Joint Nature Conservation Committee

Model development to assess the vulnerability of the Cayman Islands to storm surge and inland flooding, and the role and value of natural capital in mitigating the impacts C20-0302-1509

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Report for

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Executive summary

Purpose of this report

The Cayman Islands like many of the UK Caribbean Overseas Territories, are highly dependent on the natural environment for economic and social well-being. The unprecedented events of Hurricane Ivan in 2004 demonstrated the Islands vulnerability to natural hazards and the associated impacts to the population, damage to built infrastructure, *natural capital assets* and the resulting serious implications to the economy. As the natural environment also plays a key role in protecting built infrastructure and human well-being, it is important that it is also safeguarded against damage from human activities.

The Joint Nature Conservation Committee (JNCC), supported by the Conflict Stability and Security Fund (CSSF) is supporting the Cayman Islands Government to assess how nature can support disaster resilience. To support this process, the primary purpose of this study is to assess the role and value of natural capital to mitigate the impacts of natural disasters on built infrastructure. Specifically, this relates to the provision of protection from coastal flooding and inland flooding as a result of extreme weather events. This information will be used by the Cayman Islands Government in developing plans, policies and procedures to deal with natural disasters by enhancing their ability to prepare for and recover from the impact of storm events.

The purpose of this report is to provide a summary of the outcomes of the study which was delivered through a staged approach. Firstly, potential coastal and inland flood modelling approaches were evaluated, and appropriate models selected and complementary valuation techniques were chosen. Secondly, coastal and inland flood models were developed and subsequently run with extreme weather event inputs to quantify flooding under different scenarios of natural capital state. Thirdly, the model results were reviewed and input into the economic analysis to assess the valuation of the flood protection service provided by the Islands' natural capital assets.

Results of flooding projections and differences due to natural features

Inland flooding

The vegetation on the Cayman Islands, provide natural capital benefits which include a flood protective function. Vegetation is dense across much of the Islands, with high coverage levels of dry forest and woodland among inland areas and mangrove forest in tidal regions. The protective benefit of vegetation results from interception and evaporation of rainwater before it reaches the ground surface and holding back water temporarily, mitigating peak flows that cause the greatest flooding by slowing the passage of water through the catchment.

The effects of degraded vegetation were assessed in this study using hydraulic models developed for all three islands to simulate the catchment response to storm events. In the main scenario, simulating the effects of natural capital degradation, all vegetation - forest, shrubland, mangrove forest and mangrove shrubland - was assumed to revert to grassland leading to less interception of rainwater, greater flooding, and faster moving water. In an additional scenario with 'selective degradation' for Grand Cayman, reversion to grassland is assumed for just dry forest and woodland and tidal mangrove habitats. The model represents physical effects using a parameter for the proportion of intercepted rainfall and a parameter for the friction affecting water flows (Manning's n roughness coefficient). The results of the modelling showed that:

- There is widespread surface water flood risk across the three Islands characterised by extensive ponding of floodwater in the low-lying (<1m Above Mean Sea Level (AMSL)) regions. Owing to the Islands low elevations, there are few recognised surface water flow paths and surface water flooding is typically widespread and of low velocity. Extensive property flooding is observed in both the 4% annual exceedance probability (AEP) and 1% AEP storm events with increased peak flood depths as one would expect, although increases in flood extent are limited.

- In the degraded scenarios, the anticipated result of exacerbated peak flood depths in the lower lying areas was not typically observed, with both depth reductions and increases observed. Due to the low-lying nature of the Islands, changes to peak flood depth are relatively minor in magnitude, as the impacts tend to be borne over a wider area.
- In some instances, and despite the reduced rainfall losses, the associated reduction in roughness values is shown to improve conveyance of surface water to the sea. In these cases, the degraded scenario results in reduced flood depths. This, however, does not necessarily indicate an improved or favourable position with regard to flooding as a result of environment degradation.
- An increase in surface water flow velocities were observed in the degraded scenarios. This has the potential to increase soil erosion and sediment load within the flood water and resultant transportation into the marine environment. Increased sediment delivery and deposition on coral reefs can further accelerate reef degradation and highlight, albeit qualitatively, the positive impact of natural capital.
- Improved flood modelling results would be achieved using higher resolution DTM, rather than the coarser scale WorldDEM dataset that was used. This would be particularly beneficial as due to the low overall elevation of the Islands; water flows are dominated by small scale changes in topography, which would be better represented in the higher resolution dataset. As such, a much better understanding of individual flood vulnerability would be provided.
- Due to the very small-scale changes in flood depths observed in the model results, economic analysis was not undertaken.

Coastal flooding

Coral reefs and mangroves provide natural capital benefits which include protection from coastal flooding. The shallow water over reefs forces large deep-water waves to break, dissipating their energy and the roughness of the reefs causes further energy loss from friction as water flows over them. The vegetation in mangroves act as a source of friction against moving water, resulting in a reduction of wave heights.

Coastal flooding was assessed using the SWAN spectral wave model. The SWAN model is used to estimate offshore wave conditions which are propagated over the shelf and shallow coastal areas, where the effects of natural capital are accounted for in order to assess the resulting flood inundation onshore.

The model was run for representative Category 1, 3 and 5 tropical storms originating from the three different directions as indicated by historical conditions. The model scenarios represented change from degradation and enhancement (regeneration) of coral reefs and mangroves by adjusting their respective frictional coefficients and, in the severe degradation scenario, by reducing the height of the coral reefs by 1m to simulate reef erosion. In order to estimate overall flood depths in buildings, the significant wave heights calculated by the model are also supplemented by a height allowance for storm surge. The model results show that:

- Waves exceeding 13 metres offshore break abruptly as they approach and interact with the steep underwater shelf surrounding the islands. Nevertheless, waves of up to 4 metres still propagate across the narrow shelf and reach the coast.
- A large decrease in wave height occurs at the narrow shelf edge in locations where the shelf is wider due to the longer propagation distance to shore and illustrates the importance of the shelf width regarding its dissipative effects on waves.

- Due to the overall low elevation of Grand Cayman, 'coastal' flooding extends to large areas of the island in severe storms (Category 5) but also in those less severe (Category 3).
- In the degraded scenario, the frictional reduction from the loss of live coral reef component and mangrove die back leads to increases in wave heights of up to 0.4m over the reef (according to location), which leads to a maximum increase in flood depth of 0.25m from some buildings up to 200m inland in a Category 5 storm.
- In the severely degraded scenario, with 1m of reef erosion (and so water which is deeper by 1m at the reef crest), wave heights are increased by 1.3m at the reefs leading to increases in flood depth of up to 0.75m for some buildings up to 200m inland. Although reef depth shows a greater impact on waves than roughness, the first is a long-term effect linked to reduced coral and mangrove health in the short term. A reef with fewer live corals is both less rough and has a reduced capacity to maintain the physical reef structure through new growth. Mangroves are similarly linked to both short term and long-term impacts.
- The opportunity maps in the results show that flood risk protection has significant value along the west, south-west and north coasts. In particular, a short segment of reef to the north-west of George Town and a segment to the south-west are shown to offer greatest value in terms of damages avoided.

Improved understanding of infrastructure flooding could be obtained by using the coastal model outputs as inputs to the higher resolution inland flood model as a boundary condition. This would provide an enhanced representation of the flooding mechanisms as coastal floodwater propagates inland and flood maps. In addition, future studies could investigate the depth-induced effects of the reefs and how they might be impacted by degradation for scenarios considering sea level rise for different time horizons.

The ill health and damage to live coral/mangrove provides a key indicator to what could be instore for the future. If coral reefs are not protected and do not remain in good health the live coral can die and without the continued regeneration of the reef over the long term the reef will erode. Whilst the impact of this may not be seen immediately, the analysis observed in the severe degraded scenario provides an indication of the increased flooding as a result of reef erosion in the longer term.

National value of natural capital providing flood protection

Estimates of the value of protection from natural capital have been made for the degraded, severe degraded and enhanced scenarios and include two levels of sensitivity to address the uncertainty related to representing the physical process of wave run-up on resulting inland flood levels.

- In the severe degraded scenario, the annual economic losses to the Cayman Islands, from the need to replace and repair property and from lost business, are estimated between $33m and $87m, with the range reflecting uncertainties relating to wave run-up.
- In the degraded scenarios, the reduced friction from degraded reefs and mangroves would result in annual economic losses to the Cayman Islands of between $2m and $3m, while enhancement would lead to reduced annual economic losses of $1m.

Contents

1. Introduction

This section introduces the project, its objectives and describes the overall aim of incorporating the value of coastal protection from natural capital into policy and decision making in the Cayman Islands.

1.1 Project Objectives

The Cayman Islands like many of the UK Caribbean Overseas Territories, are highly dependent on the natural environment for economic and social well-being. Tourism is a dominant economic sector with visitors from cruise ships and air drawn to the Islands by the beaches, coral reefs and rich biodiversity.

The unprecedented events of Hurricane Ivan in 2004 demonstrated the Islands vulnerability to natural hazards and the associated impacts to the population, damage to built infrastructure, *natural capital assets* and the resulting serious implications to the economy. As the natural environment also plays a key role in protecting built infrastructure and human well-being, it is important that it is also safeguarded against damage from human activities.

In this context, and building on a long programme of previous work, the Joint Nature Conservation Committee (JNCC), supported by the Conflict Stability and Security Fund (CSSF) is supporting the Cayman Islands Government to assess how nature can support disaster resilience. The support this process, the primary objectives of this study is to assess the role and value of natural capital to mitigate the impacts of natural disasters on built infrastructure. Specifically, this relates to the provision of protection from coastal flooding and inland flooding as a result of extreme weather events. This information will be used by the Cayman Islands Government in developing plans, policies and procedures to deal with natural disasters by enhancing their ability to prepare for and recover from the impact of storm events.

The study aims to

- Identify communities and infrastructure most at risk from coastal and inland flooding through the use of appropriate high-level modelling approaches;
- Provide an economic assessment and map the functional role and value of natural capital in mitigating coastal and inland flooding making use of the models developed; and
- Build capacity within the staff in the Government of Cayman Islands.

The purpose of this report is to provide a summary of the outcomes of the study which was delivered through a staged approach. Firstly, potential coastal and inland flood modelling approaches were evaluated and appropriate models selected. In parallel, complementary valuation techniques were chosen. Secondly, coastal and flood models were developed and, using extreme weather events as inputs, were used to quantify flooding under different scenarios of natural capital state. Thirdly, an economic valuation of the flood protection service provided by natural capital was made.

2. Context

2.1 Introduction to the Cayman Islands

Location and climate

Situated in the central part of the Caribbean Basin 15 miles south of Cuba and 180 miles north west of Jamaica, the Cayman Islands consist of Grand Cayman, Little Cayman and Cayman Brac (see Figure 2.1). The islands occupy an area of 260km^2 and are of low elevation with Grand Cayman and Little Cayman reaching a maximum elevation of 20m and 16m above sea level respectively. Given this low-lying topography the area is particularly vulnerable to winds and flooding as a result of hurricanes and tsunamis and could be seriously affected by sea level rise due to climate change[1].

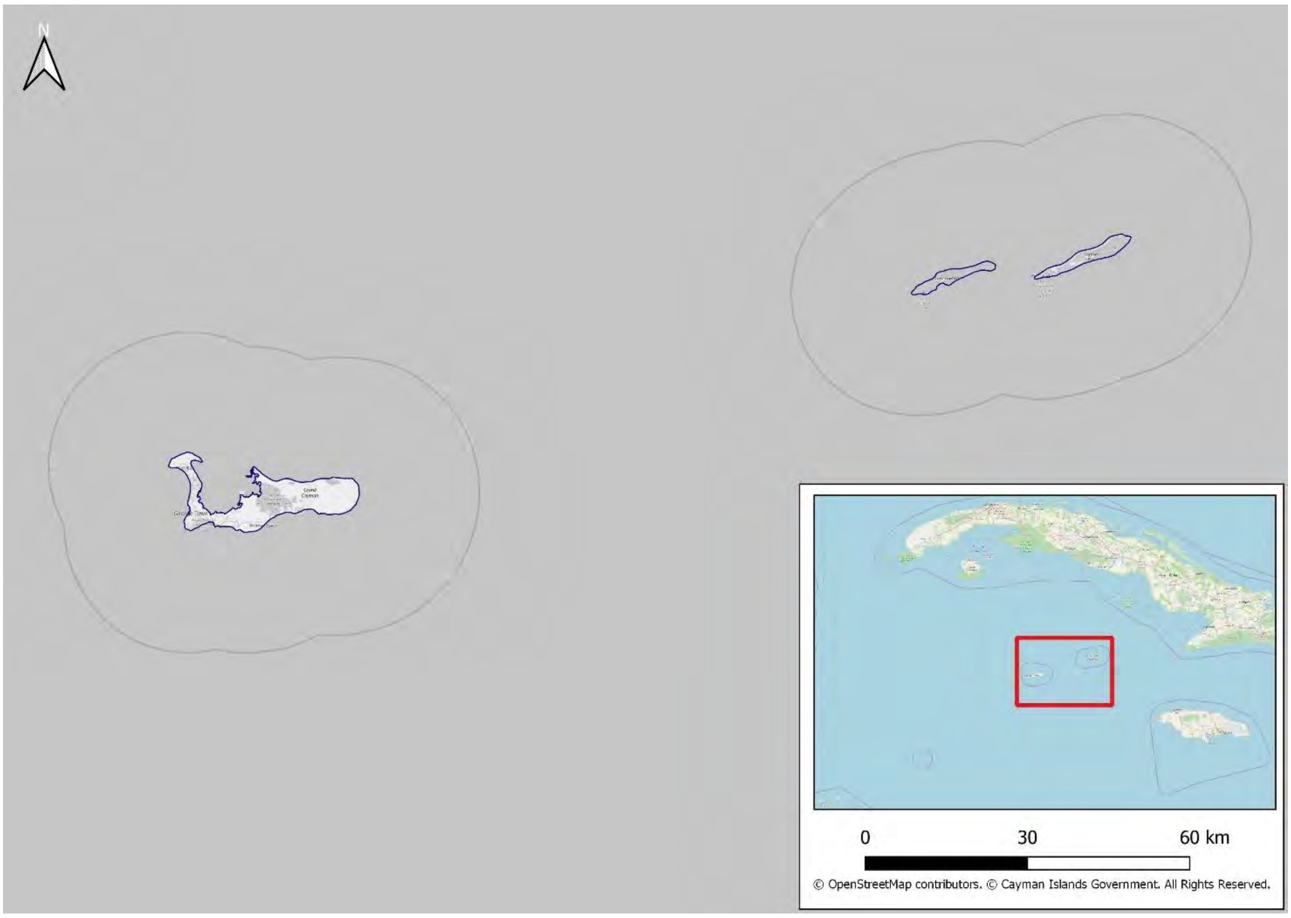
The Cayman Islands have a tropical marine climate, with a wet season of warm, rainy summers (mid-May through October) and a dry season of relatively mild winters (November to April). As the island are located in the north-west Caribbean, they are affected in the winter by cold fronts but also influenced by tropical waves and hurricanes during the summer. During the summer, average monthly rainfall is 14.5cm with maximums in May and November. In the winter, the average monthly rainfall total is 6.4cm inches. During the summer temperature averages 29.1°C with daily high temperatures averaging 31.6°C and low temperatures 25.2°C whilst in the in the winter temperature averages 27.1°C (80.9 °F) with daily high temperatures averaging 29.0 °C and low temperatures 23.0 °C[2].

During the 52 year period of 1950 to 2002, Grand Cayman has experienced seven tropical storms and six hurricanes, and the Cayman Brac and Little Cayman six tropical storms and five hurricanes. However, on 12th September 2004, Ivan, a category five Atlantic hurricane hit the Cayman Islands and is one of the worst hurricanes recorded in the Caribbean region. The eye of the storm passed within 15 miles of Grand Cayman, with the island experiencing sustained winds of 160 mph, gusts of up to 217 mph, and a storm surge reaching 8 to 10 feet. Wave heights reached up to 20-30 feet and most of the Island was under water. There was widespread property damage with more than a quarter or the buildings rendered uninhabitable and 95% having some degree of damage. It has been estimated that the hurricane caused US$2.86 billion in damages across the Cayman Islands, equivalent to over 180% of GDP.

[1] Simpson *et al.* (2009) Sea level rise and its implications on the Cayman Islands

[2] Cayman Islands Government National Weather Service http://www.weather.gov.ky/portal/page/portal/nwshome/climate accessed 10/05/2020

Figure 2.1 Location of the Cayman Islands



Habitats of the Cayman Islands

The vegetation of the Cayman Islands reflects a mixture of wetlands and areas of dry evergreen woodland. More than 50% of Grand Cayman is covered by wetlands and the central mangrove area is the largest areas of mangrove in the Caribbean. All three islands have well-developed fringing coral reefs situated on narrow coastal shelves[3].

Forest - The dry evergreen woodland of the Cayman Islands are quite distinct on each of the three islands. The trees form two densely packed canopies and they generally occur on land that is at least 6ft above the groundwater table. This type of vegetation can be found in the east and central part of Grand Cayman, the centre of Little Cayman and throughout the Bluff formation of Cayman Brac.

Extensive areas of mangrove forests can be found in wetland areas on Grand Cayman and Little Cayman, dominated by Red, Black and White mangroves.[4] In addition, large areas of seasonally flooded forests can be found on Grand Cayman and smaller areas on Little Cayman.

Shrublands – Dry shrubland areas are located predominately at the eastern end of the three islands, to the they dominate Little Cayman and can be found on the edge of the Bluff cliffs on Cayman Brac. Coastal shrubland are located on beach ridge areas and dwarf, this low-level woody shrubland are located around parts of Grand Cayman and little Cayman and most of the Coast of Cayman Brac[3]. Little Cayman and most of

[3] JNCC (2009) Implications of climate change for the biodiversity in the UK Overseas Territories

[4] Department of the Environment Habitats: Grand Cayman Department of Environment (doe.ky) accessed 10/05/2021

the coast of Cayman Brac. Invasive species are competing for space on these beach ridge areas. Mangrove shrublands include extensive areas on Little Cayman.

Coral reefs - The reef systems around Grand Cayman, Little Cayman and Cayman Brac consist of shallow-water fringing reefs encircle most of the island and form numerous shallow-water lagoons. The reefs form a series of terraces down to about 20m, descending into a steep reef slope at greater depths. The clarity of the water enables some reef growth to occur as deep as 75m[3].

Seagrass - The main area of seagrass in the Cayman Islands is in North Sound, the large lagoon that dominates the western part of Grand Cayman. Sea grass can be found in patchy areas in lagoonal areas of Little Cayman and Grand Cayman.

A summary of areas of terrestrial landcover and benthic classifications for shelf and lagoon can be found in Appendix C.

