curves that compare built capital damaged or people flooded, by storm return period. That is, we integrate the expected damage from multiple events with the probability of occurrence of each event. 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 250 x 250 meters cells.

Population Exposure to Flooding

Exposure data for people in Jamaica was obtained from the Global Human Settlement Layer (GHSL) from the Joint Research Centre (JRC) and the DG for Regional Development (DG REGIO) of the European Commission at 250 meters spatial resolution (freely available at https://ghsl.jrc.ec.europa.eu/).

Built Capital Exposure to Flooding

This study uses data from Global Assessment Report on Disaster Risk Reduction (GAR) 2017 Atlas Risk Data (UNISDR, 2017) on the economic value of the total, residential, industrial and services building stock. Throughout this report we use stock and property interchangeably to mean an estimate of the exposure of the physical buildings. The GAR17 provides a global exposure database with a standard 5 kilometers spatial resolution and a 1 kilometers 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 GAR17 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 1x1 km using geographic distribution of population data and gross domestic product (GDP) as proxies (UNISDR 2017). The study downscaled total, residential, industrial and services stock data from the GAR17 in the following manner:

1. For each point of GAR17 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. GAR17 data is referenced to 2014, so an adjustment to 2015 GHSL estimates was performed.
2. In each point of GAR17 layer, building stock for each category (total, residential, industrial and services) was calculated.
3. In each point of GAR17 layer, stock per capita was calculated by dividing stock and adjusted population.
4. A raster layer was created for stock per capita. Inverse distance weighted interpolation was used for the creation of this raster.
5. Finally, using the population raster (from GHSL, 250m resolution) a raster layer for each stock category was calculated by multiplying stock per capita and population. A scale verification was done, checking that the sum of stock from GAR17 layer was the same that the sum of stock raster layer created.

Vulnerability

National specific Flood Depth-Damage functions are needed to evaluate the sensitivity of people and property to be damaged for different flood levels. Two sources of information have been used to obtain these: a report from the EU Joint Research Centre (JRC) proposing damage functions for residential and industrial stock, commerce, transport, infrastructure and agriculture at each location (Huizinga et al. 2017); and HAZUS databases damage curves (Scawthorn et al. 2006), which were based only on US collected data but frequently extrapolated for use in other geographies. These damage functions are a common framework for assessing damages on buildings and property. For assessing flood damage to persons these functions use "threshold" curves, which simply determine a flood height at which the population becomes affected by the hazard.

Table 6: Damage functions used: threshold at 0.5 meters for population and curve points for built stock.

POPULATION			BUILT STOCK	
Flood height (meters)	**Damage factor**		**Flood height (meters)**	**Damage factor**
0	0.00		0.0	0.00
0.5	1.00		0.5	0.60
			1.0	0.85
			2.0	1.00

Potential Mangrove Restoration Benefits

An additional analysis has been carried out by comparing the protection provided by the baseline (2005) and degraded (2013) mangrove extents in Old Harbour Bay. This comparison is made for a single extreme event corresponding to a 50 year return tropical cyclone. This analysis is not feasible at national scale because of the extent of the differences between the 2005 and 2013 layers is limited and very localized what could require a spatial high resolution in the analysis not affordable at national scale. Besides the different techniques used to assess the 2005 and 2013 mangrove layers makes them not directly comparable and conclusions on local losses aggregated at national scale should be taken with care.

First, flood heights and extents are estimated for a single tropical cyclone event with a return period of 1 in 50 years, for the two mangrove extents – baseline (2005) and degraded (2013), using the model described in Section 5.2.3 above. Then, flood damages to stock in Old Harbour Bay are estimated for this cyclone event. Using the 240 exposure points previously defined in Old Harbour Bay, the severity of damage by this cyclone is determined to correspond to a flooding return period of 1 in 117 years. Using this information, and the damage associated with this event a full flood damage curve is built for Old Harbour Bay, on the assumption that the overall shape of this curve in Old Harbour Bay will be the same as the curve obtained from the national-scale study. This approach allows completing the results for different return periods and obtaining the annualized damages estimation.

Coastal Protection Ecosystem Service Assessments: Results

This section describes the results of the assessment of (i) flood risk and (ii) flood risk reduction benefits of mangroves in Jamaica. These results are presented in terms of the number of people flooded and the value of residential and industrial property damaged. The results identify areas at greatest flood risk presently and where mangroves provide the greatest benefits to people and property.

National level

At present, coastal flooding from storms in Jamaica is estimated to result in US$ 136.4 Million [JMD 18.6 Billion] in damages every year, in the presence of mangroves. If these mangroves were all lost, the expected damages from flooding would increase to $169 Million [JMD 23 Billion] annually. Thus mangrove forests in Jamaica provide over US $32.65 Million [JMD 4.3 Billion] in annual flood reduction benefits to built capital. Similarly, they protect over 1400 people every year from coastal flooding during storms. These annual benefits indicate the overall contribution of mangroves to risk reduction every year, considering a full distribution of tropical cyclones ranging from frequencies of 1 per year to 1 per 2500 years.

The average risk reduction benefits against tropical cyclones from mangrove forests across Jamaica are around $2,500 per hectare [JMD 336,000] per year, though these values can be significantly higher in more populated areas. For example, in Hunts Bay, coastal mangroves totaling 200 hectares provide risk reduction benefits of over $1 Million annually [JMD 134 Million], with an average annual value exceeding $5,000/ha/yr [JMD 672,000] (Fig 20). In the event of a 1 in 100-year storm these mangroves avoid damages by more than $30 Million [JMD 4 Billion], resulting in an average value of more than $154,000/ha [JMD 20.7 Million].

Mangrove benefits are most apparent for high intensity storms of 1 in 200-year return periods. During these storms, mangrove forests protect 177,000 people and nearly $2.4 Billion or 50% of the total affected population and built capital. This translates to economic benefits of more than $186 Million per hectare of mangroves.

Indeed, the risk reduction benefits of mangrove forests in Jamaica are apparent during intense tropical cyclones. During a 1 in 100-year cyclone, mangroves reduce flood damages by $386 Million [JMD 51.89 Billion] and protect more than 22,000 people in coastal areas. These benefits to people and property increase by an order of magnitude, to $2.4 Billion [JMD 322 Billion] and 770,0000 people protected during a 1 in 500-year cyclone.

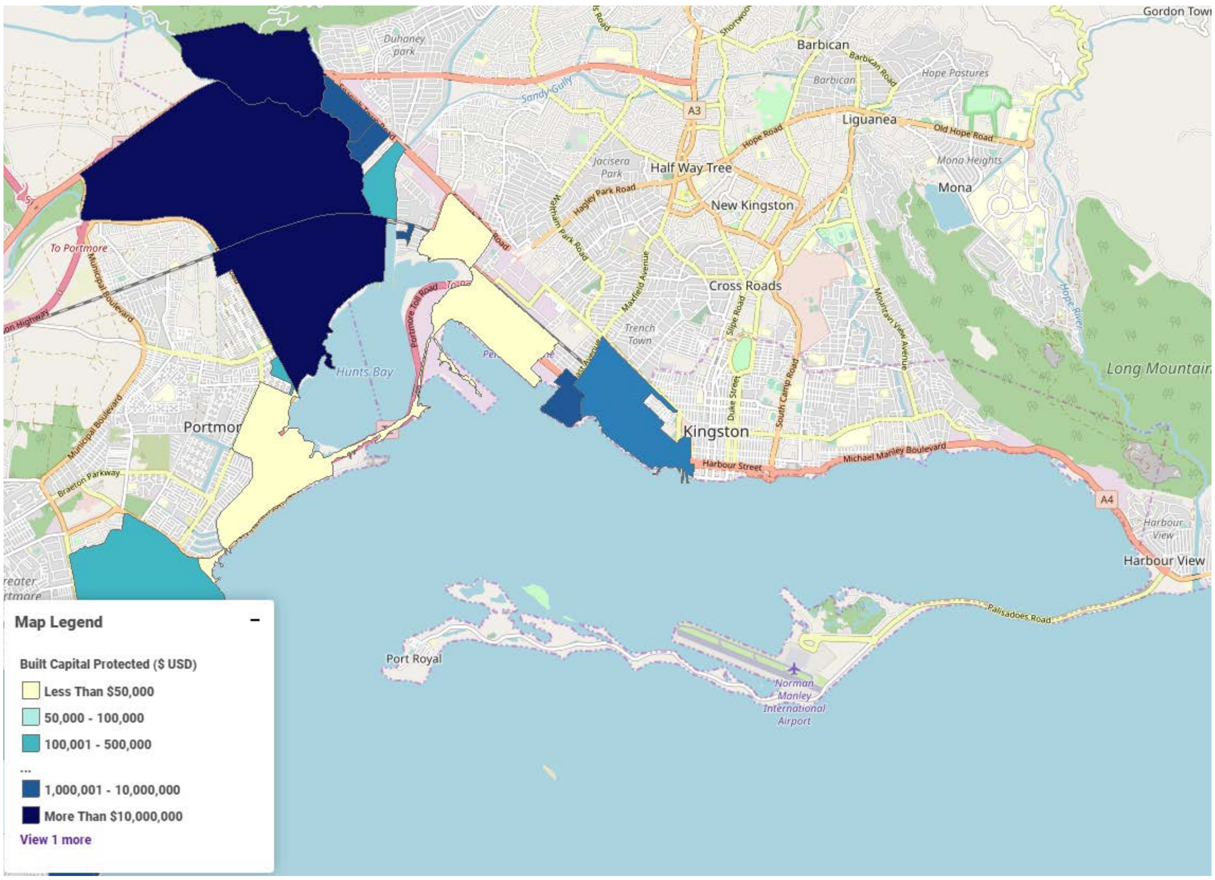

Figure 24: Mangrove Benefits by Enumeration District in Jamaica during a 1 in 100-year storm. This map is generated from an online mapping tool developed for this project and available at https://maps.coastalresilience.org/jamaica/

The size of the flood reduction benefits from mangroves depends on the original extent of flooding which will vary considerably depending on location and storm characteristics. Although not noticeable due to the scale of the maps, small floods below 0.5 m are expected to occur throughout the Jamaican coastline. As expected, due to the sharp topography that characterizes north Jamaica, flood extents are less extensive in the north than in the bays that make up the south coast. Maximum flood heights for a 1in 50-year cyclone can go up to 1.5 m in the most exposed areas of the country. The Morant Point Lighthouse to the west, the Hunt Bay in Kingston and Old Harbor Bay are the areas that suffer from more frequent and larger surges. In the western part of Old Harbor Bay, for example, the flooding from a 1 in 500-year cyclone can exceed 5 meters.

In general, mangroves reduce flooding extents and heights across all storm frequencies. The protective function of the mangroves against storm surge is shown in the bottom panels of Figure 25 in terms of flood height increase for the 50 and 500 years return periods. Comparisons of the mangrove and non-mangrove cases indicate higher effectiveness (more than 1 m increases) in the Black River Bay, where the intricate configuration of the channels and mangrove patches, which extend far inland, plays a fundamental role in slowing down the water. In other sites like the Moral Point, Kingston, Old Harbor Bay and some areas of the north coast, where mangroves are more coast aligned, the reduction of the flood height is less evident, with an average reduction of about 0.5 to 1 m for the 50 years return period. For the 500 years flood, the protection against flooding is more widespread. For such a long return period, areas like the Westmoreland Parish or Falmouth began to experience significant storm surge reduction (up to 2 m).

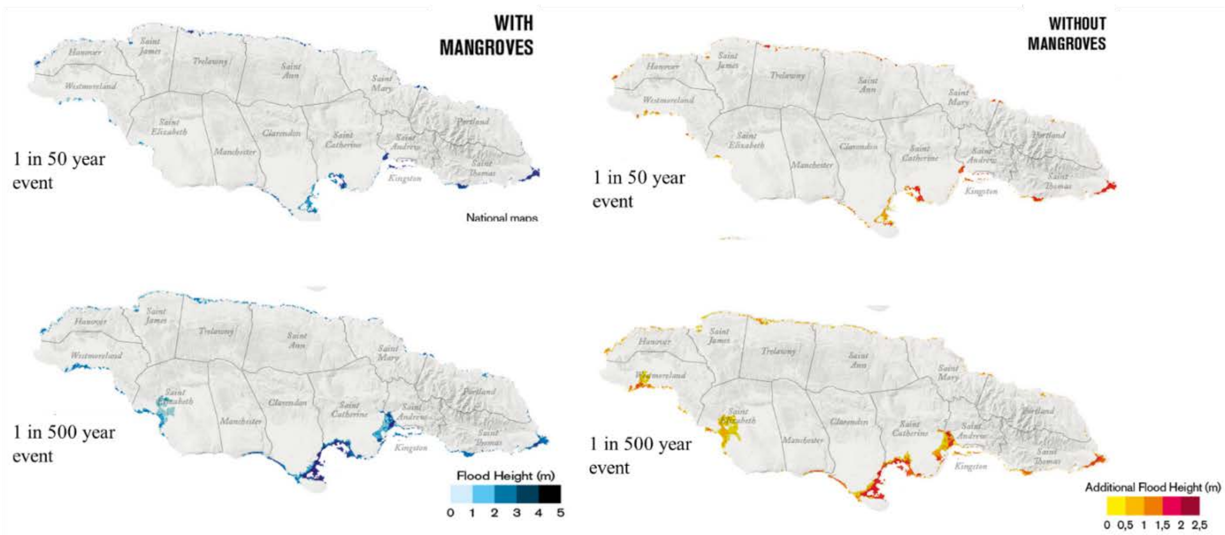

Figure 25: National maps of the flood heights associated to 50 and 500 years return periods (upper panels) and the differences of the mangrove-non-mangrove scenarios (bottom panels).

These decreases in flood extents translate directly to avoided flood damages to people and property. Thus, for tropical cyclones, mangroves reduce annual property damages by more than 23%, with an annual value of more than US$ 32 million [JMD 4.3 Billion]. 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 country. The protection benefits to people are highest in key areas in the south of the island, especially on the Kingston and Old Harbour bay areas. In other areas, such as Montego Bay for example, mangroves provide flood protection benefits but not to people or property. Most of the mangroves in the Montego Bay area are around the wastewater treatment plant and most of the changes in flooding are contained seaward of the plant and Bogue Road (Figure 30).

In some places, vulnerable populations (i.e. people under poverty) receive some of the flood protection benefits from mangroves, though these numbers are small due to the relatively low proportions of people below poverty that live in coastal areas. Damages over built capital can be separated into different stock categories: residential, industrial and services. This means that the protection offered by mangroves ($32.62 Million annually for all Jamaica) translates into a protection of $16.58 Million over residential stock (50% of total stock protected), $4.54 Million over industrial facilities (14%) and $11.38 Million protection over services stock (35% of total stock).

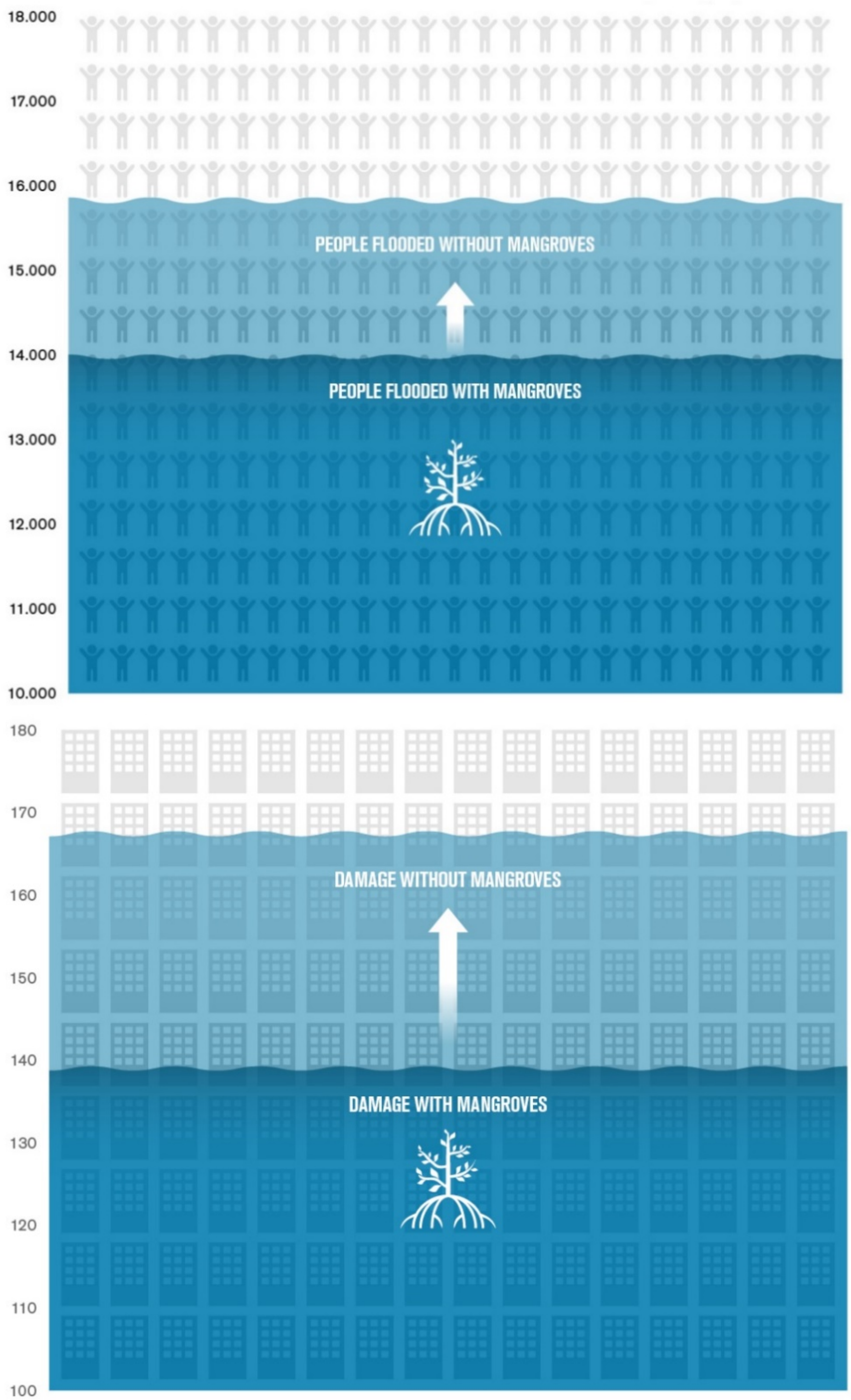

Figure 26: Current flood risk and Annual expected benefits from mangroves for flood risk reduction across Jamaica in terms of (averted) damages to people (Top panel) and property (Bottom panel).