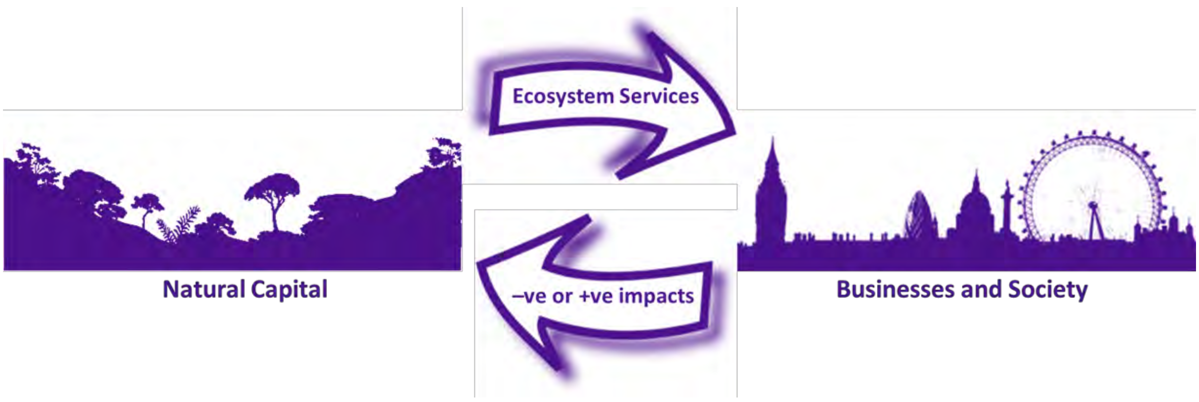
3. Approach

This section description is provided on how the selected method has been used to assess protection provided by natural capital against inland and coastal flooding.

3.1 Natural capital and ecosystem services

Natural capital is defined as the stocks of natural assets found within the Earth's critical zone which includes living things, vegetation, and animals together with the geology, soil, air, and water[5]. Natural Capital provides the renewable and non-renewable resources that combine to yield a flow of benefits to people in the form of Ecosystem Services Unsustainable use of Ecosystem Services can lead to negative impacts on the underlying Natural Capital and a reduction in benefits to people and wildlife.

Figure 3.1 The relationship between Natural Capital and Ecosystem Services



Natural Capital and Ecosystem Services such as cultural, provisioning and regulating services are potentially subject to a range of natural and anthropogenic processes and so may need to be protected and enhanced. Particularly close dependencies exist in small island states that rely on the natural environment. Flood protection is an example of a regulating ecosystem service and demand for this service is likely to increase while provision is likely to decrease due to land use changes which enhance flood severity and the exacerbating effects of climate change.[6]

Coral reefs are examples of natural capital assets in the coastal zone which provide goods and services to society, a proportion of which are exchanged in markets on a local and global scale. They reduce the exposure and vulnerability of coastal infrastructure to natural disasters as they reduce ocean swells that result in wave transformation and rapid attenuation of wave energy, along with other inherent advantages such as the provision of recreational opportunities for local people and tourists alike and opportunities for scientific benefits from academic research.[7] [8]

[5] World Forum on Natural Capital https://naturalcapitalforum.com/about/

[6] MEA (2005) *Ecosystems and Human Well-being: Wetlands and water* https://www.millenniumassessment.org/documents/document.358.aspx.pdf

[7] Pascal et al. (2016) *Economic valuation of coral reef ecosystem service of coastal protection: A pragmatic approach*

[8] de Groot, R. et al. (2012) *Global estimates of the value of ecosystems and their services in monetary units*

The protective service of natural capital has been increasingly recognised since analysis of the Indian Ocean tsunami in 2004 and Hurricane Katrina in 2005 revealed damage to be less severe in areas surrounded by coastal ecosystems including coral reefs and mangroves.[9] Given the existence of coral reef and mangrove ecosystems in the Cayman Islands, the reliance of the economy on the natural environment, and the extent of damage caused by recent hurricanes, coral reefs and mangroves are vital natural capital assets which provide value to the Cayman Islands and its inhabitants while offering flood protection.

Valuing Natural Capital

Economic valuations of the ecosystem services provided by natural capital are being increasingly reported in the literature. These valuations are being undertaken to support a number of different objectives, but a common use is to raise awareness to policy makers of the important role that natural capital plays in delivering ecosystem services and to quantify this in monetary terms. By using this approach, the costs and the benefits that can be achieved through different levels of investment in natural capital management can be understood by incorporating the present and future values of negative and positive impacts. This provides a common monetary metric that can be used to compare against other management actions and used to refine economic instruments. Natural capital assets can be valued in a number of different ways because of the variety of roles they can perform and the intended use of the valuation estimate in decision-making or accounting.

3.2 State of knowledge

Previous work on natural capital in the Caribbean

Due to the significance of natural capital to tourism in the Caribbean, there is an increased body of research that has been conducted on quantifying the value of natural capital in the provision of ecosystem services across the Caribbean region, including the Cayman Islands. The Wolfs Company (2017)[10] undertook study to assess the economic value of and the societal importance of the of the marine ecosystems of Grand Cayman, Cayman Brac, and Little Cayman. This study focused on the key provisioning, regulating and cultural services provided by coral reefs, mangroves, seas grasses and beaches and estimated that they provided a total economic value (TEV) of at least US$179 million per year. The value of regulating 'coastal protection' service was assessed at $5.1m annually.

The vulnerability of islands in the Caribbean to flooding and extreme weather events and the protection offered by reefs and mangroves to coastlines elsewhere in the world, has meant that there have been a growing number of economic studies that have been conducted to assess the value of coastal flood protection from natural disasters provided by natural capital, although few studies on inland flood protection.

A study conducted by Van Zanten *et al*. (2014) assessed coastal flood protection in the US Virgin Islands, by quantifying the physical link between hydrological services offered by coral reef ecosystems and flood damage to properties on the coastline.[11] In this study, the indicator for natural capital was coral cover and the ecosystem function was represented by the modelled wave energy dissipation offered by coral and highlighted the importance of friction linked to the percentage of living coral coverage. A wave model took

[9] Barbier (2015) *Policy: Hurricane Katrina's lessons for the world* https://www.nature.com/news/policy-hurricane-katrina-s-lessons-for-the-world-1.18188

[10] Wolfs Company (2017) The Economics of Enhancing the Marine Protected Areas of the Cayman Islands

[11] Van Zanten et al. (2014) *Coastal protection by coral reefs: A framework for spatial assessment and economic valuation.* https://www.researchgate.net/publication/262921102_Coastal_protection_by_coral_reefs_A_framework_for_spatial_assessment_and_economic_valuation

into account wave characteristics, water depth and storm characteristics. The ecosystem service being provided was quantified by reef-protected coastline and the economic value of avoided damage was represented by an estimated value of the infrastructure being protected.

Wood (2019) followed the same approach in a study in the British Virgin Islands, but rather than focus on a single storm event, extended the valuation methodology to cover tropical storms in Categories 1-5, each with different return frequency. It was found that significant damage resulted from the more minor storms as they occurred more frequently. Beck *et al.* (2018)[12] undertook a global study on the flood protective value provided by coral reefs using hydrodynamic models to represent the offshore and nearshore wave dynamics from four locally generate storms of different return periods with and without coral reefs and valued assessed using the avoided damaged approach.

Burke *et al.* (2008)[13] valued the protective service of coral reefs in Tobago and St Lucia using avoided damages. In contrast to using complex predictive models, used historical data on average wave height during extreme climatic events to determine the zones at risk. A coastal protective index (CPI) was developed that incorporated the contribution of the reef to coastal protection (reef contributing factor). The CPI is the sum of scores that contribute to coastal protection and represent the degree of protection to the shoreline, including that of the coral reef. A similar approach was undertaken by Pascal *et al.* (2016)[14] and was also applied by Wolfs Company (2017)[10] in the Cayman Islands.

The JNCC (2017) valued inland and coastal flood protection from natural capital in the UK Overseas Territories. The study combined radar-based terrain mapping and flood hazard risk models to understand the vulnerability and exposure of real estate infrastructure through the development of GIS based models. Depth-damage curves and functions were used to assess the expected damage and relative reconstruction costs used. These models were subsequently developed further by the JNCC in 2020[15].

Despite the variations in the detailed methods applied, the studies highlighted above typically follow a three staged approach. Firstly, to identify the geographic areas and assets (both natural and built) that are at risk of flooding. Secondly, to quantify the role that natural capital plays in flood protection and thirdly to provide an economic valuation.

Stage 1: Identification of the geographic areas and assets at risk of flooding

This stage combines both a hazard, and exposure and vulnerability assessment. Firstly, the flood hazard is characterised. This is typically undertaken through determining the extreme weather event that is the forcing factor that leads to the flood e.g. choosing a storm(s) of a specific severity and frequency. The storm characteristics are then used as an input to a physical model that combines information of the geographical features (e.g. coastal or terrestrial profile, land cover/habitat type) and a representation of the physical processes to determine the flood risk. It is important that a choice of such a model ensures natural capital can be represented and is sensitive to potential impacts of future changes. Secondly, the model is then used to determine the land area that is at risk of flooding and the infrastructure and buildings that may be exposed to the flood and differing levels of vulnerability.

[12] Beck et al. (2018), *The global flood protections savings provided by coral reefs*. Nature Communications 9-2186

[13] Burke, et al. (2008). *Economic Valuation of Coral Reefs in Tobago and St. Lucia.*

[14] Pascal et al. (2016). *Economic valuation of coral reef ecosystem service of coastal protection: A pragmatic approach*. Ecosystem Services 21 72-80.

[15] An assessment of the value of natural capital in the protective service against coastal and inland flooding in the UK Overseas Territory of the British Virgin Islands: BVI Flood Resilience Modelling Tool – Technical Report (2020) https://hub.jncc.gov.uk/assets/81fc103c-1d54-421e-997c-b9f7d986ee78

Stage 2: Quantifying the role of flood protection from natural capital

In this stage the role that natural capital in the flood process is determined. Coral reefs dissipate wave energy through both waves breaking on the physical structure and also by reef friction. If in Stage 1, a wave model is selected that takes into account both of these processes, it can be simulated to assess the contribution that reefs provide to the coastal flood protection service in its baseline condition and through and hypothetical scenarios of reef degradation. The differences in flood extent and depth between these scenarios can be assessed. Similarly, if landcover roughness and rainfall loss factors are represented in inland flood models, the effects of changes to habitat (e.g. degradation or restoration) on flood extent and depth can be quantified.

Stage 3: Economic valuation

The third stage involves an economic valuation of the flood protection service provided by natural capital. The most common methods reported in the literature are those that use avoided damages and replacement costs approaches. Comparisons are made between valuations of the impacts of flooding with natural capital at different states (e.g. present baseline, degraded, or enhanced).

3.3 Approach

Physical Models

In the context of Stages 1 and 2 described above, at the onset of the project, a rapid scoping review was undertaken to investigate the suitability of existing or other suitable physical models to represent and then understand the role of natural capital in coastal/inland flood resilience.

A list of potential coastal and inland flood model that could be used was developed including the JNCC's existing GIS based storm surge and inland flood models[15] providing the benchmark to which other potential models were compared against, as per the project terms of reference. A list of assessment criteria was defined against which each model could be scored against. Criteria included: data requirements; suitability of model structure; adequate representation of natural capital; calibration/validation; ease of implementation within project time period; levels of skill needed to run the model; and alignment to economic assessment. Based on the output of scoring against these criteria the advantages and disadvantages of each model were identified, and recommendations of which models are most appropriate for application in the Cayman Islands.

Inland flood model

Inland models selected for review were the JNCC's own model for determining flood risk and three more traditional hydraulic models. The JNCC have developed a simple GIS based model for determining flood risk based on topography, rainfall totals and habitat data. The model has been designed specifically for data sparse environments and does not attempt to explicitly model the rainfall-runoff flow processes using an index based weighted risk approach and does not estimate a flood depth. The model has a web-based interface, is quick to run.

An example of a traditional hydraulic model is HEC-RAS 2. HEC-RAS is a widely utilised hydraulic modelling software for flood modelling and mapping studies, replicates the physical flow processes and is capable of both 1D and 2D computations. The 2D model uses a computational mesh of user-specified resolution based on an underlying topography dataset. The model provides the option for both diffusion wave and full momentum computation calculations and provides depth, level and velocity values for each mesh/grid unit.

Due to the conservative and coarser nature of the flood results of the JNCC model, potential difficulties in calibration and the fact that a flood depth is not provided, it was recommended the use of a hydraulic model.

The flat topography of the Cayman make it particularly important to understand the detail of the flow routing process. Whilst HEC-2D is available and has no licence fee, the use of Tuflow was proposed. Tuflow provides flood outputs in GIS format and the model can be run under different natural capital scenarios (baseline, degraded and enhanced). Within the time frames of the project the outputs of Tuflow model will be combined with economic data within a GIS to provide a valuation. This will create a workflow process (not a single end to end model) to deliver the outputs. An identified limitation of this approach was that the Tuflow model does not provide an interface for the non-specialist to setup and run the model. Whilst this is a clear disadvantage of this approach, the finer resolution of results, the provision of flood depths and familiarity of the tool to the project team, coupled with the potential difficulties in calibration and conservative flood results expected from the JNCC model, the use of Tuflow was recommended.

Given this decision, a stated aim of the project team was to investigate the development of a simple relationship between water levels and extent of natural capital based on the model output results to provide a tool in GIS to allow user interaction.

Coastal flood model

Inland models selected for review were the JNCC's own model coastal flood risk model flood, coastal protection index (CPI) approach used in the Wolfs Company report for the Cayman Islands and the SWAN model.

A simple model of marine and terrestrial risk from storm surge has been developed by the JNCC based on a notional 'cost' of energy transfer from storm centre to coast. The model utilises a cost-distance analysis, which calculates the cumulative cost of travel from the storm path to at-risk marine and terrestrial areas, reflecting the physical barriers and features of topography, habitat, and wind fetch distance. The model provides a risk score output and has a user-friendly web-based interface.

An economic valuation of the role of coral reefs in coastal protection for the Cayman was calculated through the contribution/percentage of these total damages attributed to coral reefs calculated using a Coastal Protection Index approach. A relative reef contribution (RRC) is calculated as the scaled percentage of the reefs contribution to protecting coastline in relation to all other factors that contribute to total coastal protection (e.g. geomorphology, coastal exposure, wave energy, storm frequency, coral reef characteristics, coastal vegetation, coastal elevation and coastal slope). It simplistic approach has its advantages but there are clear limitations of how changes in natural capital result in changes to flood levels/extent as the approach is based on using static historic flood data. One would assume that the area of land vulnerable to flooding remains the same e.g. the same flood extent, but the RRC/CPI would change to represent the increase or loss of natural capital. This is a key limitation as we know that changes in mangrove or coral extent would change wave energy and then the flood extent.

The SWAN wave model is a widely used third generation physical wave model appropriate for shelf seas, coastal and near shore areas is developed at Delft University of Technology. It simulates wave generation, propagation and dissipation and includes the effects of refraction, shoaling and blocking of in wave propagation.

The JNCC's model has advantages of requiring limited data inputs, has a user friendly user interface and fast runtime. The model is simplistic in its approach and does not aim to represent the physical processes. The model does not include anything specifically on wave dynamics. Wave dynamics are particularly important around the Cayman Islands as the narrow shelf surrounded by deep water allows large waves to penetrate close to the coast before breaking.

Given the complex coastal bathymetry, irregular shape coast and the significance of wave dynamics, there are advantages of using a model such as SWAN that simulates hurricane waves. Given the limitations of the RRC/CPI approach highlighted above and the need to capture the wave dynamics to provide an accurate representation of coastal flooding, we recommend the use of the SWAN model.

The model will be run for a series of storms for different magnitude and wave angles from historical hurricane tracks. This is an approach that has been used and reported in recent studies in the literature for valuation of coral reefs. These models run will be repeated for scenarios of natural capital condition to understand water level impacts (water levels for different zones across the islands will be calculated). This will create a workflow process (not a single end to end model) to deliver the outputs. We will aim to develop a relationship between max water level and natural capital index to allow the user to understand the impact of different levels of natural capital and its effect on resilience.

Economic valuation

As highlighted in Stage 3 in Section 3.2 above there are a variety of different approaches that can be used to undertake an economic valuation of the flood protection service provided by natural capital and have been applied in the Caribbean, each selected by different authors at different times. This multiplication is potentially confusing, particularly for policy-makers, some of whom are likely to be new to the area and may not understand the reasoning for selecting one approach rather than another or what is included in a particular numerical estimates, leading eventually to poor decision-making.

The approach adopted in this study addresses this issue through establishing a **simple economic toolkit** that integrates, rationalises and compares previous work and supports the correct choice of natural capital value for the relevant user and circumstance. It provides references to values already existing within economic information such as government statistics, indicate how natural capital values are represented in government planning (such as for land use), and clarifies how underlying assumptions in existing economic frameworks are linked to values, particularly the values of natural assets, and which are the potential alternative assumptions and when they could be used.

The Toolkit approach helps ensure that the economic valuation in this study and future economic comparisons on the Cayman Island and other islands are well-founded. More detailed information on the economic toolkit is provided in Section 4.

4. Methodology

This section describes the methodologies that have been used to assess the protective function of natural capital in relation to inland and coastal flooding.

4.1 Inland flooding

Amongst natural capital's wider benefits is the protection offered with regards to inland flooding. Vegetation cover is dense across much of the Cayman Islands, with high coverage levels of dry forest and woodland among inland areas and mangrove forest in tidal regions. There are several benefits that vegetation provides to mitigate flooding during rainfall events, including:

- Increased interception storage – the rainfall held by the canopy, before reaching the ground or evaporating;
- Reduced catchment response - heavy vegetation provides a physical barrier to the flow of water, slowing its passage and increasing the time taken for rainfall to work its way through the catchment; and
- Increased soil stability – soil cohesion is increased through the presence of root systems, reducing sediment load in flood waters.

Urbanisation of an initially forested area not only diminishes the positive effects of the natural capital listed above, but also reduces the available area for infiltration through the soil, having generally replaced it with an impermeable surface.

However, it is acknowledged that in some cases natural vegetation can in fact have the reverse impact from a flood risk perspective and compound flood flows. The increased surface roughness coefficient associated with vegetated areas (in comparison to bare earth or urbanised regions) can in fact slow the dispersion of inland flood waters out to sea, causing elevated surface water levels.

It was therefore proposed to use hydraulic modelling to assess the role of natural capital in terms of the protection offered by reducing the catchment response to a storm event; in slowing the passage of water through the catchment. Three island-wide hydraulic models have been developed utilising the software package TUFLOW. The models have been developed to compare the flood depths encountered in two scenarios:

- Baseline – where natural capital is represented within the model to best reflect the current condition; and
- Degraded – where vegetation cover and its protection is removed.

In addition, two specific areas on Grand Cayman were identified by the Department of Environment (DoE) that could be the focus of environmental enhancement: South Sound and Meagre Pond. These two areas are investigated also.