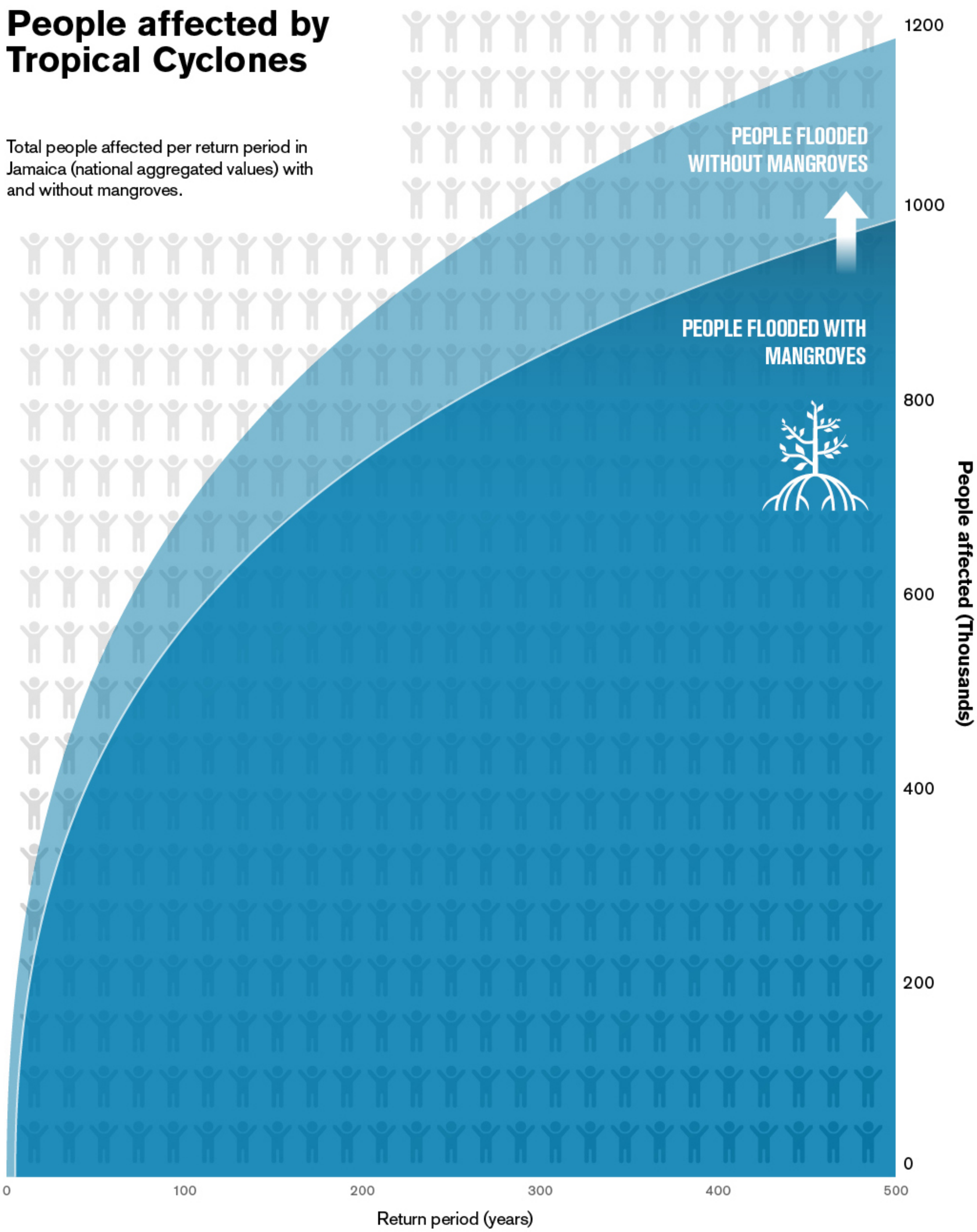

Figure 27: Total people affected per return period in Jamaica (national aggregated values) with and without mangroves.

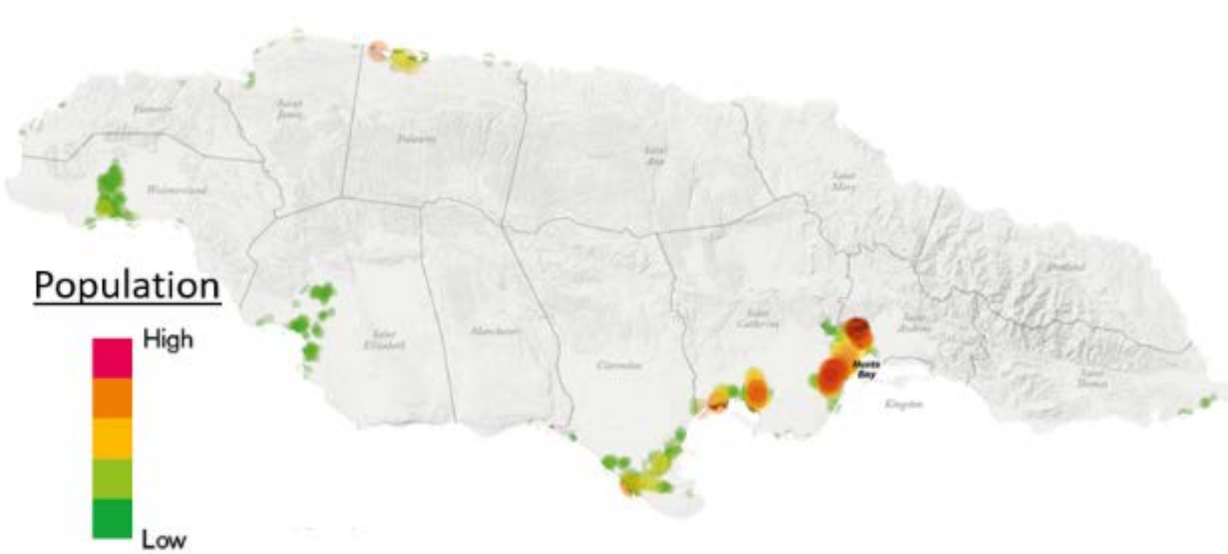

Figure 28: National distribution of the Annual Benefits provided by mangroves to people

Local scale

In addition to their risk reduction benefits at the national scale this study also analyzes the local-scale effects of mangroves on flooding from regular wave climate -induced flooding. For RWC flooding, the role of mangroves is very different depending on the zone of Jamaica considered. Figures 29 and 30 show the wave conditions with and without mangroves for two study sites: Old Harbor Bay including Portland Cottage, and Montego Bay.

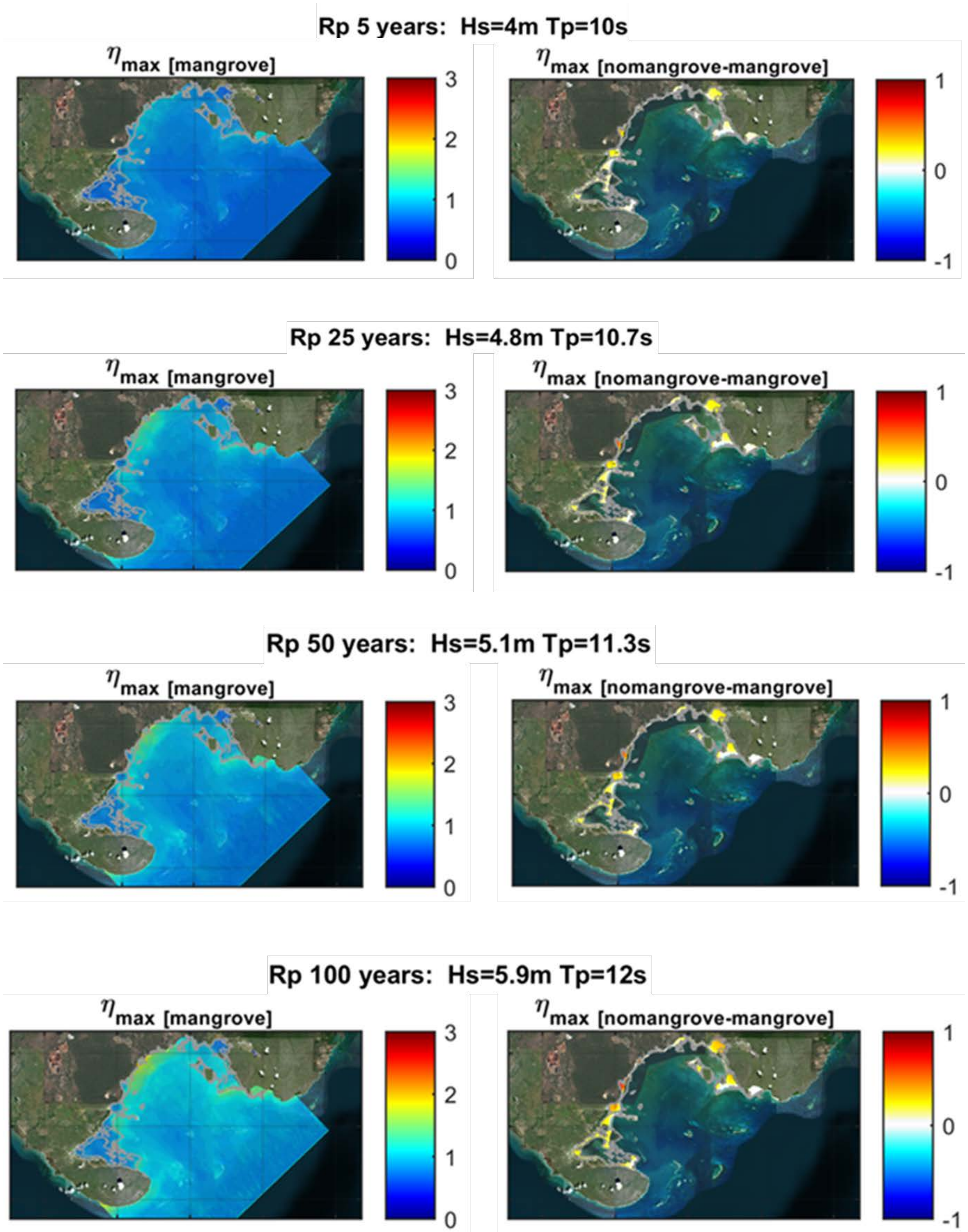

Figure 29: Results of the maximum water level for the 5, 25, 50 and 100 years return periods in Old Harbor Bay (left panels) and differences of the overland flood heights of the same simulations without mangroves. Mangrove forests are delimited by grey lines.