Hydraulic model development

TUFLOW has been selected as the hydraulic modelling package (version 2020-10-AA, released October 2020). TUFLOW allows detailed representation of drainage channels in both one-dimensional (1D) and two-dimensional surfaces and offers considerable flexibility in the representation of the land surface, in the input hyetograph and surface properties. TUFLOW was chosen due to the modest license costs (compared to ICM

InfoWorks) and existing experience of using the software by the project team, allowing for rapid modelling to undertaken.

A 2D only approach has been employed for the purpose of this study. The 2D model represents the land surface as a regular grid of 2D cells. However, the Sub-Grid Sampling (SGS) approach available in TUFLOW allows for the sampling and representation of sub 2D cell terrain data. The methodology allows for a coarse model cell size (keeping model run times to a minimum), whilst also preserving small scale topographic features present within the underlying input topography data.

Topography

Elevation data from the supplied WorldDEM Digital Terrain Model (DTM) has been used for the flood modelling study. The DTM represents the bare land surface in a gridded format of 12m resolution and has been pre-processed to remove vegetation and man-made surface features such that it represents the bare earth land surface. The WorldDEM was acquired from TerraSAR-X satellite data in 2019.

A more detailed 0.5m resolution digital *surface* model (DSM) was provided under licence from the Government of Cayman Islands Lands and Surveys Department derived from LiDAR data. A DSM differs from a DTM in that it includes all features present on the earth's surface (buildings, vegetation etc.). Despite the higher resolution DSM, it was deemed that this was not suitable for the purposes of flood modelling since the Cayman Islands are heavily vegetated with the potential for surface features to produce erroneous outputs. A comparison between the datasets is discussed further below and shown in Figure 4.4.

Roughness

Detailed habitat data for the three islands has been provided by the DoE, and this forms the basis of the Manning's n coefficients within the 2D model. The Manning's n is a coefficient representing the surface roughness or friction applied to flow. The habitat data has been re-classified into a generic land cover, and further simplified to remove unnecessary small polygons. In cases where the habitat classification was too broad (i.e. 'man-modified') or did not align uniformly to a single simplified land cover as seen in satellite imagery, the habitat classification has been disaggregated into several land covers. The classification of the habitat data into land cover is shown in Table 4.1 below, along with the associated Manning's n roughness value.

Table 4.1 Land cover classification and associated roughness values

2013 habitat classification	Land cover	Manning's n
Black candlewood	Forest	0.12
Coastal mahogany forest	Forest	0.12
Coastal shrubland	Shrubland	0.05
Dry forest and woodland	Forest	0.12
Dry lakebed	Water	0.035
Dry shrubland	Shrubland	0.05
Dwarf vegetation and vines	Shrubland	0.05
Invasive species - casuarina	Forest	0.12
Man-modified[1]	Forest	0.12
Man-modified with trees	Forest	0.12
Man-modified without trees	Grassland	0.04
Ponds, pools, and mangrove lagoons	Water	0.035
Salt tolerant succulents	Shrubland	0.05
Seasonally flooded / saturated semi-deciduous forest	Forest	0.12
Seasonally flooded grasslands V.A.1.N.g	Grassland	0.04
Seasonally flooded mangrove forest and woodland	Mangrove Forest	0.12
Seasonally flooded mangrove shrubland	Mangrove Shrubland	0.07
Seasonally flooded/saturated semi - deciduous forest	Forest	0.12
Semi-permanently flooded grasslands V.A.1.N.h	Wetland	0.04
Shoreline	Bare Earth	0.025
Sparsely vegetated rock	Sparse vegetation	0.03
Tidal tropical or subtropical annual forb vegetation	Water	0.035
Tidally flooded mangrove forest and woodland	Mangrove Forest	0.12
Tidally flooded mangrove shrubland	Mangrove Shrubland	0.07
Urban	Urban	0.017
Xeromorphic semi-deciduous forest	Forest	0.12

[1] Man-modified habitat has been disaggregated into several different land covers. Forest is the most dominant land cover within this region.

The unprocessed and processed datasets are shown for reference in Figure 4.1 and Figure 4.2 below.

Figure 4.1 Unprocessed 'raw' habitat data classified into simplified land covers.

Figure 4.2 Processed land cover dataset.

Rainfall losses

Rainfall losses have been applied to each land cover within the Materials Definition file as per the Manning's n coefficients specified in Table 4.1 above. Rainfall losses aim to account for the interception and evaporation of rainwater before it reaches the ground surface and removes the loss depth directly from the input storm hyetograph before it is applied as a boundary to the 2D model cells.

Losses have been applied on an initial and continuing loss basis and defined based on available literature and guidance[16]. Losses associated with each land cover are specified in Table 4.2 below.

Table 4.2 Rainfall losses

Land cover	Initial Loss (mm)	Continuing Loss (mm/hr)	Fraction Impervious
Bare Earth	5	1	0
Forest	30	5	0
Grassland	10	2	0
Mangrove Forest	30	5	1

[16] Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors) Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019.

Mangrove Shrubland	20	4	1
Shrubland	20	4	0
Sparse Vegetation	5	1	0
Urban	2	0	1
Water	0	0	1
Wetland	20	2	1

The fraction impervious applied to each land cover allows for the materials and the soils to be independent (i.e. the same soil can be present under both urban and forest land covers). The fraction impervious only applies to the infiltration into the soil and not to the rainfall losses.

The land cover data has been altered to create an additional 'Degraded' scenario. For the degraded scenario, all Forest, Shrubland, Mangrove Forest and Mangrove Shrubland regions have been updated to Grassland to simulate the effects of degradation and entire loss of natural capital. This corresponds to an overall reduced Manning's n roughness coefficient, and reduced rainfall losses associated with the diminished vegetation canopy.

Infiltration

Soil infiltration has been defined using the Green-Ampt method and based on the underlying United States Department of Agriculture (USDA) soil type dictated by the global International Soil Reference and Information Centre (ISRIC) soils data. Two types of soil texture are present across the Cayman Islands, Clay and Clay Loam. The Green-Ampt approach varies the rate of infiltration over time based on the soil's hydraulic conductivity, suction, porosity and initial moisture content. Infiltration only occurs on wet 2D cells, and is also dictated by the fraction impervious value of the overlying material layer.

Downstream boundary condition

The downstream boundary condition dictates how water is able to leave the model. For the purpose of this study, an initial water level and downstream boundary has been set to 0.44m AMSL (Above Mean Sea Level) to represent a typical high tide level[17]. Therefore, tidal regions will be 'wet' prior to any rainfall occurring within the model, and water will only be able to leave the model if the depth exceeds this level.

Pluvial hyetographs

Pluvial hyetographs have been generated based on analysis of daily precipitation totals from individual station records provided by the Department of Environment (DoE) in the Cayman Islands and the long-term official estimate of island precipitation produced by the Cayman Islands National Weather Service (CINWS). Hourly estimates were extracted from the European Centre for Medium Range Weather Forecasts Reanalysis Version 5 (ERA5)[18]. Following a preliminary review of the available data, the CINWS estimates, which provided consistent daily coverage up to 2020, were chosen as the primary source for annual maximum values, given

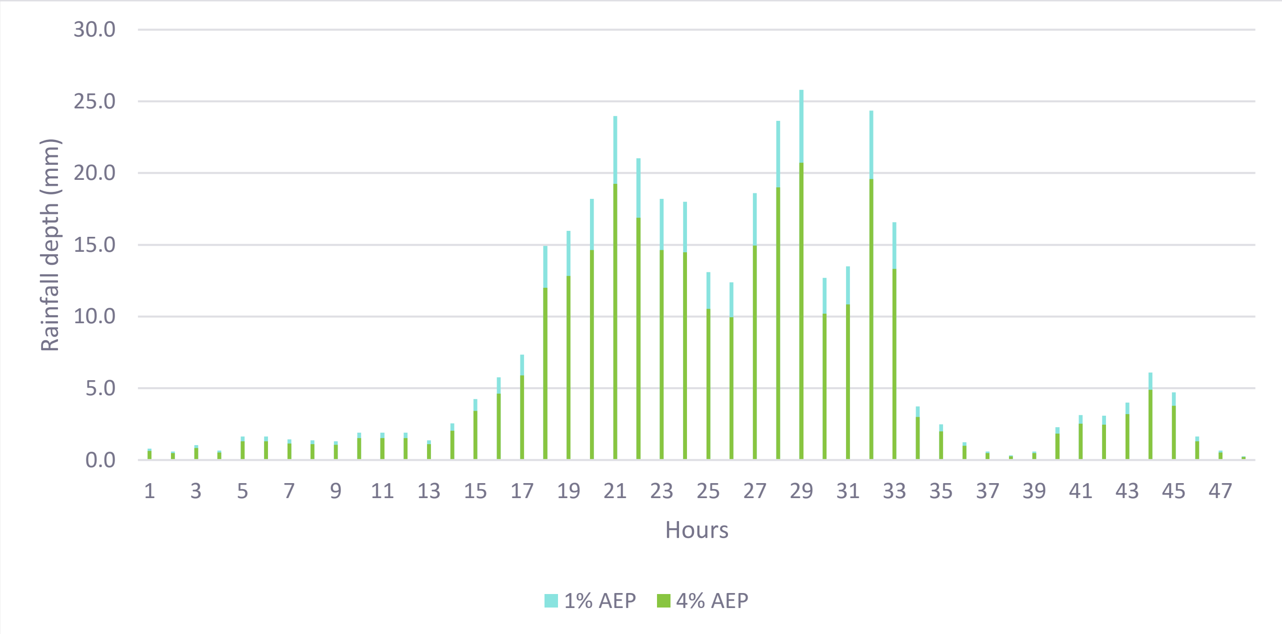
[17] https://www.tide-forecast.com/locations/Grand-Cayman-Cayman-Islands/tides/latest (Accessed 19/03/2021)

[18] https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.3803 (Accessed 18/03/2021)

their relatively complete record. The annual maximums extracted from the CINWS estimates sit consistently within or above the 1sigma range of individual station values (DoE), with only one exception in the 32-year record. Data gaps within the CINWS record have been infilled with the ERA5 hourly estimates.

To estimate extreme event values for the desired return periods, three series of potential (single and multiple day) annual maxima were used. Values for the 25- and 100-year return period (4% and 1% annual exceedance probability (AEP), respectively) 1, 2, and 3-day events were estimated using a variety of extreme value distributions (using L-Moments). The relative accumulation in each hourly time step follows that of Hurricane Ivan. For the purposes of this study, the 2-day (48-hour) duration hyetograph has been used in the flood model, given that the majority of precipitation recorded for Hurricane Ivan occurred within 48-hours and this results in the most conservative estimate. Figure 4.3 below shows the hyetographs for the 4% AEP and 1% AEP events generated.

Figure 4.3 Rainfall hyetographs



Limitations of methodology

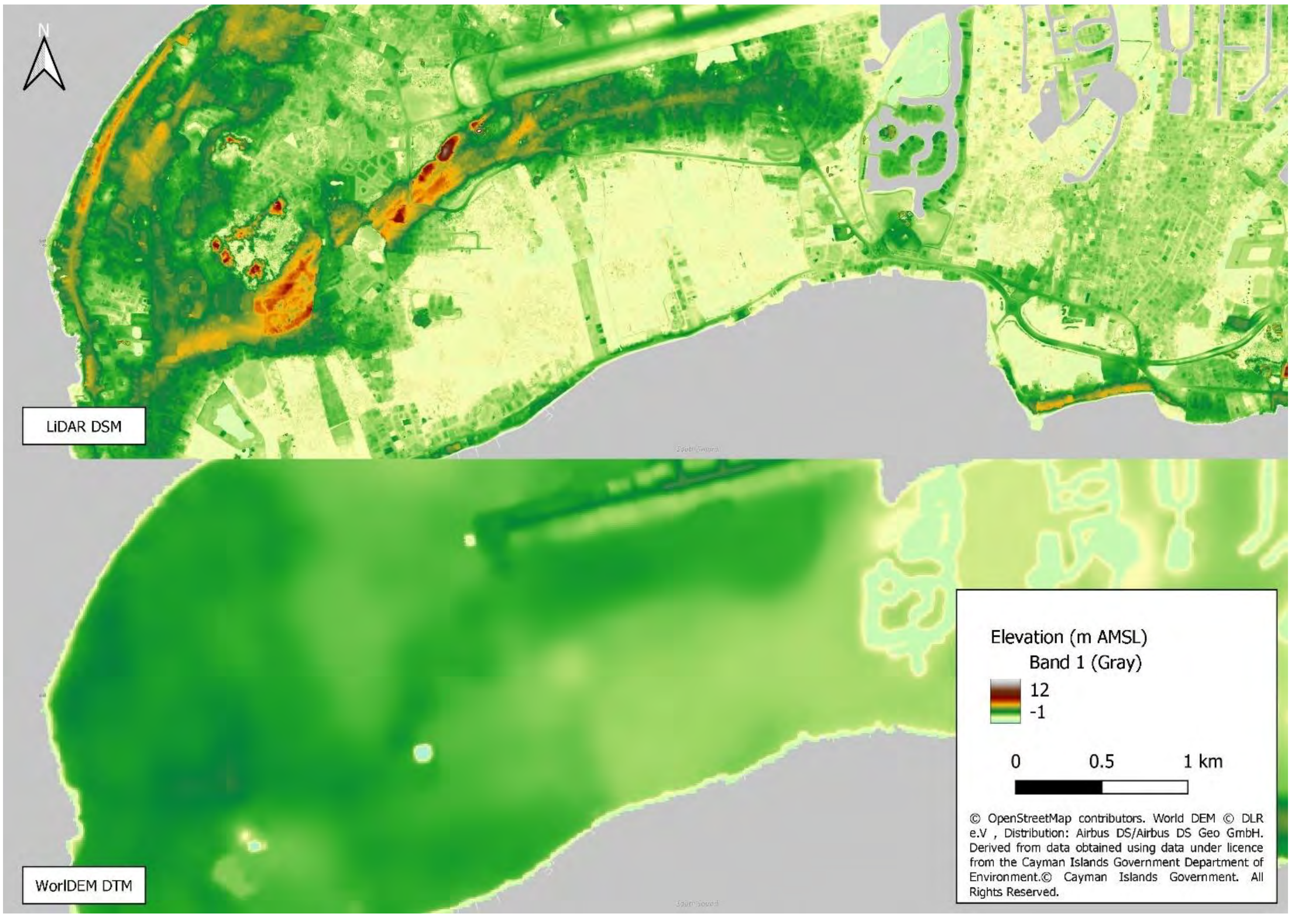
It is acknowledged that there are a number of limitations associated with the chosen methodology for assessing the protection offered by natural capital. The key limitations are:

- Topography resolution; and
- Property count methodology.

The underlying WorldDEM DTM data is of relatively coarse resolution for the purposes of accurate surface water flood depth mapping. Whilst the data is of reasonable quality and allows for a high-level overview of flood risk areas and the potential impacts of natural capital enhancement and degradation, the coarse resolution likely masks small scale surface water flowpaths along roads and between buildings for example, that can be critical in determining whether an individual building is flooded.

A comparison between the two datasets within the South Sound mangrove basin is shown in Figure 4.4. As seen, the WorldDEM does not accurately capture the small-scale topography features and infilled developments within the basin. As discussed in Section 4.1, DSMs are typically not deemed suitable for the purpose of surface water flood modelling given the inclusion of all surface features and vegetation, which may lead to erroneous modelling results. Processing of the high-resolution DSM into a 'bare-earth' DTM of similar resolution and incorporation into the model would lead to more accurate flood modelling results if used in a further iteration.

Figure 4.4 LiDAR digital surface model vs WorldDEM digital terrain model



A depth of 0.15m was used as a threshold to consider whether an individual building was considered flooded, and the maximum flood depth recorded over each building footprint was used as the metric of the potential damage caused by each model run. Depth is, of course, a key parameter in assessing the likely impact of a flood, however, the velocity is also key since this value may determine the scour of the hillsides, sediment load within the flood volume, and potential for landslides. Therefore, the method does not account for the potential for shallow (<0.15m), high velocity water to erode and destroy the foundations of an individual building.

4.2 Coastal flooding

Coastal flooding has been seen to have caused much damage in the Cayman Islands with both the intensity of tropical storms and their frequency important to overall effects on society. Coastal flooding occurs as a result of the combined increase in water level from storm surge and waves on a now elevated sea level. Mangroves and coral reefs are examples of natural capital assets or "green infrastructure" located in the coastal zone which have the ability to reduce exposure and vulnerability of property and populations to natural disasters (de Groot *et al.,* 2012[19]; Pascal *et al.*, 2016[20]).

Coral reefs provide coasts with natural protection from erosion and flooding by absorbing wave energy. Reefs protect against less frequent high energy events such as Category 4 and 5 hurricanes, but also against higher frequency lower energy events by reducing swell waves. Provided they are healthy, reefs have the ability to accrete carbonate structures which keep in time with sea level and can provide a significant role in coastal protection even during cyclones. However, it is important to note that given the projected increases in ocean acidification and sea level rise, as well as the effects of coastal infrastructure on sediment availability, their protective function may be compromised as health deteriorates. (WAVES, 2016[21]; Ferrario *et al*., 2014[22]).

The coastal protection service provided by mangroves is related to the ability of the vegetation to act as a source of friction, which acts on a body of moving water, resulting in the reduction of wave heights and storm surges as they approach a shoreline, as well as their ability to buffer wind speed (Barbier, 2016a[23], 2016b[24]).

Coastal flood model

To assess the geographic areas and assets at risk from coastal flooding and the protection to flooding provided by natural capital, the SWAN wave model was used. The SWAN wave model is a widely used third generation spectral wave model appropriate for shelf seas, coastal and near shore areas. It simulates wave generation, propagation and dissipation and includes the effects of refraction, shoaling and depth-limited breaking on wave propagation. The model is used to estimate offshore wave parameters under the influence of severe hurricane wind forcing, and the waves are then propagated over the shelf and shallow coastal areas, whereby shoaling over the near shore bathymetry and effects of natural capital are calculated in order to assess the resulting flood inundation onshore.

Scenarios investigated

The model was run for three different magnitude hurricane storms, each with three wave angles from historical hurricane tracks. For each of these storms four scenarios were run:

- Baseline – where natural capital is represented within the model to best reflect the current condition;
- Degraded – hypothetical reef degradation due to live coral die-off where the wave energy reduction from coral friction is lost;

[19] de Groot, R. et al. (2012) 'Global estimates of the value of ecosystems and their services in monetary units', Ecosystem Services, 1(1), pp. 50–61.

[20] Pascal et al. (2016) Economic valuation of coral reef ecosystem service of coastal protection: A pragmatic approach. Ecosystem Services (21) pp 72-80

[21] WAVES/ The World Bank (2016). Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs. http://documents.worldbank.org/curated/en/995341467995379786/pdf/103340-WP-Technical-Rept-WAVES-Coastal-2-11-16-web-PUBLIC.pdf

[22] Ferrario, F., M. W. Beck, C. D. Storlazzi, F. Micheli, C. C. Shepard, and L. Airoldi. (2014). "The Effectiveness of Coral Reefs for Coastal Hazard Risk Reduction and Adaptation." Nat Commun, 5

[23] Barbier, E. B. (2016) 'The protective service of mangrove ecosystems: A review of valuation methods'

[24] Barbier, E. B. (2016b) 'The Protective Value of Estuarine and Coastal Ecosystem Services in a Wealth Accounting Framework', Environmental and Resource Economics. Springer Netherlands, 64(1), pp. 37–58.

- Severe degraded – building on the degraded run, hypothetical 1m loss[12] of reef height is assumed due to reef substrate erosion due to death of the living coral from a range of impacts including ocean acidification; and
- Enhanced - where natural capital is represented in full health.

SWAN numerical wave model setup

The SWAN (Simulating WAves Nearshore) wave model, developed at the Delft University of Technology (the Netherlands), utilizes a finite difference scheme to compute random, short-crested, wind-generated waves and allows for spectral wave input at specified boundaries. In the current implementation, SWAN incorporates physical processes such as wave propagation, white-capping, shoaling, wave breaking, bottom friction, wave set-up and wave-wave interactions in its computations. SWAN computes the wave field over a specified range of geographical space, time, wave frequencies and directions. The model inputs include the gridded bathymetry and topography, and still water and surge levels, that allow the model to propagate the wave conditions in nearshore areas while taking into account shallow-water dissipation and depth-limited wave breaking. The model was set up using an approach of fine scale domains nested inside a coarser domain that covers the totality of the Cayman Islands. The coarser domain is developed with a spatial resolution of 1 km and extends geographically from 18.5 N to 20.25N and 79W to 82.5W. The dimensions and resolution of this coarser grid allow appropriate propagation of waves toward the islands without excessive computational cost. As the line of reefs along the coasts of the Cayman Islands are at a distance of approximately 500 m from the coast, a 150 m resolution nested grid was used to capture the finer bathymetric details and wave dynamics that dominate the wave interactions during storm events. The nested grid extends approximately 10 km from the coast, providing a sufficient transition distance from the deep water to the shallow water as the shelf in the Cayman Islands is narrow.

The significant wave heights near the shore are computed by the model are used in conjunction with the corresponding surge levels for each hurricane category, in order to allow the propagation of the coastal flood levels inland. The waves propagating to the shoreline are expected to cause additional inundation due to wave runup above the still water levels defined by the tides and storm surge. The wave runup inundation level is highly variable on small spatial scales, due to variations in the cross-shore profile, coastal slope and materials, as well as the presence and characteristics of any man-made structures and vegetation.

While wave runup was not explicitly calculated for the shoreline at Grand Cayman, a range of plausible wave runup values was used to estimate the potential range of inundation heights on land. The wave runup values were assumed to range from a factor of 1 to 2 times the offshore significant wave height above the still water level, as calculated by the SWAN wave model in the immediate vicinity of the shoreline. The significant wave height is considered to represent the average wave height of the highest one third of the waves in a given sea state, while the maximum wave height within a given sea state is constrained by approximately 2 times the significant wave height, under an assumed Rayleigh distribution of wave heights.

Bathymetry and topography grids

In the coastal waters the high resolution DoE bathymetry dataset was interpolated into the SWAN computational grid. For all areas not covered by the DoE data the SRTM15_PLUS product (https://topex.ucsd.edu/WWW_html/srtm15_plus.html) with a spatial resolution of 500 m was used for the interpolation onto the computational model grids.

Parameterization of reef roughness and depth effects

Accounting for coral reefs and mangroves

To account for the dissipative effects of provided by coral reefs and mangroves (and hence reduced wave heights) the SWAN wave model uses Manning's n values which were assigned to the areas of reefs and mangroves identified from the habitat maps (0.2 - reefs; 0.4 – mangrove) provided by the DoE. This approach has been successfully used by Dr. Gonzalez-Lopez to incorporate the effect of reefs and mangroves for storm surge and wave modelling in Puerto Rico and the Virgin Islands (Joyce *et al.*, 2019)[25].

Three scenarios were used to account for the frictional effect cause by the degradation and enhancement of reef structures. The current state of reefs (baseline) was modelled by applying 80% of the full Manning's n coefficient value (representing the current reef not being at 100% health). For a degraded state of reefs 50% of full Manning's n value was applied, and for an enhanced scenario where reefs recover, a 100% of the Manning's n value was used. The difference between wave heights under different reef and mangrove coverage scenarios can then be used to quantify the importance of these features on the coastal hazard mitigation and its associated risk.

Table 4.3 Manning's n values and modified depth values used across the wave model scenarios

Scenario	Ambient Manning's n	Reef Structure Manning's n	Depth Modification(m)
Baseline Scenario	0.02	0.16	0
Degraded Scenario	0.02	0.11	0
Degraded Scenario with depth change	0.02	0.11	-1 (depth increase)
Enhanced Scenario	0.02	0.22	0

Storm surge

We have approximated the effect of storm surge into the SWAN wave model by increasing the water depth in the model by 0.5, 1.0, and 1.5 m for the Category 1, 2, and 3 hurricane wind speeds respectively. Previous high-resolution modelling and observations of storm surge and waves during Hurricanes Irma and Maria in Puerto Rico and the Virgin Islands indicate that the shelf characteristics of islands limit the storm surge (driven by atmospheric pressure and wind) to a range of 1 – 2 m for Category 4 and 5 hurricanes (Joyce, et al., 2019). This is most noticeable in coastal areas in Southeast and Northeast Puerto Rico, which have similar characteristics to the coasts in the Cayman Islands. This increase in water depth allows for the wave model to show the effect of wave transformation during storm surge, mainly by allowing larger waves to reach the coastline instead of breaking farther away due to depth. A higher water level due to storm surge would also change the effectiveness of the friction caused by reefs and mangroves.

The outputs from SWAN model for each of these scenarios were converted to GIS (250m grid squares) for further analysis to understand the impact of flooding on land from the maximum water level from combined storm surge and wave height.

[25] Joyce, B. R., Gonzalez-Lopez, J., Van der Westhuysen, A. J., Yang, D., Pringle, W. J., Westerink, J. J., & Cox, A. T. (2019). U.S. IOOS coastal and ocean modeling testbed: Hurricane-induced winds, waves, and surge for deep ocean, reef-fringed islands in the Caribbean. Journal of Geophysical Research: Oceans, 124, 2876– 2907. https://doi.org/10.1029/2018JC014687

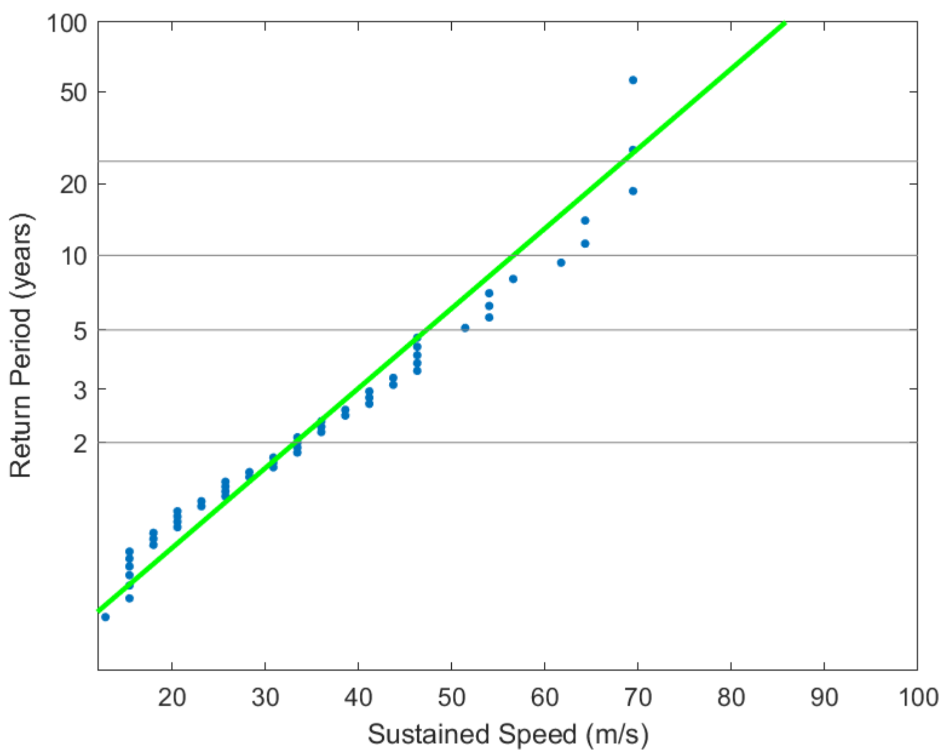
Hurricane wind forcing scenarios

To consider the variability of hurricane tracks, while constraining the number of scenarios to be modelled explicitly, three main wind forcing speeds and angles were determined from the historical hurricane tracks in the HURDAT2 dataset (https://www.nhc.noaa.gov/data/#hurdat). HURDAT2 is a long-term hurricane database containing six-hourly information on the location, maximum winds, central pressure, and size of all known tropical cyclones and subtropical cyclones, covering the years 1851-2019 (Landsea *et al.*,2013)[26]. The SWAN model was then forced with winds from directions for all of the scenarios considered.

In order to constrain the number of simulations while covering the whole range of hurricane wind speeds the wave model was forced with uniform wind speeds representing the highest wind speeds of category 1, 3, and 5 hurricanes. This corresponds to 42.50, 57.60, and 72.00 m/s respectively. For each wind speed three directions were considered with winds blowing from the north (0º), south (180º), and southwest (225º). The purpose of this approach was to model with a relatively low number of simulations the effect of hurricane-forced wind waves as they transform and propagate over the narrow shelf from the deep water into the coastal zone. Using a constant wind over the computational domain avoids the need of requiring a high number of synthetic storms to obtain full island coverage of wind forcing at the coasts.

Figure 4.5 shows the return period of maximum sustained winds, resulting from analysis of the hurricane records available from the HURDAT2 database. For the wind speeds used in the wave model the return periods are 4 years for Category 1, 10 years for Category 3, and 34 years for Category 5.

Figure 4.5 Return period of maximum sustained winds. Underlying wind data obtained from HURDAT2.



[26] Landsea, C.W. and Franklin, J.L. (2013): Atlantic Hurricane Database Uncertainty and Presentation of a New Database Format. Mon. Wea. Rev., 141, 3576-3592.

Limitations of the methodology

While the numerical model used in this study is considered to represent the details of wave development and transformation from deep to shallow waters reasonably well, the present implementation is subject to several notable limitations.

- The SWAN wave model is not dynamically coupled to a hydrodynamic model such as Delft3D or ADCIRC, and therefore the still water levels in the wave model are constant throughout the domain. Such a coupling would allow the water level to vary locally, with feedback between the hydrodynamics and wave processes calculated by SWAN. Also, it would allow to model coastal currents, which can be used to determine coastal hazards and processes such as sediment transport.
- Due to the size of Grand Cayman and the narrow length of its shelf the spatial resolution of 100 m could be made finer to capture in more detail the energy dissipation of waves as they propagate from deep to shallow waters. This would be particularly of advantage if dynamically coupling SWAN with a circulation model, since coastal flooding and water levels are sensitive to changes in the wave height gradients. As these gradients are large due to the steep and narrow shelf, a finer resolution would provide more details of the wave field near the coast. In addition, a finer spatial resolution would allow to include more localized detail of the reefs in the model grid.
- An important refinement to improve estimate of coastal flooding would be to use the wave heights computed by the SWAN model as inputs in the inland model, in conjunction with the corresponding surge levels for each hurricane category, in order to allow the propagation of the coastal flood levels inland at a higher spatial resolution.
- The wave runup heights used for coastal inundation are based on an estimated range based on the incident significant and maximum wave heights, that can be expected for certain coastal profiles, however the present implementation does not take into account the actual coastal cross-shore profile, slope roughness, buildings or vegetation for any of the Cayman Islands coastline that might influence actual wave runup elevations in any given location.

4.3 Economic valuation

Introduction

Flooding is a natural process and not something external to the economic system but something to which it is related. Responses to flooding are part of a wider perspective of environmental management which is inherently part of society's relationship with its environment. An overall objective is for society to continuously seek to better withstand the expected level of natural hazards and adapt effectively and efficiently.

The range of potential effects from flooding is extensive. Land may be temporarily transformed into sea or inland torrent with dramatic short-term effects as well as long term consequences. In times and places where flooding is foreseeable, society reacts by avoidance or the acceptance of risks and may also organise to seek to deliberately benefit, with the classic example being the regular flooding of the Nile.

These themes are apparent in the Cayman Islands which, like any individual place, has a unique combination of expectation, exposure to hazard, management options and levels of risk. These depend on the underlying geographical and societal features and their influence on local community organisation, the economy, and nature itself. The Cayman government has overall responsibility for national policy towards nature through the implementation of legal and regulatory regimes which set a context for behaviour and action by individuals and businesses.

Amongst the main societal response strategies are:

- Avoidance, such as not building on areas likely to be flooded, as well as short term action to avoid immediate effects such as use of storm refuges and, in the context of climate change, adaptation
- Prevention, primarily physical protection through the use of physical barriers, but in the context of climate change, also includes mitigation
- Sharing and Compensation, such as through insurance and community schemes which although not reducing the physical effects of flooding, allow costs to be shared across a population which may share an equal expectation but only some of whom will be affected by any specific event.

The level and deployment of these strategies depends on prevailing circumstances and will change over time. There will be corresponding changes in the costs and benefits of each strategy Individually and collectively, both of which will include changes in societal attitudes and economic values. The feasibility of future strategies will also depend on actions in previous time periods ranging from effects seen as positive in general, such as harbour defences, to those with more negative future impacts, such as unlicensed construction.

A previous study identifies the relationship between ecosystem services and their value to the Cayman Islands. This used an approach to valuing coastal protection which assess flooding impacts in terms of damage to property. The implementation of the

Steps in valuation

The valuation follows the steps in the toolkit. The aim of the toolkit is to identify an appropriate valuation framework and maximise comparability of economic analysis. The toolkit has five steps which are implemented as described below.:

Step 1 – Purpose of an economic assessment

The purposes of the economic assessment are:

- To establish values of the environmental benefits of natural assets for flood protection so that they can be compared with other values relevant to policy makers
- To compare alternative environmental outcomes within a consistent economic framework

Step 2 - Selection of comparators

The relevant comparators for this assessment are:

- National accounts, which are a key consideration for national budgeting processes.
- Previous work on the value of marine protected areas, including their contribution to coastal protection[10], which provides an estimate of the value of coastal protection in the Cayman Islands
- Previous work on a similar subject in the BVI[27] which provides a precedent methodology and a quantification in the Caribbean.

The national accounts are a useful reference for understanding and valuing flood effects. The local economy will be the first source of supply for immediate needs before and after an event and may itself be forced to adapt to changed circumstances. Figure 2.2 presents information related to the national accounts of Cayman Islands.

In the Cayman Islands, the dominance of services in the economy is clear as well as the correspondence between growth in population (17%) and the overall growth in the economy (16%). Similar levels of growth are seen in related sectors such as transport, utility services, trade, education and public administration. In contrast, more than double this level of growth is seen in the Hotel and restaurant sector and in professional, scientific and technical activities. The fall in construction and the lower growth in the Cayman Islands in real estate is surprising given the overall growth and may indicate a maturing market with less new build.

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[27] Wood (2019) An assessment of the value of natural capital in the protective service against coastal and inland flooding in the UK Overseas Territory of the British Virgin Islands.

Figure 4.6 Breakdown of economic activity in the Cayman Islands as reported in the national accounts

Demographic indicators					
Population	65,813		18%		
Economic Indicators					
Cayman Islands GDP by Industrial Origin ($'000 At Constant Basic Prices (2015=100))					
	GDP 2018	(as %)	2009-2018 growth	Compared to population growth	
Economy Total (Goods and Services)	4,083,929	100.0%	16%	=	
Goods-total	227,219	5.6%	3%	-	
Agriculture & Fishing	15,798	0.4%	23%	+	
Mining & Quarrying	9,521	0.2%	7%	-	
Manufacturing	38,516	0.9%	17%	=	
Construction	163,384	4.0%	-1%	Falling	
Services - total	3,856,710	94.4%	12%	=	
Electricity, Gas & Air Conditioning Supply	60,913	1.5%	12%	=	
Water Supply, Sewerage & Waste Management	39,020	1.0%	-4%	Falling	
Wholesale & Retail Trade	273,315	6.7%	14%	=	
Transport & Storage	148,075	3.6%	17%	=	
Hotels & Restaurants	231,580	5.7%	42%	++	Related to tourism
Information & Communication	115,959	2.8%	5%	-	
Financial & Insurance Services	1,337,240	32.7%	8%	-	
Real Estate Activities	369,444	9.0%	10%	-	
Professional, Scientific & Technical Activities	570,201	14.0%	33%	++	Related to tourism
Administrative & Support Service Activities	109,400	2.7%	27%	+	
Public Administration & Defense	223,419	5.5%	15%	=	
Education Services	97,268	2.4%	14%	=	
Human Health & Social Work	157,457	3.9%	41%	++	Related to non Cayman population
Other Services	123,418	3.0%	28%	+	

Step 3 – Description of project and Step 4 – Physical-Economic links

These steps are combined in this application of the toolkit because in this case the specification of the project itself is closely linked to, or even could be said to be derived from, the links between physical causes and economic effects.

The high-level project description is summarised as the aim of 'valuing the reefs for coastal protection'. The links between physical assets and the economic effects are primarily based around representation of a flood event. Within an assumed chain of causality, the location and condition of reefs leads to flooding in certain locations which is then attributed to that reef. The representation of the economic effect of flooding is considered in the next Step, but the primary driver of value is the link between the hydrological conditions and the economic activity within the flooded zone.

Step 5 – Setting estimates within an economic framework

A simple assumption related to the aim of valuing the reefs for coastal protection might be that the value can be estimated based on the difference between a world with and without reefs. The example in the toolkit for reefs indicates the general issues in assessing the values of this type of change. The challenge is that this while a small change may be represented by a small increase in flood depth, the removal of reefs is somewhat unrealistic and would lead to potentially much more significant effects. At one extreme, the loss of reefs might be an existential issue.

From the perspective of establishing the ongoing level of costs related to flooding, while the physical causes of flooding leads to events of different scale and extent, because flooding is a repeated event and can be mitigated to an extent, activities related to it are visible in the national accounts as represented by the SNA economic framework. An indicative list of the possible elements in the SNA that could be considered related to events and/or to the societal responses to them is shown in Figure 0.7. For further clarification of the potential economic-related changes, the last column indicates how changes in the frequency or severity of events might affect the level of costs.