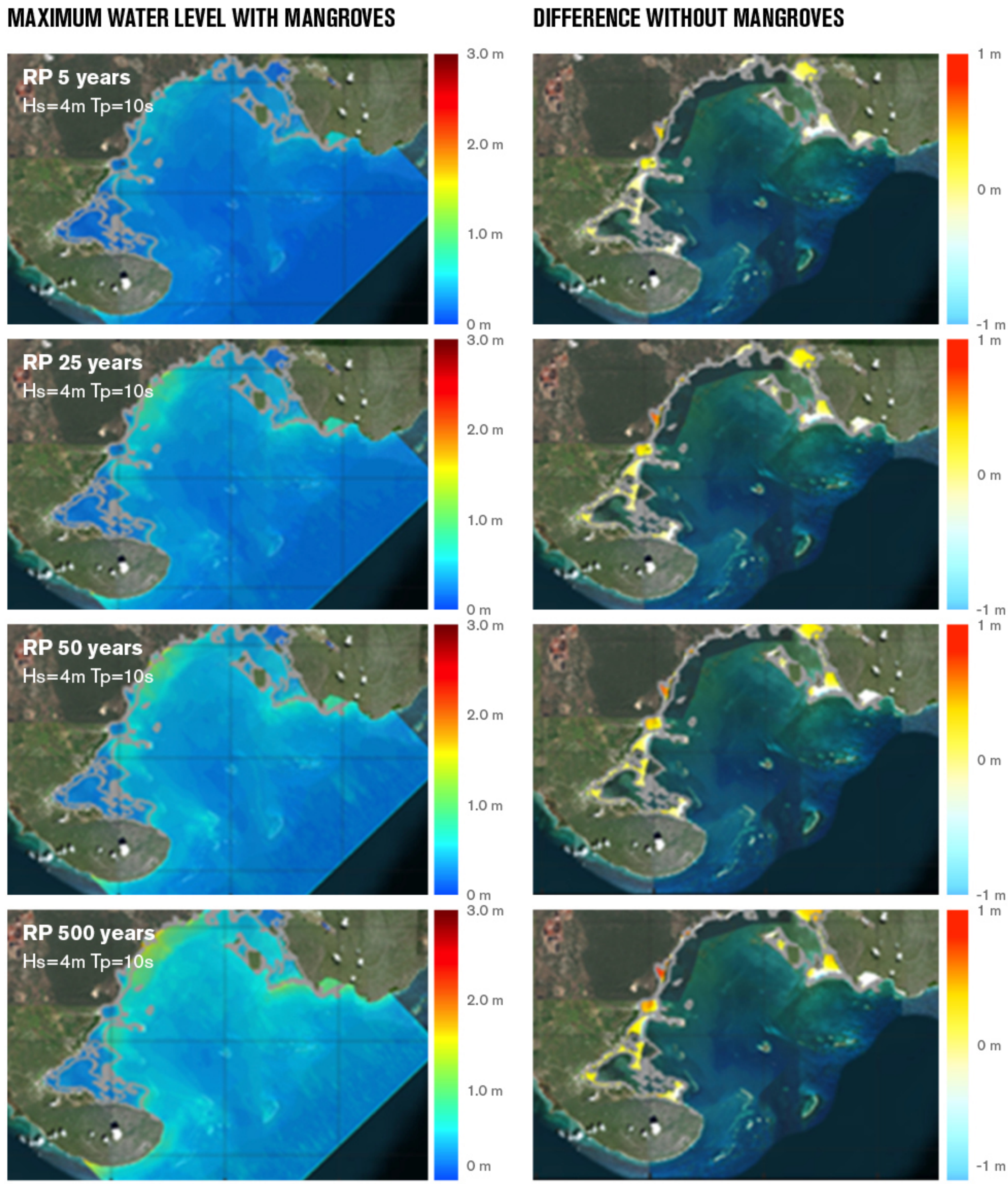

FIGURE 19

Results of the maximum water level for the 5, 25, 50 and 100 years return periods in Old Harbor Bay (left panels) and differences of the overland flood heights of the same simulations without mangroves. Mangrove forests are delimited by grey lines.

Hs: significant wave height
Tp: wave period
RP: storm period e.g., (1 in 5 year event).

Figure 30: Results of the maximum water level for the 5, 25, 50 and 100 years return periods in Montego Bay (left panels) and differences of the overland flood heights of the same simulations without mangroves. Mangrove forests are delimited by grey lines.

In Old Harbor Bay, the benefits from mangrove presence is most evident during more intense tropical cyclone events and are less apparent during smaller wave-driven flood events. Old Harbor Bay is oriented to the prevailing wave conditions (from the SE), nonetheless, wave propagation from offshore to the mangrove areas is interrupted by the presence of shallow fringing reefs that produce dramatic wave dissipation due to wave breaking. Despite this attenuation, results show a clear increase of the total water level (in this case produced by the steady wave setup and the infragravity component of the wave runup) ranging between 0.8 m (5 years return period) and 1.8 m (100 years return period) in the center of the bay. The role of the mangroves is evident as water levels remain under 1 m over the forested areas (Peake, Colon and Santa Helena Bays) for wave conditions below 50 years return period. Maximum water levels are predicted between Port Esquivel and the Old Harbor power plant were the mangrove is not present. According to these results, most of the population in Old Harbor Bay is not at risk due to wave-driven flood, including the most vulnerable settlements such as Portland Cottage. Even the without mangroves scenario does not suppose great changes, with average differences below 0.4 m for the 100 years return period. These differences can be largest (around 1 m for the 100 years wave conditions) in the inner parts of the mangrove forest as to the right of the Salt river or leewards the Great Goat island. In these places, two combined factors make the attenuation more evident: on the one hand, the waves have a more perpendicular incidence, and, on the other hand, it is where mangroves fields have greater widths with respect to the angle of incidence of the waves.

Flood height differences, which are apparently small, translate into protection for people and built capital. For regular climate, in presence of mangroves, annualized damages on built stock reach $16.27 Million [JMD 2.2 Billion]. Without mangroves, these damages would reach $19.72 Million [JMD 2.6 Billion]. This means that in the Old Harbor Bay study site mangroves protect $3.45 Million [JMD 470 Million] in built stock every year. For extreme events, national level data shows that protection from mangroves against tropical cyclones adds an extra $1.69 Million [JMD 230 Million] in annual benefits at the study site. These figures translate into a total value of $1,454 /ha/yr [JMD 198,355 /ha/yr].

Benefits of Potential Mangrove Restoration

Comparisons of local flooding in Old Harbour Bay for baseline (2005) and degraded (2013) mangrove extents show that the degradation suffered by mangrove cover translates into an increase in flood height in a range varying from 0 to 0.40 meters, reaching in some areas an exceptional 0.80 meters (see figure 31, bottom). This translates to the value of the lost mangrove area between 2005 and 2013 (1811 ha) being $990 /ha/yr [JMD 135,056 /ha/yr] accounting for an annual total of $1.79 Million [JMD 244 Million] of lost mangrove benefits in Old Harbour Bay.