Figure 4.7 Types of financial effects of societal responses to flooding as reported in national accounts (SNA)

Public sector actions/costs	Regular/Event	Examples	Effects of increased frequency and severity
General legislation and regulation affecting resilience to flooding	Regular	Building standards	More specific regulation
Public investment in flood specific infrastructure & programmes	Regular/Event	Flood defences, reputational management	Greater defences, less desirable location
General provision of emergency social, health and economic services	Regular/Event	Flood Refuges; Bottled water; Mental health servic	More formalised services
Maintenance & repair of public sector infrastructure	Regular/Event	Road restitution	Budget increases
Government expenditure & revenue raising	Regular	WB/IMF loans	Credit rating reduced
Private sector actions/costs			
Insurance	Regular	Flood insurance; business interruption insurance	Higher level of market activity
Physical defences (e.g. sandbags)	Regular	Purchase of sandbags	Higher level or limit reached for market
Purchase of goods to replace damaged	Event	House contents replacement	Higher level or limit reached for market
Structural repair	Event	Building and construction work	Higher level or limit reached for market
Disposal of damaged materials	Event	Waste services	Disposal capacity limits
Temporary/new accommodation	Event	Substitute accommodation for businesses	Price increases in housing and rental markets
Borrowing to enable repair	Event	Personal/corporate loans	Higher level or limit reached for market

This list includes the purchase of good to replace damage, as well as structural repair and disposal of damaged materials. These are headline items often used in assessing flood costs are used again here, with further explanation provided below. Damage and repair costs are immediate consequences of a flood event and reflect an underlying perspective of a desire for continuity in current behaviours and in prioritising protection and restitution.

Business losses are recognised as an important category of effect and these have been considered directly in the more recent references (Wood, 2019; USGS, 2019). Note that business interruption is simply a loss and so will not be included under SNA as only activities which actually took place are reported. However, business losses that are insured will be included in the SNA as they will be seen as financial transactions from insurers to business owners. Also, any additional social security payments resulting from loss of business will be seen under government expenditure. Business losses are assessed here.

The assessment of damage and repair provides an example of approach to valuation relying on use of market information. Goods and property that are damaged can be replaced on a like-for-like basis by simply repurchasing them from a market. Similarly, services are available from a market for repair and renewal. The advantage of this approach is that the types of goods and services required are common and market prices are well established and so cost estimates can be calculated that are reasonably certain and objectively based. Possible alternative policies can be compared in terms of the different levels of anticipated effects denominated in terms of the avoided costs of damage and the costs of implementation.

In practice, the inclusion damage and repair costs as an effect of flooding is also adopted for the following reasons:

- Because of the general nature of flooding, studies are often concerned with comparison across quite wide areas (e.g. the globe) and are seeking a standard approach. The most basic and understandable loss is that of private property and possessions, so it is a common (though incomplete) metric.
- A well-researched and standardised 'depth-damage' method for valuing property damage is published by the US government (USACE). While it acknowledges clearly relevant causal factors, such as the depth of the flooding and the number of stories in a building, it reflects evidence only from the United States.
- Because the common standard is at a US level, it is higher than might be applicable in poorer countries and so appears a more 'equitable' approach which addresses any criticism that impoverished communities are less costly to flood. This aspect is prioritised over any more subtle consideration but can also obscure how local economies actually work.

- The main output from many physical models is flood depth which can be easily linked with the associated valuation model, although it also may obscure aspects such as flood duration, impacts from flood extent and the effects of wave energy.

Data availability is a primary consideration for all valuation. Here, data for individual properties is the primary need, including detail of the parameters such as elevation and numbers of stories that are required to implement the depth-damage function estimates.

Valuation approaches listed in the references include methods which could be employed and rely on a basic link between flood depth and damage to properties and these are relevant to the estimation of damage costs. An implication regarding the choice of physical models for flood representation is that as long as they represent the basic parameter of flood depth, they can all be linked to a depth-damage economic valuation. The representation of additional economic effects from other physical effects such as waves within a coastal area of particular importance to the economy may be important.

For assessing business losses, the methodology in USGS, 2019 cannot be applied in an identical way as it uses US specific data sets (for GDP per capita) but would otherwise have the advantage of being consistent with other US data for depth-damage relationships. However, it provides guidance on a general approach and this can be used for guidance, noting that the better data for Cayman Islands allows a better representation than the more standardised US approach which uses a broader area-based methodology. Wood, 2019 also demonstrates a representation of business losses focused on the bar and restaurant hospitality sector.

Integration with the physical model

In implementation, the steps in the toolkit are integrated with physical modelling, in the following sequence:

1. Use physical model results for flood depth to assess damage impacts based on depth-damage functions
2. Calculate additional business losses based on whether properties are flooded or not
3. Using and adopting precedent approaches, represent the scale of significant knock-on impacts where possible drawing on the same results for flood depth and other physical impacts in order to represent wider economic impacts
4. Review adjusted valuation approach for catastrophic events with major and widespread effects (such as flooding over the majority of Grand Cayman).

5. Results: assessment of the effect of natural capital on flood protection

5.1 Inland flooding impact assessment

Baseline flood modelling

The following sub-section describe the baseline surface water flood risk for each island. Full island-wide depth results are shown in Appendix A for each island.

Grand Cayman

Surface water flood risk across Grand Cayman is typically characterised by extensive ponding of floodwater in the low-lying (<1m AMSL) central regions of the island. In particular, significant ponding of floodwater is anticipated across the central wetland in North Side, the eastern nature reserves in East End, and in several urban regions within Georgetown. Owing to the low-lying nature of the island as a whole, there are few recognised surface water flowpaths and surface water flooding is typically widespread and of low velocity.

Extensive property flooding is anticipated in both the 4% AEP and 1% AEP storm events, as indicated in Table 5.1 and Figure 5.1 below. Floodwater is predicted to exceed 0.5m across much of low-lying Georgetown, and in particular adjacent to North Sound Road. The property dataset was provided by the Land & Surveys Dept.

Table 5.1 Grand Cayman inland flooding baseline property counts

	Baseline	
Building Classification	**4% AEP**	**1% AEP**
Apartment/Condo	698	940
Education/Religion	42	53
Government/Civic	43	50
Hotel/Tourism/Leisure	47	55
Industrial	95	110
Mixed Use	13	16
Non-Addressable	1000	1345
Residential	2065	2937
Restaurant/Bar	41	50
Retail/Commercial/Professional	371	444
Unclassified	19	27

Unknown	21	27
Utility	51	57
Total	**4506**	**6111**
% Buildings Impacted	**18%**	**24%**

Figure 5.1 Georgetown 1% AEP peak flood depths

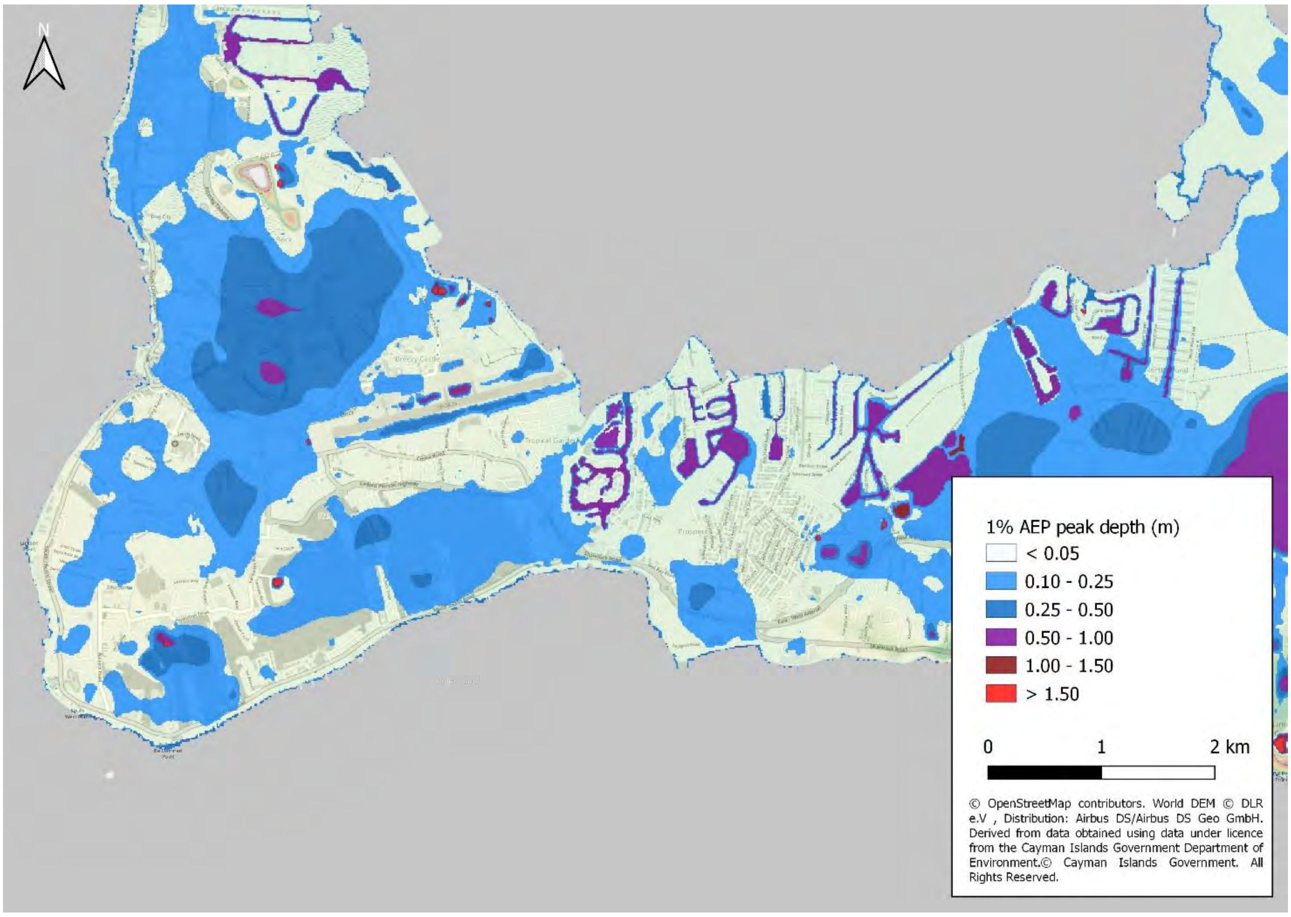
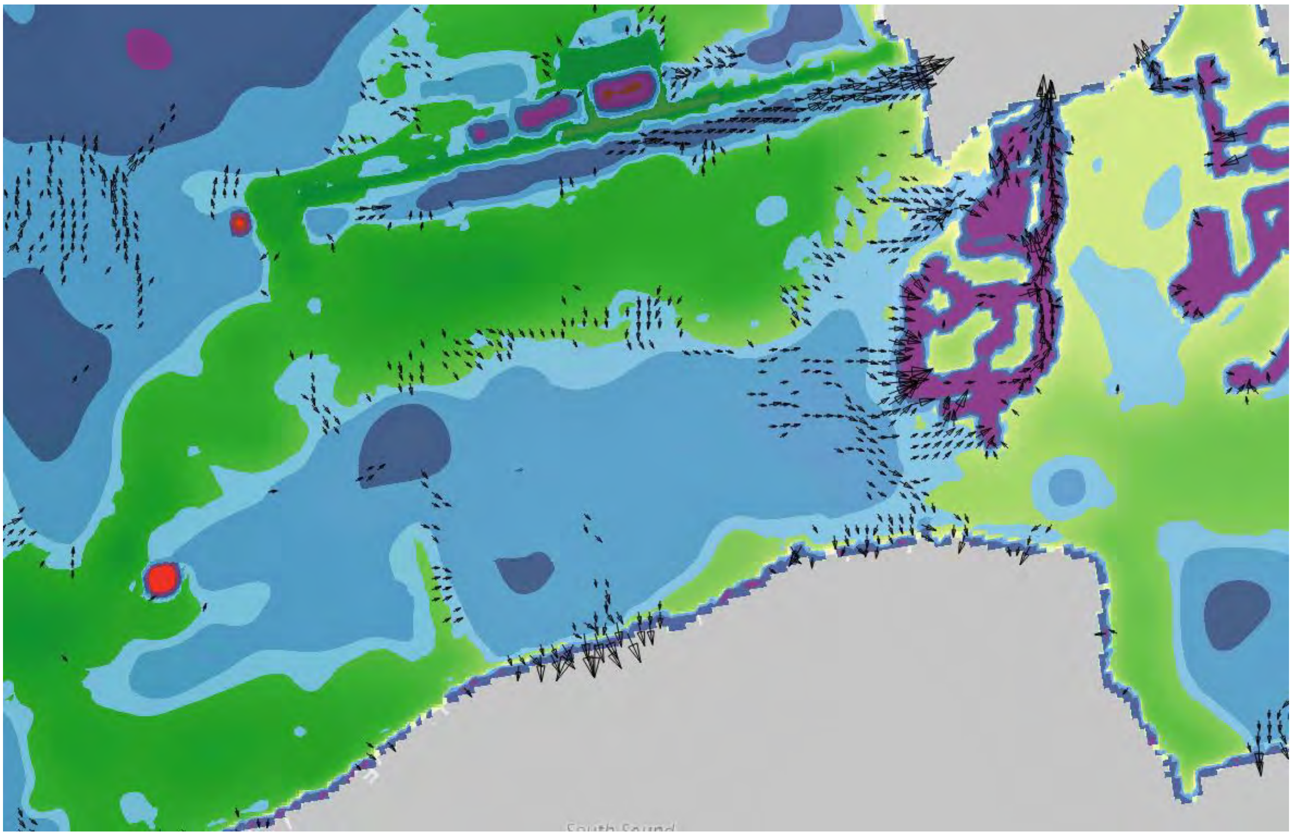


Figure 5.2 below displays the detailed flooding mechanisms associated with the South Sound basin, including shallow flood depths of >0.025m and flow velocity vectors. The basin is an area acknowledged to be at risk of future development and infilling (DoE 2015[28]). The basin is shown to capture surface water runoff from elevated land to the north and west, and is anticipated to discharge to the sea at several points to the south, and into the canal network to the east. However, the model is limited by the underlying WorldDEM resolution in accurately predicting the flooding mechanisms within and around the basin. Comparison between the higher resolution DSM as seen in Figure 4.4 shows that numerous road embankments within the region, that would serve as significant hydraulic controls, are not captured within the WorldDEM dataset. As a result, the small-scale flooding mechanisms at the building level are not captured within the modelling results. It is recommended that a more detailed DTM and stormwater drainage networks be incorporated in a

[28] Department of Environment (2015). South Sound Drainage Basin Stormwater Management. Memorandum.

further iteration of the model for a more accurate understanding of the flooding mechanisms in the basin, and for the purposes of assessing the impact of the proposed developments if desired.

Figure 5.2 South Sound basin flooding mechanisms

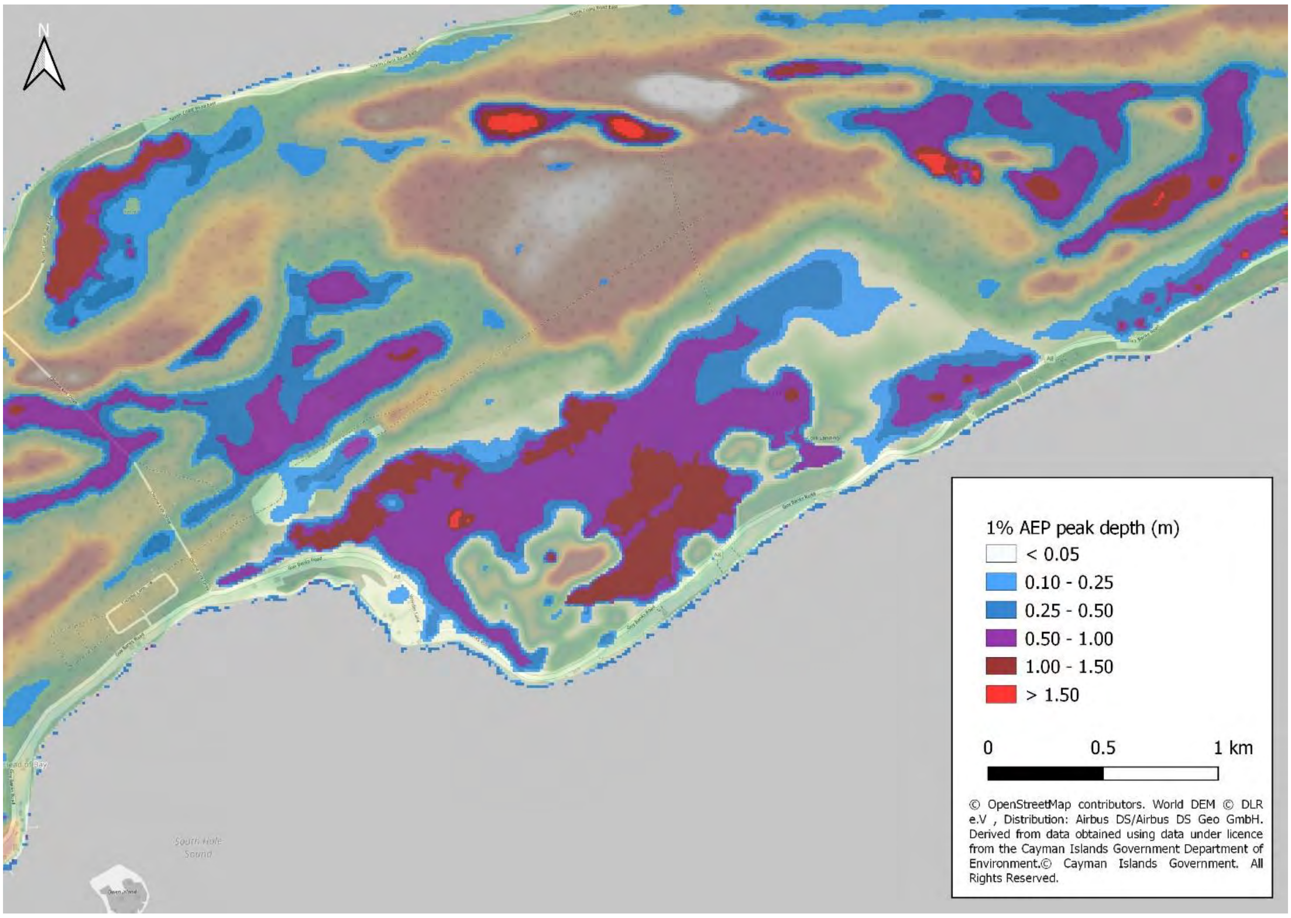


Note: Arrows show flow velocity and direction, indicating that water within the basin discharges to the South Sound Bay at several points to the south, and into the canal network to the east.

Little Cayman

Similar to Grand Cayman, surface water flooding across Little Cayman is characterised by extensive, low velocity ponded water that accumulates in the wetland and low-lying (< 1m AMSL) regions within the central and coastal portions of the Island. Floodwater typically ponds to depths of 0.5-1.5m in these areas. Given the low-lying nature of the island, there are few typical surface water flow paths visible from the model results. Figure 5.3 below shows expected surface water ponding within Tarpon Lake on the south coast of Little Cayman in the 1% AEP event.

Figure 5.3 Tarpon Lake 1% AEP peak flood depths



Owing to the low level of development on the island, relatively few numbers of properties are anticipated to be impacted as seen in Table 5.2 below.

Table 5.2 Little Cayman inland flooding baseline property counts

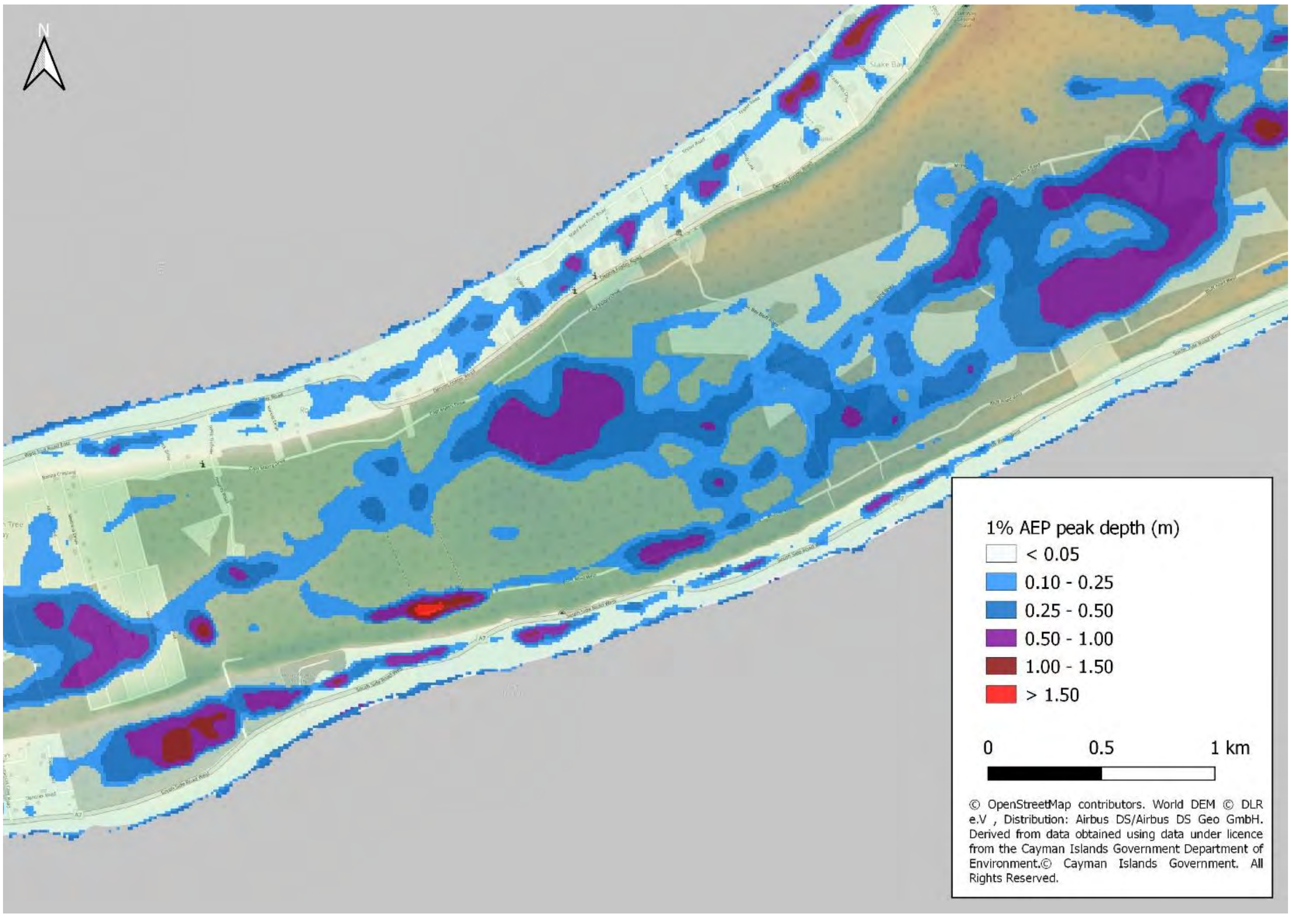
	Baseline	
Building Classification	**4% AEP**	**1% AEP**
Apartment/Condo	1	1
Education/Religion	0	0
Government/Civic	0	1
Hotel/Tourism/Leisure	1	1
Industrial	0	0
Mixed Use	0	1
Non-Addressable	8	10
Residential	5	6
Restaurant/Bar	0	0
Retail/Commercial/Professional	0	0
Unclassified	0	0
Unknown	0	0
Utility	1	1
Total	**16**	**21**
% Impacted	**4%**	**5%**

Cayman Brac

Owing to the topography of Cayman Brac, surface water is anticipated to flow in an east to west direction within the central portion of the island following the topographical gradient. Surface water flooding along these flow paths is typically shallow (<0.5m), and of relatively higher velocity exceeding 2m/s in some regions. However, floodwater is anticipated to pond significantly to depths regularly exceeding 1.5m in the numerous low-points within the DTM and both the Juniper Bay quarry and Scotts quarry.

Surface water flooding across the low-lying coastal regions that straddle the north and south coast of the island is typically characterised by isolated regions of ponded water where surface water is anticipated to accumulate. Given the lack of contributing catchment in these regions, surface water flow paths are limited. Figure 5.4 below demonstrates the typically isolated regions of ponded floodwater on the north and south coastal regions, and the more extensive surface water flooding within the central portion of the island that accumulates towards the southwest end.

Figure 5.4 Cayman Brac 1% AEP peak flood depths



Extensive property flooding is anticipated in both the 4% AEP and 1% AEP events, as indicated in Table 5.3 below. A relatively minor incremental increase in property counts is seen between the 4% AEP and 1% AEP events, given the low-lying populated regions which limit substantial increases in flood extent.

Table 5.3 Cayman Brac inland flooding baseline property counts

	Baseline	
Buildings Classification	**4% AEP**	**1% AEP**
Apartment/Condo	14	18
Education/Religion	2	3
Government/Civic	11	12
Hotel/Tourism/Leisure	3	4
Industrial	4	4
Mixed Use	2	2
Non-Addressable	97	116
Residential	219	270
Restaurant/Bar	1	1
Retail/Commercial/Professional	16	16
Unclassified	4	8
Unknown	6	6
Utility	7	8
Total	**386**	**468**
% Impacted	**17%**	**20%**

Degraded model scenarios

The following sub-sections outline the impact to peak flood depth results associated with the degraded scenarios run for each island. 'Severe degradation' scenarios have been established simulating the removal of all forest, shrubland, and mangrove land covers to grassland – to represent entire loss of natural habitat. Full island-wide depth difference maps are presented in Appendix A.

Grand Cayman

As discussed above, the severe degradation scenario simulates the removal of all forest, shrubland, and mangrove land covers to grassland. An additional 'selected degradation' has been simulated for Grand Cayman, discussed further in the sub-section below.

As seen in Figures A.7 and A.8 in Appendix A, the severe degradation scenario results in both positive and negative impacts in terms of peak flood depth. Whilst the removal of full canopy cover results in reduced rainfall losses (associated with interception and evaporation), the associated reduction in Manning's n roughness coefficients result in generally greater surface water flow velocities. In turn, this leads to increased surface water runoff and therefore reduced water ponding in some areas in the degraded scenario. This is the reverse of what one would typically expect, as described in Section 4.1. Depth increases are typically in the region of 0.01 – 0.10m, though do exceed 0.40m in some isolated ponded regions. Similarly, depth reductions are typically in the region of 0.01 – 0.10m. Some minor differences in the magnitude of differences are anticipated between the 4% AEP and 1% AEP events although the general picture remains the same.

The associated property counts for the degraded scenario are shown in Table 5.4 below. In accordance with the peak flood depth increases and reductions as discussed above, the degraded scenario results in both increases and reductions in property counts spatially. The overall net impact is a minor increase in properties flooded across the island in both the 4% AEP and 1% AEP results. This is most significant in the lower magnitude 4% AEP event.

Table 5.4 Grand Cayman inland flooding degraded scenario property counts

	4% AEP		1% AEP	
Building Classification	**Degraded Scenario**	**Difference from Baseline**	**Degraded Scenario**	**Difference from Baseline**
Apartment/Condo	687	-11	920	-20
Education/Religion	41	-1	60	+7
Government/Civic	43	0	51	+1
Hotel/Tourism/Leisure	47	0	52	-3
Industrial	95	0	107	-3
Mixed Use	14	+1	16	0
Non-Addressable	1022	+22	1353	+8
Residential	2131	+66	2972	+35
Restaurant/Bar	39	-2	48	-2
Retail/Commercial/Professional	367	-4	426	-18
Unclassified	22	+3	28	+1
Unknown	22	+1	28	+1
Utility	50	-1	56	-1
Total	4580	+74	6117	+6
% Impacted	18%	+0.3%	24%	+0.0%

The results highlight that despite the reduced rainfall losses with the removal of forest and mangrove, the associated reduction to surface roughness values plays a significant role in determining the peak flood depth recorded and in some cases negates any impact associated with the reduced rainfall losses. One would typically expect to see corresponding detrimental impacts (in terms of increased peak flood depth) downstream of any regions with a reduced Manning's n coefficient. However, this is not always the case as seen in these scenarios, since the associated increase to surface runoff typically affects wide, low-lying regions rather than a well-defined flowpath. As a result, detrimental impacts downstream are borne over a wide area and are therefore often negligible. Additionally, in areas with coastal mangrove forest lining the coastline, the mangroves are shown to slow the dispersion of inland floodwater out to sea, and therefore their removal can often have a positive impact to upstream inland flood depths.

Little Cayman

The associated depth difference results for the severe degradation scenario on Little Cayman are shown in Figures A.11 and A.12 in Appendix A. As seen in Grand Cayman, the degradation scenario results in both depth reductions and increases. However, the general impact is typically an increase in peak flood depth, as seen in the low-lying depressions across the island. Depth increases are typically in the region of 0.02 – 0.10m in both the 4% AEP and 1% AEP events. Some minor depth reductions of up to 0.06m are predicted associated with the reduced Manning's n coefficient.

The associated property counts for the degraded scenario are shown in Table 5.5 below. In both the 4% AEP and 1% AEP events, the degraded scenario results in two additional properties being flooded.

Table 5.5 Little Cayman inland flooding degraded scenario property counts

	4% AEP		1% AEP	
Building Classification	**Degraded Scenario**	**Difference from Baseline**	**Degraded Scenario**	**Difference from Baseline**
Apartment/Condo	1	0	2	+1
Education/Religion	0	0	0	0
Government/Civic	1	+1	1	0
Hotel/Tourism/Leisure	1	0	1	0
Industrial	0	0	0	0
Mixed Use	0	0	1	0
Non-Addressable	9	+1	11	+1
Residential	5	0	6	0
Restaurant/Bar	0	0	0	0
Retail/Commercial/Professional	0	0	0	0

Unclassified	0	0	0	0
Unknown	0	0	0	0
Utility	1	0	1	0
Total	**18**	**+2**	**23**	**+2**
% Impacted	**5%**	**+0.5%**	**6%**	**+0.5%**

Cayman Brac

The associated depth difference results for the severe degradation scenario on Cayman Brac are shown in Figures A.13 and A.14 in Appendix A for the 1% AEP and 4% AEP events respectively. The impacts of degradation in this case are more 'typical' and as one would expect in comparison to Grand Cayman and Little Cayman. This is associated with the topography of the island and evident surface water flowpaths that drain in a southwest direction through the central portion and following the topographic gradient. A typical depth reduction is anticipated in the central northeast portion of the island, and an associated depth increase is predicted in the downstream central southwest portion. Surface water flow paths flowing in a southwest direction experience typically greater velocities as a result of reduced surface roughness, and therefore pond to a reduced depth compared to the baseline scenario. As a result, and combined with the reduced rainfall losses, the downstream southwest portion of the island typically experiences exacerbated flood depths as floodwater experiences reduced attenuation across the upstream flow paths and accumulates to a greater depth prior to receding.

The associated property counts for the degraded scenario are shown in Table 5.6 below. In accordance with the peak flood depth increases and reductions as discussed above, the degraded scenario results in both increases and reductions in property counts spatially. The net impact is a minor increase in the total number of properties flooded in the 4% AEP event, and a minor reduction in the 1% AEP event. Typically, in regions of anticipated depth increase, the degraded scenario does not result in significant increases in properties flooded since these areas are generally inundated significantly in the baseline. Hence, few additional properties are recorded as flooded in the degraded scenario.

Table 5.6 Cayman Brac inland flooding degraded scenario property counts

	4% AEP		**1% AEP**	
Building Classification	**Degraded Scenario**	**Difference from Baseline**	**Degraded Scenario**	**Difference from Baseline**
Apartment/Condo	15	+1	18	0
Education/Religion	2	0	2	-1
Government/Civic	10	-1	11	-1
Hotel/Tourism/Leisure	2	-1	2	-2
Industrial	4	0	5	+1

Mixed Use	2	0	2	0
Non-Addressable	92	-5	102	-14
Residential	228	+9	252	-18
Restaurant/Bar	1	0	1	0
Retail/Commercial/Professional	17	+1	17	+1
Unclassified	6	+2	6	-2
Unknown	6	0	6	0
Utility	7	0	7	-1
Total	**392**	**+6**	**431**	**-37**
% Impacted	**17%**	**+0.3%**	**19%**	**-1.6%**

Grand Cayman scenarios

A series of targeted case study scenarios have been run on Grand Cayman, simulating the effects of both degradation and enhancement of the natural habitat. The scenarios target specific areas of known degradation and areas with the potential for enhancement.

Selected degradation

The 'selected degradation' scenario in this case simulates the conversion of 'dry forest and woodland' habitat to grassland, and the loss of tidal mangroves within Little Sound and South Sound to grassland (this differs from the severe degradation scenario discussed above, which simulates the removal of all forest, shrubland, and mangrove land covers to grassland). Both dry forest and woodland and the tidal mangrove habitats are acknowledged by the DoE to be a risk from future development. The existing inland mangrove basin at South Sound has undergone upfilling and encroachment from coastal developments, and has further been separated from the coastal mangroves with the development of the coastal South Sound road. The inland basin is at risk from further infilling with a number of proposed major developments.

The depth difference results associated with the targeted degradation scenario are seen in Figures A.9 and A.10 in Appendix A for the 1% AEP and 4% AEP events respectively. As one would expect, the associated impact is reduced in comparison to the severe case. Depth increases typically of 0.01-0.03m are anticipated across a widespread area in the eastern portion of the island associated with the loss of dry forest and woodland to grassland (and the reduced rainfall losses). Isolated bands of depth reductions varying from 0.01 – 0.07m are predicted in the regions where tidal mangroves have been lost to grassland. The magnitude of difference remains similar between the 4% AEP and 1% AEP events.

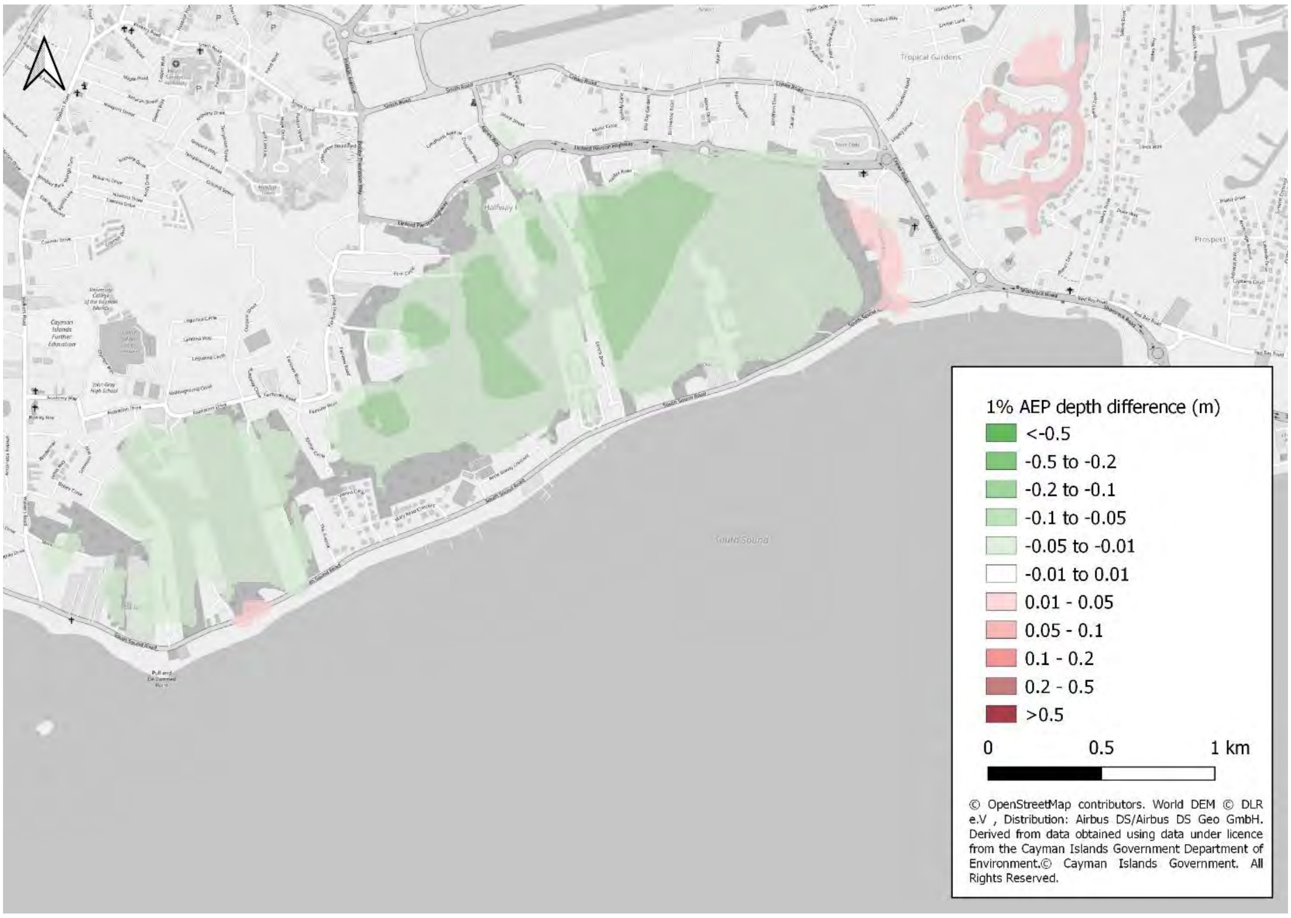
South Sound

A targeted degradation and enhancement scenario has been run for South Sound. As discussed above, the South Sound basin is at risk of further development and infilling, and there is the need for flood risk mitigation measures to address the existing and future flood risk.

The degraded scenario for South Sound mirrors the changes made in the selected scenario above, simulating the loss of all mangrove to grassland. No modification has been made to the underlying WorldDEM topography to simulate the infilling of the mangrove basin since the elevations across the basin already sit above 1.2 mAMSL.