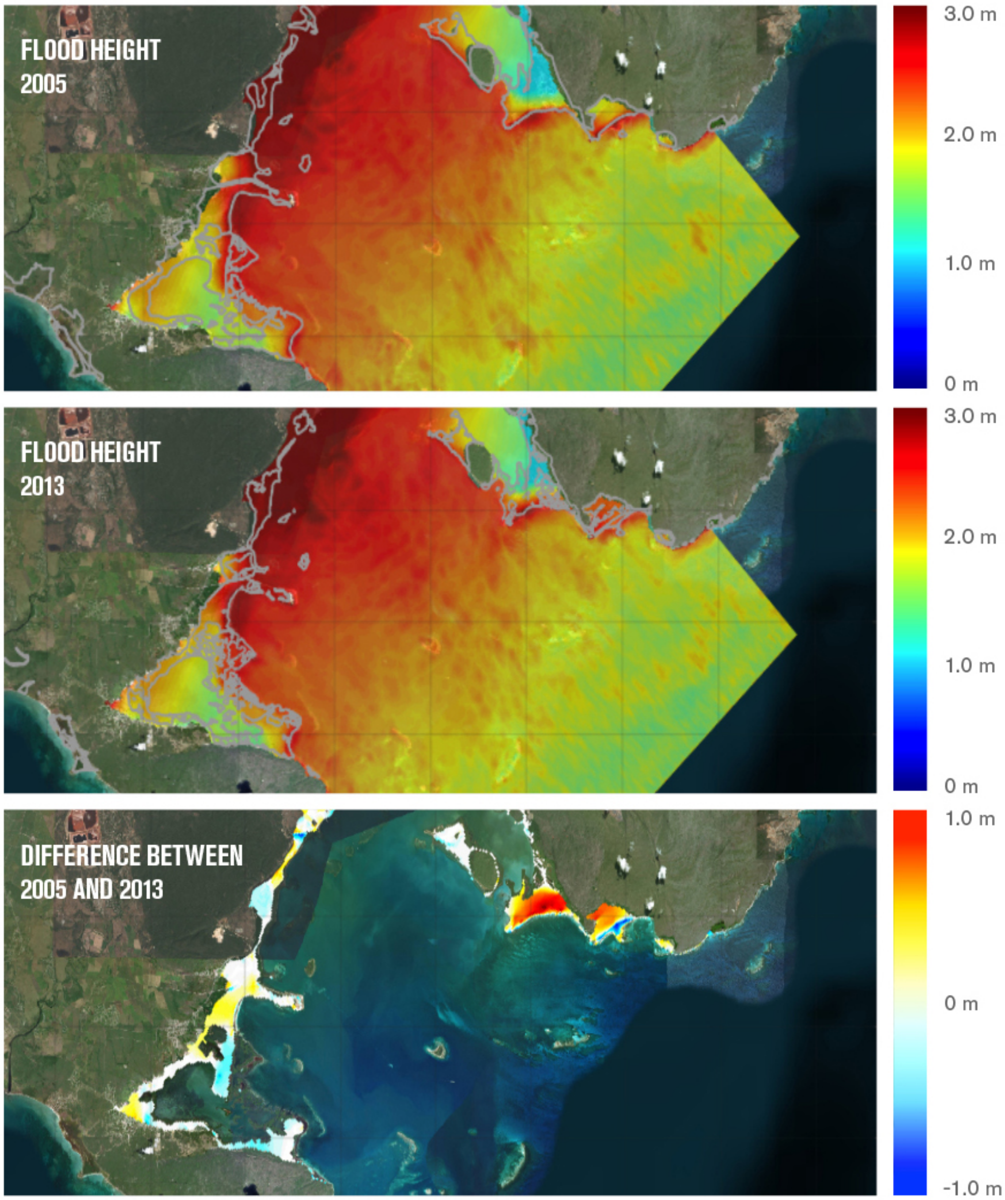

Figure 31: Results of the flood height comparison between 2005 and 2013 mangrove extents for a 50-years return period tropical cyclone event. Top: Flood extent for 2005 mangroves (GOJ data). Middle: Flood extent for 2013 mangroves (TNC data). Bottom: Differences

In Montego Bay mangroves provide the most protection for wave conditions below a 1 in 50 year return period. Surprisingly, there is less attenuation of the maximum water levels for the 100 years return period wave conditions. This effect is due to the appearance of resonant modes within the bay as it increases the wave period. However, as explained above, in this case there is no direct protection on assets or population, mainly because these elements are not located in the area directly protected by the mangroves.

But even in cases where mangroves do not reduce wave or surge levels greatly, or offer protection to socio-economic assets, they also offer benefits in terms of trapping sediments and building elevation. In many situations, and under the right conditions, these mangroves can keep pace with rising sea-levels.

In addition to the analyses of the synthetic hurricane database, this study also looked at the flooding from significant historic hurricanes that made landfall in Jamaica. Across Jamaica's long history of hurricanes, Hurricane Dean stands out as the strongest cyclone to struck Jamaica in recent years. Dean took a west-northwest path from the eastern Atlantic Ocean through the Saint Lucia Channel and into the Caribbean. It strengthened into a major hurricane, reaching Category 4 status on the Saffir–Simpson hurricane wind scale before passing just south of Jamaica on August 19-20. Even without making a direct hit, Dean brought hurricane conditions to most parts of Jamaica with heavy rain, high winds, huge waves and storm surge. Hurricane Dean affected more to the eastern and southeastern parishes of Jamaica. In Rocky Point and Portland Cottage, 889 houses sustained damage to varying intensity. Approximately 65% of these housing units sustained major damage or were destroyed due to the storm surge (Office of disaster and emergency management, 2007). This study shows the places where the presence of coastal mangroves helped reduce flooding and flood damages during Hurricane Dean in Jamaica (Figure 31). It is noteworthy how, despite the presence of a large mangrove forest around the Portland Cottage, the water level exceeded 4 m above the mean sea level, and the water passed from West Harbor to the Carlisle Bay. The comparison between both scenarios indicates that mangroves were able to reduce water levels around 0.3 and 0.6 m. This apparently small contribution was responsible of Mitchell Town remaining safe against Dean's storm surge thanks to the protective role of the mangroves, otherwise, a 1 m water layer would have covered the streets of the village.

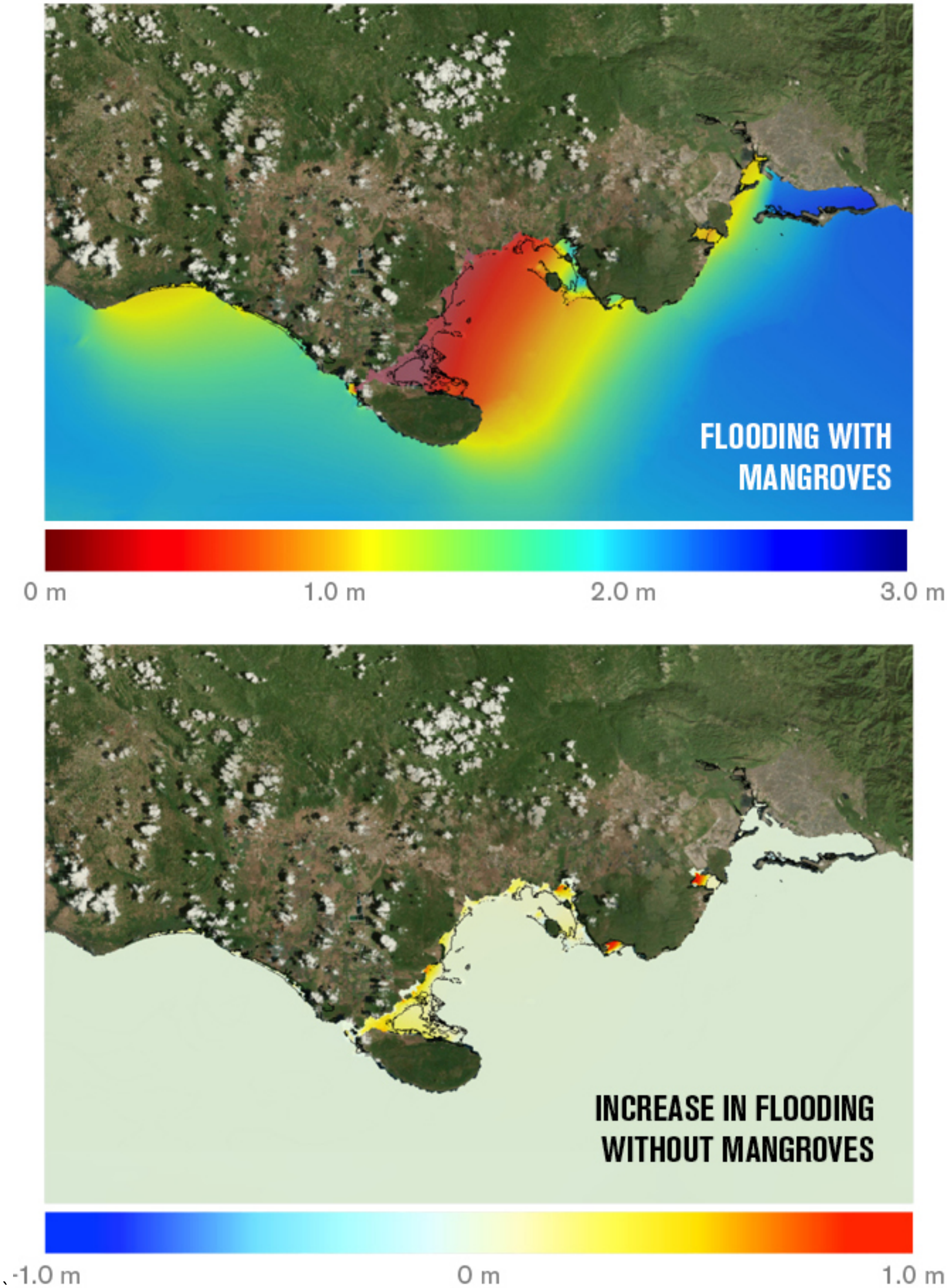

Figure 32: Storm surge along the southwestern Jamaica produced by hurricane Dean in August 2007 for the mangrove scenario (upper panel) and differences of removing mangroves from the model setup (bottom panel).

Discussion and Conclusions

Jamaica faces substantial flood risk from coastal storms and mangroves provide substantial flood risk reduction benefits. Annually, the value of Jamaica's mangrove forests for flood risk reduction to the nation's built capital is more than $2,500 [JMD 336,000] per hectare per year. This represents a nearly 24% annual reduction in flood risk. The loss of Jamaica's mangroves would further result in a 10% increase in the total number of people flooded every year. Mangrove benefits are most apparent for high intensity storms of 1 in 500-year return periods. During these storms, mangrove forests protect 770,000 people and nearly $2.4 Billion [JMD 322 Billion] or 50% of the total affected population and built capital. This translates to economic benefits of more than $186 Million [JMD 25 Billion] per hectare of mangroves.

Additional analyses of recently lost mangroves in Old Harbour Bay show that the loss of these mangroves has resulted in the loss of flood protection benefits of more than $1 Million [JMD 136 Million] each year. Conversely, this represents the potential value of restored mangroves in this region at almost $1,000/ha/yr [JMD 136,000 /ha/yr]. As we describe in our assessment of mangrove habitat status across Jamaica, the loss and gain of mangrove extents is a mixed story. While a lot of areas like Old Harbour Bay have lost critical and valuable mangroves over the last decade, other areas such as parts of Kingston have also seen valuable gains in mangrove extents which in turn can be expected to offer valuable additional flood protection benefits.

These results are obtained using the best available datasets and a high-resolution process-based model. These datasets and model come with inherent limitations in their ability to represent reality. Previous studies by our team and others have identified topography as one of the key datasets for accurate representation of coastal flooding (Menendez et al., 2018; Others). Here we obtain and use a highly accurate 6 m LIDAR topography dataset for the entire country which represents a significant improvement over previous assessments.

One limitation of this study is the availability of high-resolution bathymetry which is crucial for estimating nearshore and coastal waves and water levels. To overcome this, we combine a freely available global 1 km dataset for offshore analyses with a commercially obtained 10 m resolution dataset for Jamaica, for the analyses of nearshore and coastal regions. We use a state-of-art numerical modelling system (ADCIRC + SWAN) to accurately represent nearshore coastal wave and water levels and their interaction with mangrove vegetation.

In this model we use of uniform friction coefficient to represent the effect of mangroves. Based on published studies, constant values have been assumed throughout Jamaica, which roughly represent the friction associated to these ecosystems. More detailed models such as we use for the mangrove benefit assessments in Old Harbour Bay and Montego Bay can use detailed information on structural parameters of a mangrove forest (such density, trunk width, vertical structure) which would help improve the estimation of waves and storm surge by calculating the forces of drag produced by each single submerged element of the plant. These data have now been collected for three sites in Jamaica by the University of West Indies (Mandal et al., 2019). and will be collected by the National Environmental Protection Agency (NEPA) of Jamaica in future mangrove monitoring efforts.

The restoration potential analyses are based on available spatial datasets of mangrove extents for the country. More detailed assessments of realistic restoration potential will require refined analyses of land-use patterns across the country to identify where mangrove restoration action will be possible versus not (for example, it will be difficult to restore mangroves in areas that have since been converted to intense urban use such as an airport).

Mangrove restoration costs are influenced by factors unique to coastal and inter-tidal ecosystem restoration projects. Since these typically happen in the inter-tidal zone, the availability and price of land are important factors. Large-scale projects on government owned land typically have much lower unit costs than smaller projects on private lands (Lewis, 2001). Another critical issue is ease of permitting for activity in offshore and inter-tidal locations, especially in countries like the U.S.A where the modification of coastal and marine waters is governed by strict regulations. While in some locations like Florida the clearing of existing mangrove forests cannot happen without a permit, similarly, new activity in coastal waters – including ecological restoration – also requires permits from multiple agencies. This process can often be time-consuming and costly (Bilkovic et al., 2017). Larger projects on government-owned land typically have easier, expedited permitting processes than projects on private land, substantially reducing these initial costs. For restoration projects that primarily involve mangrove planting, labor costs and the availability of volunteers to offset these costs can make a significant difference to the overall cost of the project. Often, restoration projects involve voluntary mangrove planting activities that are also combined with outreach and education initiatives. Projects involving hydrological restoration and sediment management can be substantially more expensive due to the need for specialized equipment, labor and, in some cases, the purchase and transportation of sediment from external sources. While most projects reviewed here do not report maintenance and monitoring costs and efforts, this is nevertheless an important and significant aspect of successful mangrove restoration. Examples of mangrove maintenance include clearing debris after hurricanes, removing invasive species and maintaining hydrological flows. The costs of these activities will depend on the scale of the project and the availability of volunteers.

The factors influencing the costs of coastal protection structures are broadly similar to the factors for restoration projects. Typically, coastal structures like seawalls and levees take up less space than a mangrove restoration project, though the taller a structure, the more space it generally requires, and the costlier it becomes (Aerts, 2018; Ward et al., 2017). Artificial structures can also be costly to build in terms of material, labor and expertise; and costly to maintain in terms of repairing damage or upgrading in response to changes in sea-level. Offshore structures such as sea dykes or offshore breakwaters are typically costlier due to more difficult working environments. The costs of offshore structures will also be significantly influenced by the depth of water at the installation site (Narayan et al., 2016).

Implications and the Way Forward

Mangrove conservation and restoration can be an important part of the solution for reducing coastal risks in the Jamaica, especially as those risks increase with climate change. This Report provides a social and economic valuation of mangroves that can inform the policy and practice of many Jamaican agencies, businesses and organizations across development, aid, 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 finance and development 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 in the Jamaica.

These results have important implications for the consideration of nature-based solutions within adaptation, insurance, hazard mitigation and disaster recovery decisions. The results presented here show that mangroves offer significant benefits for flood risk reduction and that restoring mangroves can be cost effective for flood risk reduction particularly when compared to the costs of grey infrastructure.

These results can be used by public agencies to inform hazard mitigation and disaster recovery funding decisions. Following hurricanes (for example from the 2017 season) significant aid and support has flowed in to the Caribbean and much of this support is going to build or re-build gray infrastructure including dikes, levees and seawalls. The results presented here show that it can also make economic sense to support restoration of mangrove with disaster recovery funds.

The work by FEMA in Puerto Rico and the US Virgin Islands illustrates opportunities for considering how to direct recovery funds to more nature-based solutions. For example, FEMA is actively working to identify where reef restoration may meet requirements for funding from the 2017 hurricane recovery funding. The key criterion for eligibility for FEMA disaster recovery funding is to show that the reef restoration projects achieve, say over a 25-year period, a flood reduction benefit (B) that exceeds the cost (C) of habitat restoration (i.e. a B:C ratio > 1). In the past nature-based measures for coastal protection, such as mangrove restoration, were not assessed for their cost effectiveness for risk reduction, because rigorous values of their coastal protection benefits were missing. These services can now be rigorously valued to inform national accounting, cost-benefit analyses and comparisons of different coastal protection options, including natural, hybrid and built defenses. Many funders (from development banks to climate adaptation funds) could be compelled by assessments that show where nature-based solutions such as mangrove restoration have B:C > 1. This assessment provides. much of the core material for such a benefit cost assessment across the country and this same approach could be applied widely throughout the Caribbean.

The results presented here on flood reduction benefits and costs also could be used to support national applications to the green climate fund, World Bank, IDB and other supporters of infrastructure, risk reduction and adaptation projects in the region. Even where these costs of restoration may seem high it is important to note that (i) the benefits of restoration can extend over long time periods, (ii) include indirect flood reduction benefits (i.e. to especially vulnerable populations) and (iii) also include many co-benefits such as fisheries and tourism.

Numerous programs can incorporate these results into their plans and analysis, including, but not limited to, the National Environment and Planning Agency (NEPA), Office of Disaster Preparedness and Emergency Management (ODPEM), Water Resources Authority (WRA), National Works Agency (NWA), Jamaica Social Investment Fund (JSIF) and the Planning Institute of Jamaica (PIOJ).

These results can be considered in risk industry models, which may influence insurance premiums in Jamaica and the development of innovative finance mechanisms to support mangrove management. Catastrophic hazard bonds, resilience bonds, and blue bonds among others could use the risk reduction benefits of mangroves to support habitat conservation and restoration.

This work can also be used to inform the development of insurance approaches like those being tested on the MesoAmerican Reef in Mexico (Reguero et al., 2019) where a policy has been taken out on the reef based on the flood protection benefits to coastal hotels and the Mexican economy. The value of the policy was determined in part by the costs of restoring benefits if the reef were damaged in a storm. We can now test similar approaches in Jamaica.

References

Aerts, J., 2018. A Review of Cost Estimates for Flood Adaptation. Water 10, 1646.

Arcement, G. J., and V. R. Schneider, 1989: Guide for selecting Manning's roughness coefficients for natural channels and flood plains. U.S. Geological Survey Water Supply Paper 2339, U.S. Geological Survey, Denver, CO, 38 pp.

Baldwin, A., Egnotovich, M., Ford, M., Platt, W., 2001. Regeneration in fringe mangrove forests damaged by Hurricane Andrew. Plant Ecol. 157, 151–164.

Barbier, E.B., Burgess, J.C., Dean, T.J., 2018. How to pay for saving biodiversity. Science (80-.). 360, 486–488.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193.

Barnes, H. H., 1967: Roughness characteristics of natural channels. U.S. Geological Survey Water Supply Paper 1849, U.S. Geological Survey, Washington, DC, 213 pp

Bayraktarov, E., Saunders, M.I., Abdullah, S., Mills, M., Beher, J., Possingham, H.P., Mumby, P.J., Lovelock, C.E., 2016. The cost and feasibility of marine coastal restoration. Ecol. Appl. 26, 1055–1074.

Beck, M.W., Lange, G.-M., 2015. Guidelines for Coastal and Marine Ecosystem Accounting: Incorporating the Protective Service Values of Coral Reefs and Mangroves in National Wealth Accounts, Wealth Accounting and Valuation of Ecosystem Services. World Bank, Washington D.C.

Beck, M.W., Lange, G.M., 2016. Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs. Washington, D.C.

Beck, M.W., Losada, I.J., Menéndez, P., Reguero, B.G., Díaz-Simal, P., Fernández, F., 2018. The global flood protection savings provided by coral reefs. Nat. Commun. 9, 2186.

Beetham, E. P., Kench, P. S., O'callaghan, J., & Popinet, S. (2015). Wave transformation and shoreline water level on Funafuti Atoll, Tuvalu. Journal of Geophysical Research: Ocean, 120, 1–16. https://doi.org/10.1002/2014JC010472

Bilkovic, D., Mitchell, M., Peyre, M. La, Toft, J. (Eds), 2017. Living shorelines: the science and management of nature-based coastal protection. CRC Press.