The depth difference associated with this scenario for the 1% AEP event is shown for South Sound in Figure 5.5 below. Depth reductions of 0.01-0.06m are anticipated over the basin and can be explained by an associated increase in flow velocities and runoff of surface water associated with the reduced Manning's n roughness coefficient. In turn, exacerbated flood depths of 0.01-0.02m are anticipated within the downstream canal network due to the faster response of surface water runoff.

Figure 5.5 1% AEP South Sound basin degradation scenario



The enhanced scenario for South Sound assesses the impact of two potential storage basins that sit against the South Sound coastal road embankment. Additional drainage channel 'cuts' into the topography have been made to simulate the effects of drainage culverts to the sea. The 1% AEP event depth difference for this scenario is shown in Figure 5.6 below.

Figure 5.6 1% AEP South Sound basin enhancement scenario

Typical depth reductions of 0.01-0.03m are anticipated within the eastern portion of the mangrove basin and adjacent canal network. More substantial reductions exceeding 0.10m are predicted in the local vicinity of each storage basin.

Given the relatively small contributing catchment, and combined with the existing developments in the area, the potential for nature-based solutions to mitigate flood risk is limited. Whilst the results above provide a high-level overview of the potential impacts of development and a possible enhancement scenario, it is recommended that a more detailed modelling study be undertaken to provide a more accurate understanding of flooding mechanisms within the basin and the potential impact of individual developments. As discussed above, detailed modelling should make use of a finer resolution DTM dataset and incorporate the drainage network elements within the region.

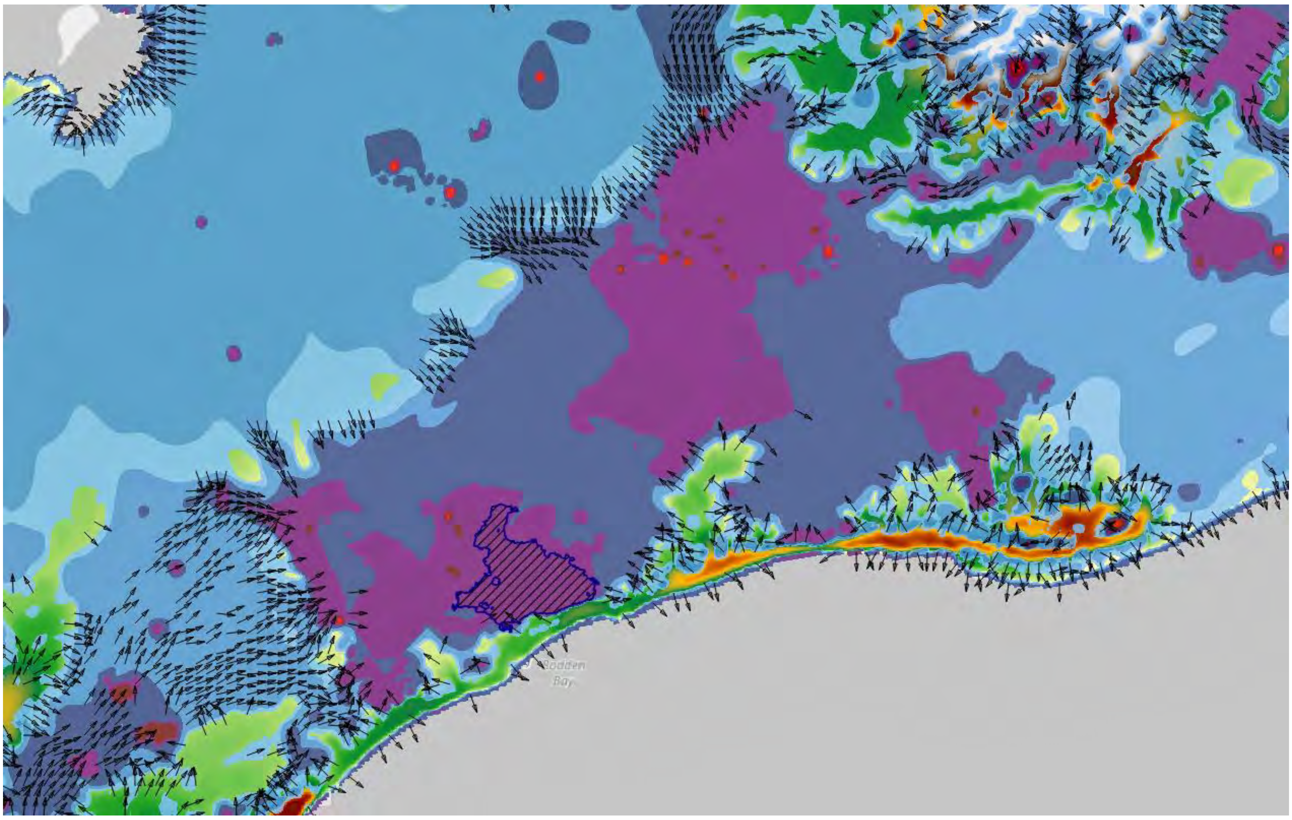
Meagre Bay

Targeted degradation and enhancement scenarios have been simulated for Meagre Bay Pond. The pond provides an important feeding ground for sea birds and has undergone significant habitat deterioration in recent decades associated with industrial quarrying to the west. Changes to the hydrological and salinity cycle to the pond have resulted in degradation of the black mangrove forest around the edge of the lake (DoE, 2020).

The degraded scenario has been established simulating the loss of 300ft of mangrove forest along the edge of the lake. The enhanced scenario simulates the impact of a 50ft expansion of mangrove forest into the lake, in addition to a raised bund running along the western edge of the pond to separate quarry and pond waters.

In both scenarios, the resultant impact to peak flood depths in the region is negligible (<0.005m). As seen in Figure 5.7 below and indicated by the flow velocity vectors, the pond sits within a wider low-lying region that is subject to inundation from elevated land that bounds the region to the north and southwest. Therefore, the land cover changes around the edges of the lake play only a minor role in the flooding mechanisms within the wider catchment. Similarly, the separation of the quarry from the pond with the addition of a bund is predicted to have negligible impact to flood depths within the region given the wide contributing catchment that drains to the pond.

Figure 5.7 1% AEP Meagre Bay Pond flooding mechanisms



Whilst enhancement of the natural environment and habitat at the pond is likely to provide significant benefits from an ecological perspective, there is anticipated to be negligible benefit from a flood risk perspective.

Commentary on results

The hydraulic modelling demonstrated an increase in flooding depths with event severity, as would typically be expected with heavier rainfall. However, as seen in the peak flood depth figures and as reflected in the property count tables, the increases in flood extent are generally limited. This is a reflection of the low-lying topography of the islands, and in particular Grand Cayman and Little Cayman, which creates a ‘bucket-like’ effect as increased flood depth does not necessarily result in a linear increase in flood extent.

It had been anticipated that the reduction in rainfall losses and roughness values associated with the degraded scenarios, at both island and case study level, would increase the speed of the catchment response to rainfall, causing water to move more quickly to the lower-lying areas and exacerbating peak flood depths. However, this has not always been the case with both exacerbated and reduced peak flood depths anticipated. Resultant impacts to peak flood depth are often anticipated to be relatively minor in magnitude, given that the impacts are borne over a wider area owing to the low-lying nature of the islands.

In some instances, and despite the reduced rainfall losses (i.e. Increased rainfall reaching the ground), the associated reduction in roughness values is often shown to improve conveyance of surface water to the sea. In these cases, the degraded scenario results in reduced flood depths. This, however, does not necessarily indicate an improved or favourable position with regard to flooding as a result of degrading the environment.

In a severe rainfall event such as those modelled as part of this study, the depth of flooding is only one aspect of the risk and damage that the event may cause. The velocity of flood water is another important aspect, and one not considered for valuation here. As discussed in the sub-sections above, the degraded scenario typically results in an increase in surface water flow velocities associated with the reduced roughness coefficient. Given that only depth has been used as a metric to determine whether a building is considered flooded, this ignores the potential for shallow (<0.15m), high velocity water to erode and destroy the foundations of an individual building.

In addition, the increased velocities would contribute to increased soil erosion and sediment load within the flood water, transporting greater volumes of clay, silt and sand to the lower-lying areas and into the marine environment. The accumulation of sediment at downstream locations has the potential to reduce channel capacities and exacerbate surface water flooding if not maintained, particularly at culverts discharging to the sea for instance. Furthermore, increased delivery and deposition of sediment to the marine environment and to the coral reefs in particular has the potential to further accelerate reef degradation. Both mechanisms discussed here have not been valued as part of this study, but highlight qualitatively the positive impact of natural capital.

The inland modelling has not benefited from the use of a high resolution DTM dataset, relying on the coarser scale WorldDEM. Processing of the high-resolution DSM into a 'bare-earth' DTM of similar resolution and incorporation into the model would lead to more accurate flood modelling results if used in a further iteration. This would improve the understanding of small-scale flooding mechanisms and the vulnerability at an individual building level, as highlighted in Figure 4.4.

The result of reduced flood depths observed in the degraded scenario highlights a key limitation of the modelling and assessment method, in that only extreme rainfall events have been considered. In a more frequent, lower magnitude event, the role of rainfall interception and evaporation becomes more significant. In a lower magnitude event, the rainfall losses applied to account for interception and evaporation will make up a greater proportion of the total rainfall, and therefore the resultant effective rainfall (rainfall converted to runoff) is reduced.

TUFLOW was chosen as the tool to model the rainfall-runoff processes. Recognising the complexity of the model does not lend itself to the non-specialist, it was an original project objective to create a simple GIS based tool to interpolate between a natural capital protection index and flood depth. Given the results reported above, it was decided at this stage not to proceed with this development or to undertake a full economic analysis on the inland flood results.

5.2 Coastal flooding impact assessment

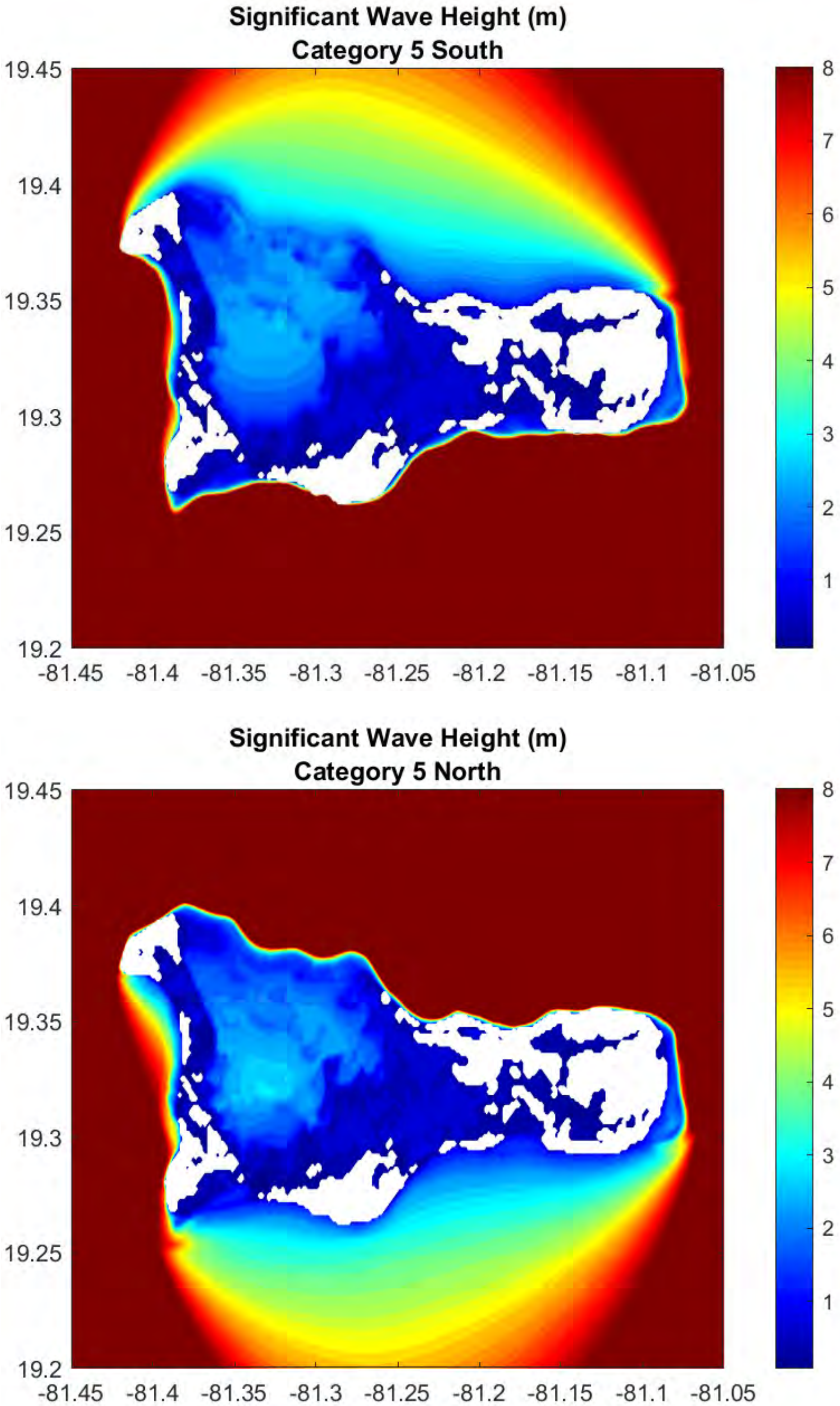
The following section presents results from selected numerical wave modelling scenarios, that illustrate the propagation and transformation of waves generated by the severe hurricane scenarios onto the shelf and coastal areas of Grand Cayman, as well as the effects of the degraded and enhanced reef scenarios on the nearshore modelled wave heights relative to the baseline case.

Baseline: wave propagation from deep to shallow water

Figure 5.8 below shows the significant wave height in Grand Cayman under Category 5 hurricane winds from the south and north directions. For both wind scenarios the wave field with heights of 13 m abruptly breaks as it approaches and interacts with the steep shelf. This results in waves with a height of less than 4 metres propagating over the narrow shelf and reaching the coast. The baseline wave height results are shown for all storm categories and wind directions in Appendix B.

In locations where the shelf is wider (e.g. the southeast and southwest of the island), the longer propagation distance to shore allows for a larger decrease in wave height after the initial abrupt breaking at the shelf edge. As these wider shelves have reef coverage, the combination of shelf length and reef friction increases the wave height reduction. This illustrates the importance of the shelf width regarding its dissipative effects on waves. The wave heights on the coastline opposite of the incident wind and wave direction are generally significantly lower. Namely, when the waves propagate from the south, the island acts as an obstacle, and the north side and main bay then receive low wave heights nearshore. When the waves are incident from the north, there is a similar behaviour where the south coast is sheltered from the wind, and would experience lower wave heights. However due to the refraction of the wave field after hitting the north western most corner of the island, part of the wave field incident from the north then hits the western coast of Grand Cayman. The impact of the shelf line and reefs that are located across the entrance to the lagoon can be clearly seen, with wave heights becoming significantly lower.

Figure 5.8 Significant wave height as modelled by SWAN with Category 5 hurricane winds from the south (top) and north (bottom).



Flooding impact onshore

As seen in Figure 5.8 large areas of Grand Cayman are flooded, particularly to the east of central lagoon where inundation extends extensively inland. Southern areas of Georgetown become flooded (including South Sound) and the inundated area bridges across from the south coast across Grand Harbour and Bonnie View Estates into the central lagoon region. Flooding is also extensive along the Seven Mile Beach region and along the coastline west of the lagoon. Here wave heights of 8-12 m (depending on wind direction) reach close to the coast before breaking, generating a strong wave energy gradient, contributing to wave induced setup and inundation. Higher elevated land at West Bay, Boden Town and the East End largely escape from the flood waters. The flood extents of the category 5 results follow a broadly similar pattern to the floods recorded as a result of Hurricane Ivan, based on photographs and anecdotal information.

The significant wave heights as shown in Figure 5.8 have been converted to a peak water level incorporating an allowance for the storm surge as described in Section 4.2. This has been used to extract a maximum flood depth onto each building, incorporating the building elevation and used for the economic valuation.

Wave propagation in Category 3 and Category 1 storms

Figures 5.9 and 5.10 show the significant wave height of storms originating from the north direction for lower Category 3 and Category 1 storms. The wave model results show lower levels of inland inundation with decreasing storm severity, both due to the lower incident wave heights, as well as due to the lower storm surge levels associated with the less severe hurricanes.

Figure 5.9 Significant wave height as modelled by SWAN with Category 3 hurricane winds from the south (top) and north (bottom).