Blankespoor, B., Dasgupta, S., Lange, G., (2017). Mangroves as a protection from storm surges in a changing climate. Ambio, 46, 478-491. doi:10.1007/s13280-016-0838-x

Bretschneider C.L., H.J. Krock, E. Nakazaki, F.M. Casciano (1986). Roughness of Typical Hawaiian Terrain for Tsunami Run-Up Calculations: A Users Manual. J.K.K. Look Laboratory Report, University of Hawaii, Honolulu.

Bunting, P., 2019. Global Mangrove Watch Datasets [WWW Document]. JAXA Kyoto Carbon Initiat. URL https://www.globalmangrovewatch.org/datasets/

Cheriton, O. M., Storlazzi, C. D., & Rosenberger, K. J. (2016). Observations of wave transformation over a fringing coral reef and the importance of low-frequency waves and offshore water levels to runup, overwash, and coastal flooding. Journal of Geophysical Research: Ocean, 121, 3121–3140. https://doi.org/10.1002/2015JC011231

Chow, V. T., 1959: Open-Channel Hydraulics. McGraw-Hill Book Company, 680 pp.

Cortés, J., Oxenford, H.A., van Tussenbroek, B.I., Jordán-Dahlgren, E., Cróquer, A., Bastidas, C., Ogden, J.C., 2019. The CARICOMP Network of Caribbean Marine Laboratories (1985–2007): History, Key Findings, and Lessons Learned . Front. Mar. Sci. .

Daily, G.C., 1997. Nature's services. Island Press, Washington, DC.

Dalrymple, R.; Kirby, J., and Hwang, P., 1984. Wave diffraction due to areas of energy dissipation. Journal of Waterway, Port, Coastal and Ocean Engineering, 110(1), 67–69.

Dietrich, J.C., Zijlema, M., Westerink, J.J., Holthuijsen, L.H., Dawson, C.N., Luettich, R.A. Jr., Jensen, R.E., Smith, J.M., Stelling, G.S., Stone, G.W. (2012). Modeling hurricane waves and storm surge using integrally-coupled, scalable computations. Coast. Eng. 58, 45–65

Doyle, T., III, T.S., Robblee, M., 1995. Wind damage effects of Hurricane Andrew on mangrove communities along the southwest coast of Florida, USA. J. Coast. Res. 21, 159–168.

Doyle, T.W., Krauss, K.W., Conner, W.H., From, A.S., 2010. Predicting the retreat and migration of tidal forests along the northern Gulf of Mexico under sea-level rise. For. Ecol. Manage. 259, 770–777.

Edwards, P.T. Valuation of Selected Ecosystem Service Co-Benefits Beyond Coastal Protection. World Bank, 2019. Kingston, Jamaica.

FAO, 2005. Global Forest Resources Assessment 2005: Thematic Study on Mangroves: Jamaica Country Profile.

FEMA 511. (n.d.). Barriers. In Selecting Appropriate Mitigation Measures for Flood prone Structures. (chapter 5). https://www.fema.gov/media-library-data/20130726-1608-20490-6445/fema551_ch_05.pdf

Galeano, A., Urrego, L.E., Botero, V., Bernal, G., 2017. Mangrove resilience to climate extreme events in a Colombian Caribbean Island. Wetl. Ecol. Manag. 25, 743–760.

Gawehn, M., van Dongeren, A. R., van Rooijen, A., Storlazzi, C. D., Cheriton, O. M., & Reniers, A. J. H. M. (2016). Identification and classification of very low frequency waves on a coral reef flat. Journal of Geophysical Research: Ocean, 121, 7560–7574. https://doi.org/10.1002/2016JC011834

Gilman, E.L., Ellison, J., Duke, N.C., Field, C., 2008. Threats to mangroves from climate change and adaptation options: A review. Aquat. Bot. 89, 237–250.

Government of Jamaica, 2017. National Forest Management and Conservation Plan (NFMCP).

Hagen, S.C., Westerink, J.J., and Kolar, R.L. (2001), One dimensional finite element grids based on a localized truncation error analysis, International Journal for Numerical Methods In Fluids, 32 (2): 241-261.

Hagger, V., Dwyer, J., Wilson, K., 2017. What motivates ecological restoration? Restor. Ecol. 25, 832–843.

Heck, N., Narayan, S., Beck, M.W., Acosta-Morel, M., 2019. Benefits of Mangroves and Coral Reefs in the Caribbean. The Nature Conservancy, 2019. Dominican Republic.

Henry, A., Webber, D., Webber, M., 2018. Rapid Assessment Methods Developed for the Mangrove Forests of the Great Morass, St. Thomas, Eastern Jamaica. In: Dorney, J., Savage, R., Tiner, R.W., Adamus, P. (Eds.), Wetlands and Stream Rapid Assessments. Academic Press, London, UK, pp. 529–538.

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. Proc. Natl. Acad. Sci. U. S. A. 111, 3292–7.

Hoeke, R. K., McInnes, K., Kruger, J., McNaught, R. J., Hunter, J. R., & Smithers, S. G. (2013). Widespread inundation of Pacific islands triggered by distant-source wind-waves. Global and Planetary Change, 108, 128–138. https://doi.org/10.1016/j.gloplacha.2013.06.006

Holland, G. J. (1980), An analytic model of the wind and pressure profiles in hurricanes. Mon. Wea. Rev. 108, 1212-1218.

Huizinga, J., H. De Moel, W. Szewczyk. 2017. Global flood depth-damage functions: Methodology and the database with guidelines. Publications Office of the European Union.

Imbert, D., 2018. Hurricane disturbance and forest dynamics in east Caribbean mangroves. Ecosphere 9, e02231.

Jennerjahn, T.C., Gilman, E., Krauss, K.W., Lacerda, L.D., Nordhaus, I., Wolanski, E., 2017. Mangrove Ecosystems under Climate Change BT - Mangrove Ecosystems: A Global Biogeographic Perspective: Structure, Function, and Services. In: Rivera-Monroy, V.H., Lee, S.Y., Kristensen, E., Twilley, R.R. (Eds.), . Springer International Publishing, Cham, pp. 211–244.

Kauffman, J.B., Heider, C., Norfolk, J., Payton, F., 2014. Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. Ecol. Appl. 24, 518–527.

Knapp, K. R., M.C. Kruk, D.H. Levinson, H.J. Diamond, and C.J. Neumann (2010), The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. Bull. Am. Meteorol. Soc. 91, 363-376.

Krauss, K.W., Doyle, T.W., Doyle, T.J., Swarzenski, C.M., From, A.S., Day, R.H., Conner, W.H., 2009. Water level observations in mangrove swamps during two hurricanes in Florida. Wetlands 29, 142–149.

Krauss, K.W., From, A.S., Doyle, T.W., Doyle, T.J., Barry, M.J., 2011. Sea-level rise and landscape change influence mangrove encroachment onto marsh in the Ten Thousand Islands region of Florida, USA. J. Coast. Conserv. 15, 629–638.

Krauss, K.W., McKee, K.L., Lovelock, C.E., Cahoon, D.R., Saintilan N., et al. (2014). How mangrove forests adjust to rising sea level. New Phytol. 202:19–34

Lewis, R.R.I.I.I., 2001. Mangrove restoration-Costs and benefits of successful ecological restoration. In: Proceedings of the Mangrove Valuation Workshop, Universiti Sains Malaysia, Penang.

Losada, I.J., Beck, M., Menendez, P., Espejo, A., Torres, S., Diaz-Simal, P., Fernandez, F., Abad, S., Ripoll, N., Garcia, J., Narayan, S., Trespalacios, D., Quiroz, A., 2017. Valuing Protective Services of Mangroves in the Philippines: Technical Report. World Bank, Washington, DC.

Losada, I.J., Menendez, P., Espejo, A., Torres-Ortega, S., Diaz-Simal, P., Abad, S., Beck, M.W., Narayan, S., 2018. The Global Value of Mangroves for Risk Reduction. Berlin.

Luettich, R.A. and Westerink, J.J., 2004. Formulation and numerical implementation of the 2D/3D ADCIRC finite element model version 44. XX (p. 74). R. Luettich.

Madren, C. (2012). Mangroves in the mist. http://www.americanforests.org/magazine/article/mangroves-in-the-mist/

Madsen, O., Poon, Y., and Graber, H. (1988). Spectral wave attenuation by bottom friction: Theory, paper presented at the 21st International Conference on Coastal Engineering, American Society of Civil Engineers, 978-0-87262-687-4 / 0-87262-687-3, 1989, 3040 pp., 3 vols, Torremolinos, Spain.

Mandal, A., Smith, R.A., Edwards, T., Kinlocke, R., Mitchell, S., Webber, M., Trench, C., Francis, P., Spence, A. Local Scale Assessments on Mangrove Ecosystems Status and their Role in Coastal Resilience. World Bank, 2019. Kingston, Jamaica.

Mazda, Y., Magi, M., Kogo, M., & Hong, P. N. (1997). Mangroves as a coastal protection from waves in the Tong King delta, Vietnam. Mangroves and Salt Marshes, 1, 127-135. https://doi.org/10.1023/A:1009928003700

McDonald, K.O., Webber, D.F., Webber, M.K., 2003. Mangrove forest structure under varying envrionmental conditions. Bull. Mar. Sci. 73, 491–505.

McIvor, A.L., Spencer, T., Möller, I., Spalding, M., 2013. The response of mangrove soil surface elevation to sea level rise. Nat. Coast. Prot. Ser. Rep. 3.

McKee, K.L., Cahoon, D.R., Feller, I.C., 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. Glob. Ecol. Biogeogr. 16, 545–556.

Mendez, F.J., Losada, I.J., 2004. An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields. Coast. Eng. 51, 103–118.

Menéndez, P., Losada, I.J., Beck, M.W., Torres-Ortega, S., Espejo, A., Narayan, S., Díaz-Simal, P., Lange, G.-M., 2018a. Valuing the protection services of mangroves at national scale: The Philippines. Ecosyst. Serv. 34, 24–36.

Menéndez, P., Losada, I.J., Beck, M.W., Torres-Ortega, S., Espejo, A., Narayan, S., Díaz-Simal, P., Lange, G.-M., 2018b. Valuing the protection services of mangroves at national scale: The Philippines. Ecosyst. Serv. 34, 24–36.

Menz, M.H.M., Dixon, K.W., Hobbs, R.J., 2013. Hurdles and opportunities for landscape-scale restoration. Science (80-.). 339, 526–527.

Millenium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Wetlands and Water Synthesis. Island Press, Washington DC.

Mott McDonald, 2007. Falmouth Cruise Terminal Environmental Impact Assessment. Surrey, UK.

Millennium Ecosystem Assessment (2005). Ecosystems and human well-being: Synthesis. Island Press, Washington, DC.
National Oceanic and Atmospheric Administration (2017). Costliest U.S. tropical cyclones tables updated. https://www.nhc.noaa.gov/news/UpdatedCostliest.pdf

Nakajo S., N. Mori, T. Yasuda, and H. Mase (2014), Global Stochastic Tropical Cyclone Model Based on Principal Component. Journal of Applied Meteorology and Climatology, 53, 1547-1577.

Nakka, S., 2010. Engineering Response to Global Sea Level Rise: Case Study - Port of Kingston, Jamaica. Stanford University.

Narayan, S., Beck, M.W., Reguero, B.G., Losada, I.J., van Wesenbeeck, B., Pontee, N., Sanchirico, J.N., Ingram, J.C., Lange, G.-M., Burks-Copes, K.A., 2016. The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. PLoS One 11, e0154735.

Narayan, S., Bitterwolf, S., Beck, M.W., Acosta-Morel, M., 2019. The Costs of Mangrove and Reef Restoration Relative to Coastal Protection Structures in the Caribbean. The Nature Conservancy, 2019. Dominican Republic.

Narayan, S.; Suzuki, T.; Stive, M.J.; Verhagen, H.; Ursem, W., and Ranasinghe, R., (2011) .On the effectiveness of mangroves in attenuating cyclone-induced waves. Coastal Engineering Proceedings, 1(32), waves.50. doi:https://doi.org/10.9753/icce.v32.waves.50.

NEPA, 2013. State of the Environment Report. Planning Institute of Jamaica, 2004. Macro-Socio-Economic and Environmental Assessment of the Damage done by Hurricane Ivan Sept 10-12, 2004.

Passeri, D., Hagen, S., Smar, D., Alimohammadi, N., Risner, A., White, R. (2011), Sensitivity of an ADCIRC tide and storm surge model to Manning's n. Estuar. Coast. Model.

Pearson, S. G., Storlazzi, C. D., van Dongeren, A. R., Tissier, M. F. S., & Reniers, A. J. H. M. (2017). A Bayesian-based system to assess wave-driven flooding hazards on coral reef-lined coasts. Journal of Geophysical Research: Oceans, 122, 10,099–10,117. https://doi.org/10.1002/2017JC013204

Perez, J., Menendez, M. & Losada, I. J. (2017). GOW2: a global wave hindcast for coastal applications. Coast. Eng. 124, 1–11

Primavera, J.H., Savaris, J.P., Bajoyo, B.E., Coching, J.D., Curnick, D.J., Golbeque, R.L., Guzman, A.T., Henderin, J.Q., Joven, R. V, Loma, R.A., 2012. Manual for community-based mangrove rehabilitation, Mangrove Manual Series. Zoological Society of London, London, UK.

Reguero, B.G., Secaira, F., Toimil, A., Escudero, M., Diaz-Simal, P., Beck, M.W., Storlazzi, C.D., Silva, R., Losada, I.J., 2019. The Risk

Reduction Benefits of the Mesoamerican Reef in Mexico. Front. Earth Sci. 7, 125.

Roeber, V., & Bricker, J. D. (2015). Destructive tsunami-like wave generated by surf beat over a coral reef during Typhoon Haiyan. Nature Communications, 6, 7854. https://doi.org/10.1038/ncomms8854

Roelvink, D., A. Reniers, A. van Dongeren, J. van Thiel de Vries, R. McCall, and J. Lescinski (2009), Modelling storm impacts on beaches, dunes and barrier islands, Coastal Eng., 56(11), 1133–1152, doi:10.1016/j.coastaleng.2009.08.006.

Roelvink, J. A., van Dongeren, A. R., McCall, R., Hoonhout, T., van Rooijen, B., van Geer, A., … Quataert, E. (2015). XBeach technical reference: Kingsday release (technical report). Delft, the Netherlands: Deltares.

Richards, A., 2008. Development trends in Jamaica's coastal areas and the implications for climate change. Plan. Inst. Jamaica.

Schuhmann, P.W., Mahon, R., 2015. The valuation of marine ecosystem goods and services in the Caribbean: A literature review and framework for future valuation efforts. Ecosyst. Serv. 11, 56–66.

Sheng, Y.P., Lapetina, A., Ma, G., 2012. The reduction of storm surge by vegetation canopies: Three-dimensional simulations. Geophys. Res. Lett. 39.

Sherman, R.E., Fahey, T.J., Martinez, P., 2001. Hurricane Impacts on a Mangrove Forest in the Dominican Republic: Damage Patterns and Early Recovery1. Biotropica 33, 393–408.

Sheng, Y. P., & Zou, R. (2017). Assessing the role of mangrove forest in reducing coastal inundation during major hurricanes. Hydrobiologica, 83, 87-103. doi:10.1007/s10750-017-3201-8

Shimozono, T., Tajima, Y., Kennedy, A. B., Nobuoka, H., Sasaki, J., & Sato, S. (2015). Combined infragravity wave and sea-swell runup over fringing reefs by super typhoon Haiyan. Journal of Geophysical Research: Ocean, 120, 4463–4486. https://doi.org/10.1002/2015JC010760

Spalding, M., Kainuma, M., Collins, L., 2010. World atlas of mangroves. Earthscan, London.

Suzuki, T., M. Zijlema, B. Burger, M. C. Meijer, and S. Narayan (2012), Wave dissipation by vegetation with layer schematization in SWAN, Coastal Eng., 59(1), 64–71, doi:10.1016/j.coastaleng.2011.07.006.

The World Bank, 2018. Advancing Disaster Risk Finance in Jamaica. Washington D.C.

Valiela, I., Bowen, J.L., York, J.K. (2001). Mangrove forests: One of the world's threatened major tropical environments. BioScience, 51(10), 807-815. https://doi.org/10.1641/0006-3568(2001)051[0807:MFOOTW]2.0.CO;2

Valiela, I., Kinney, E., Culbertson, J., Peacock, E., Smith, S., 2009. Global Loss of Mangroves and Salt Marshes. In: Duarte, C.M. (Ed.), Global Loss of Coastal Habitats Rates, Causes and Consequences. Fundacion BBVA, pp. 107–142.

Ward, P.J., Jongman, B., Aerts, J.C.J.H., Bates, P.D., Botzen, W.J.W., Loaiza, A.D., Hallegatte, S., Kind, J.M., Kwadijk, J., Scussolini, P., 2017. A global framework for future costs and benefits of river-flood protection in urban areas. Nat. Clim. Chang. 7, 642.

Ward, R.D., Friess, D.A., Day, R.H., Mackenzie, R.A., 2016. Impacts of climate change on mangrove ecosystems: a region by region overview. Ecosyst. Heal. Sustain. 2, e01211.

Woodroffe, C.D., Rogers, K., McKee, K.L., Lovelock, C.E., Mendelssohn, I.A., Saintilan, N. (2016). Mangrove Sedimentation and Response to Relative Sea-Level Rise. Annual Review of Marine Science 2016 8:1, 243-266.

Worthington, T., Spalding, M., 2019. Mangrove Restoration Potential: A global map highlighting a critical opportunity. Cambridge, UK.

Wylie, L., Sutton-Grier, A.E., Moore, A., 2016. Keys to successful blue carbon projects: Lessons learned from global case studies. Mar. Policy 65, 76–84.

UNISDR (2017). GAR Atlas: Unveiling Global Disaster Risk, Geneva, Switzerland: United Nations Office for Disaster Risk Reduction (UNISDR).

Yen, B. C. (1995). Hydraulics and effectiveness of levees for flood control. U.S.-Italy Workshop on the hydrometeorology, impacts and management of extreme floods, Perugia, Italy, November, 1995.

Zhang, K., Liu, H., Li, Y., Xu, H., Shen, J., Rhome, J., Smith III, T. J. (2012). The role ofmangroves in attenuating storm surges. Estuaries, Coastal and Shelf Science, 102-103, 11-23. doi:10.1016/j.ecss.2012.02.021

Zijlema, M.; Van Vledder, G.P.; Holthuijsen, L.H. (2012), Bottom friction and wind drag for wave models. Coast.Eng., 65, 19–26–118.

Forces *of* NATURE

The Flood Protection Benefits and Restoration Costs for Mangroves in Jamaica

World Bank Caribbean Office
www.worldbank.org/caribbean
Follow us on Twitter @WBCaribbean

Additional Information:
Juliana Castaño-Isaza
E: jcastanoisaza@worldbank.org