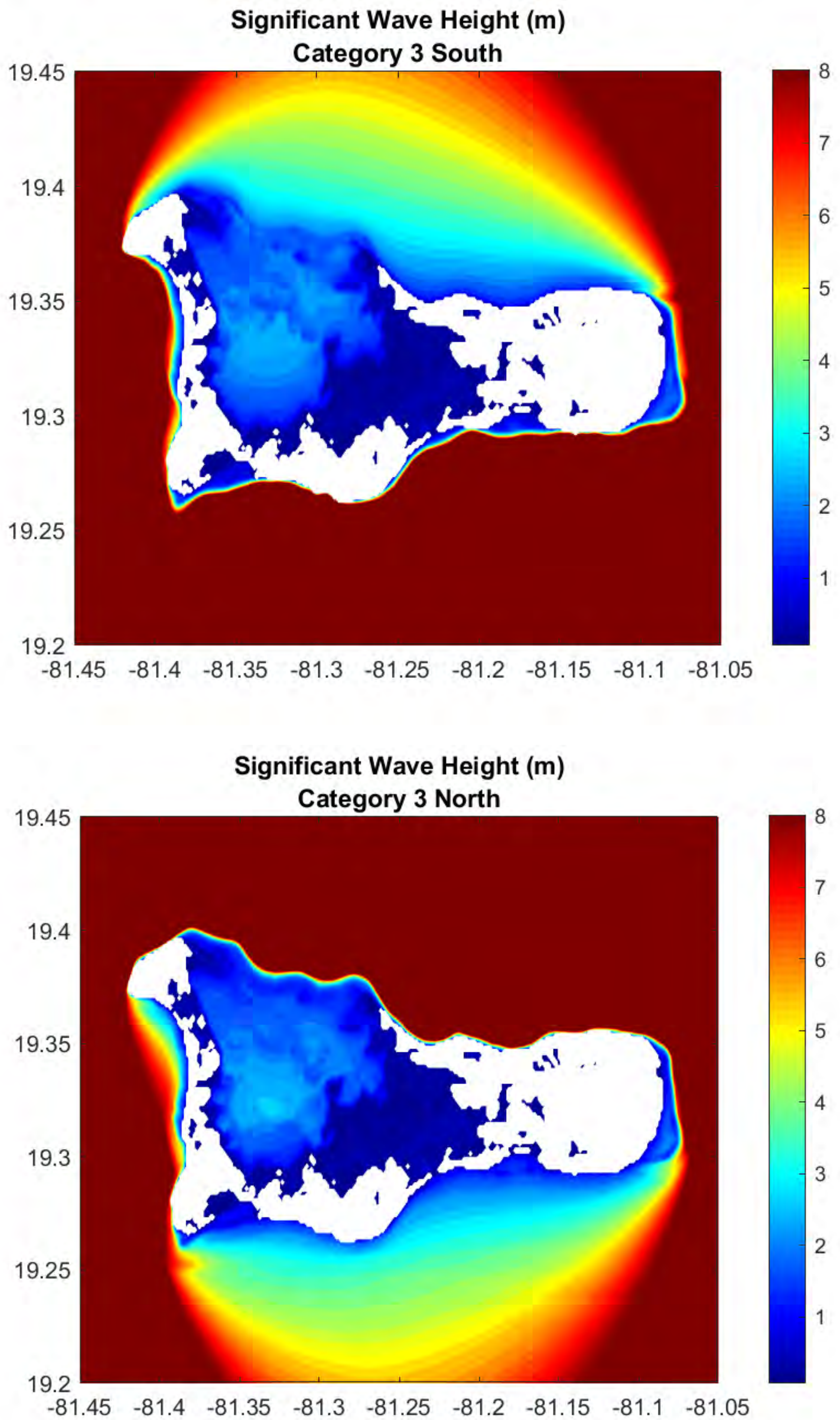
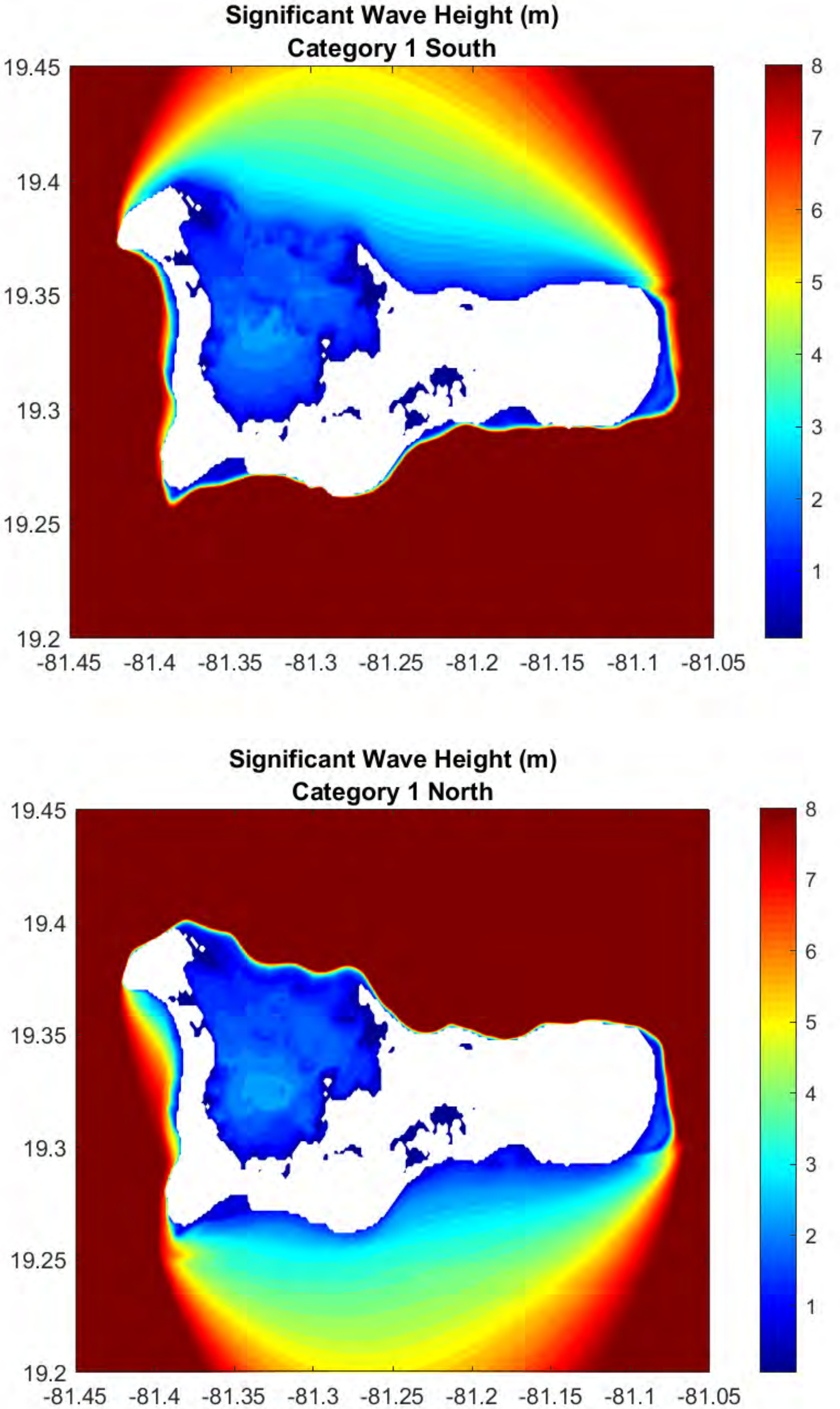


Figure 5.10 Significant wave height as modelled by SWAN with Category 1 hurricane winds from the south (top) and north (bottom).



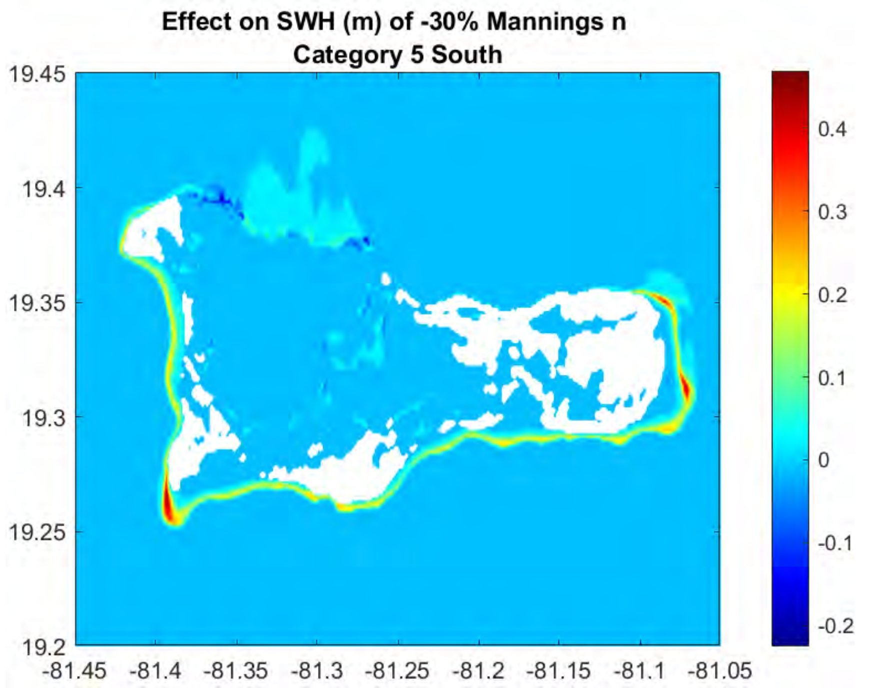
Impact of natural capital degradation and enhancement

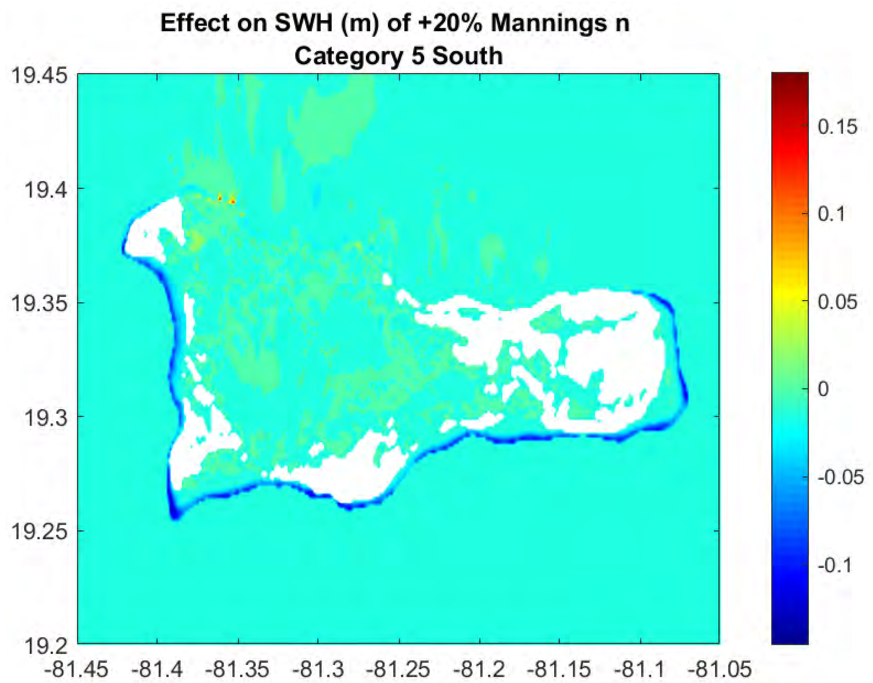
The impact of reef degradation, or reef enhancement through the loss or enhancement of the live coral and therefore the friction component is simulated in the model through changing the roughness, parameterised through the Manning's n coefficient. The impact of this change is illustrated in Figure 5.11 for a Category 5 storm with waves incident from the south. Significant wave height difference maps are provided in Appendix B for both the enhanced and degraded scenarios and wind directions for a category 5 storm, and for category 1 and 3 storms with wind direction incident from the north.

Decreasing the friction coefficient by 30% (representing effects of reef degradation) results in an increase of wave heights ranging from 0.20m to more than 0.40m at some locations. The effect of increased wave height appears strongest in the areas where the shelf is the widest. This observation again stresses the importance of shelf width in wave dissipation, and illustrates that the protective benefits to the coastline are variable across different locations on Grand Cayman, depending on the amount of wave energy dissipation provided by the geometry and depth configuration of the coastal areas (independent of the presence of the coral reefs).

Increasing the Manning's n coefficient by 20% resulted in a slight decrease of wave height of approximately 0.1 to 0.2 m. Contrary to the degraded case with a decrease in Manning's n, the effect of increased roughness under the enhanced scenario appears uniform throughout the reef coverage area. These results give an indication that a loss of the frictional effects of the reef might have a larger negative effect on nearshore wave heights, compared to a possible benefit due to an increase of frictional effect due to reef conditions.

Figure 5.11 Effect on significant wave height of reduction of Manning's n coefficient by 30% (top) and increase of Manning's n coefficient by 20% (bottom).





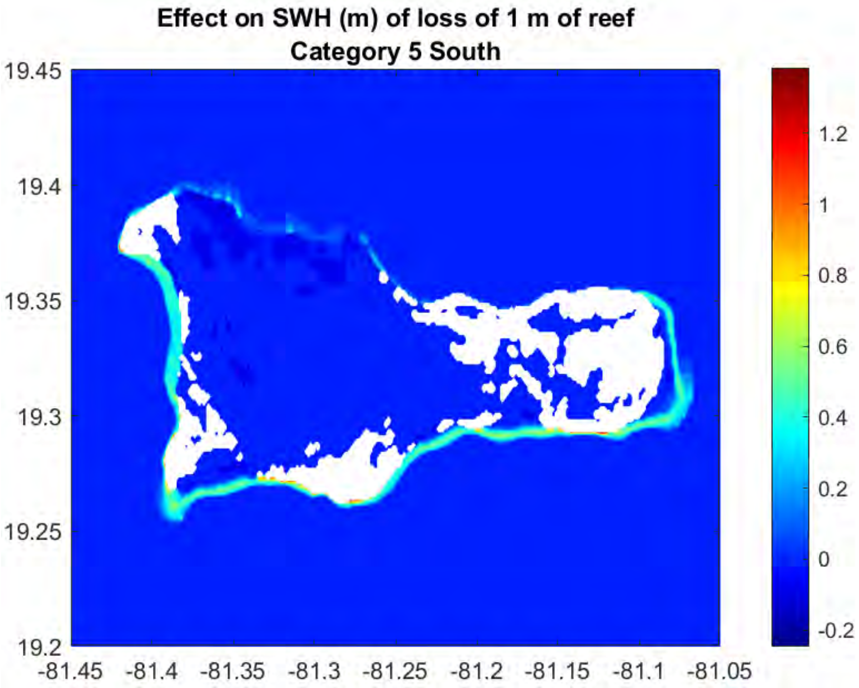
Flooding impact on shore

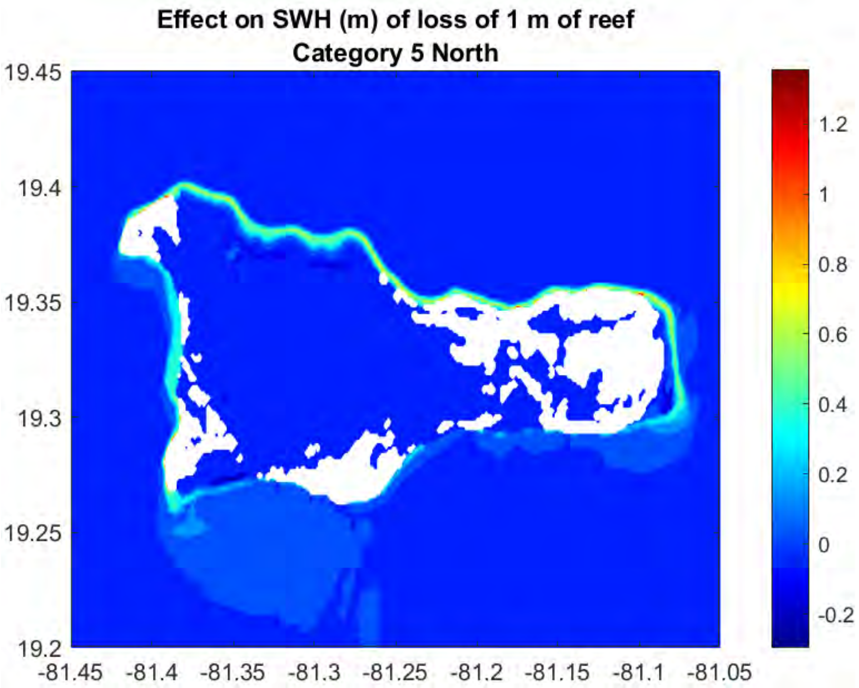
As seen in Figure 5.11 above and in wave height difference maps presented in Appendix B, the associated impact to significant wave heights under the enhanced and degraded scenarios is typically limited to above the reefs and the nearshore areas only. Very limited difference in significant wave heights is anticipated across the inland regions that are subject to inundation, with differences typically not exceeding 0.05m. Most significant impacts to buildings are anticipated on the western coastline of George Town, with differences of up to 0.25m anticipated to some nearshore buildings in the category 5 storm and southwest wind direction.

Severe degradation: impact of 1m loss of coral reef structure on nearshore wave heights

A hypothetical increase of water depth due to the erosion/loss of 1m of reef structure was represented in the wave model by increasing the water depth at the computational cells which have an associated reef classification by 1m. Results of this scenario for a Category 5 hurricane forcing and southern wind direction are shown Figure 5.12. In this case there is an overall increase of wave height of about 0.6 m, and localized increases reaching more than 1.3 m at locations along the coast such as Prospect Park, Savannah, East End for south winds and West Bay, Old Man Bay, and the north eastern coast for north winds. The increase of wave height is mostly uniform throughout the reef coverage area, and with a similar behaviour for all wind directions. When compared to the modelling of the isolated effect of a decrease in roughness due to reduced coral friction under the degraded scenario, a possible loss of reef structure and its subsequent effect of increasing the local water depth would likely have a larger impact on allowing larger waves to reach the coastline and inland during a hurricane event. Significant wave height difference maps are provided in Appendix B for the severe degradation scenario and all wind directions for a category 5 storm, and for category 1 and 3 storms with wind direction incident from the north.

Figure 5.12 Effect on significant wave height of increase of 1 m of depth over reef areas due to loss of reef structure.





Flooding impact on shore

Despite the more substantial increases in wave heights anticipated in the severe degradation scenario, the impacts are typically confined to the coastline and nearshore only as observed in the degraded scenario discussed above. Increases to significant wave heights observed inland are typically isolated and minor in magnitude, generally less than 0.05m. However, more substantial increases are seen on the nearshore buildings, in particular on the west coast of George Town, North Side and Drift Wood Village. Depth increases of up to 0.75m are anticipated at some nearshore buildings, and the magnitude of increase anticipated remains similar between the category 1, 3 and 5 storms.

Comparison to coastal flooding effects from modelling in the Wood/JNCC BVI study.

The present study uses a coastal inundation modelling approach with some similarities, as well as differences compared to the approach by van Zanten *et al.* (2014)[11] (and used as a basis of analysis for Wood's coastal protection assessment of the BVI[27]), as follows.

- The still water levels associated with storm surge are considered as spatially varying levels from FEMA's flood insurance rate maps (FIRMs) by van Zanten *et al.* (2014), while they are prescribed as spatially uniform levels in the present study.
- The van Zanten *et al*. (2014) study considers significant wave heights of 8 m as incident from offshore, while the present study considers offshore waves in the range of 10-13 m representing severe hurricane conditions due to a range of hurricane categories (Category 1, 3 and 5).
- Even though different models are used, both studies considered the effects on wave dissipation of both roughness due to coral reefs, as well as the effects of depth at the location of the coral reefs;
- The most notable differences between the present study and that of van Zanten *et al.* (2014) are found in the approach taken to propagate the waves between the reef locations and the shoreline:
    - van Zanten *et al.* (2014) first calculate the wave dissipation due to different classifications of coral reefs in a 1D cross-shore transect model, and they extrapolate the calculated dissipation rates to develop a quasi-2D map of wave heights, based on assumed buffer zones surrounding the coral reef areas and assumed dissipation rates between reef areas and the shoreline;
    - in contrast, the wave model in the present study incorporates wave propagation and dissipation in 2 dimensions over the full coastal bathymetry and shoreline, and the reef-induced roughness is represented within the ambient roughness map. The approach in the present study therefore allows for the wave propagation and transformation processes to be represented without additional parameterizations or assumptions of wave energy dissipation rate beyond the reef locations.

As a result of the approach taken in the present study, the wave dissipation rates modelled over the shelf and coastal areas vary across locations, and the amount of energy loss that can be attributed to the coral reefs is highly variable, depending on the geometry of the shelf, the coastline, and ambient depths in the coastal areas. In coastal locations where wave propagation occurs over a larger distance to shore beyond the location of the reefs, and where the wave heights are limited by the ambient depths, the amount of wave energy loss attributed to the presence of the reefs would be smaller compared to areas where the shoreline is located in the immediate vicinity of the reefs. Nevertheless, the findings of the present study indicate that the reefs' contribution to the local depths have a larger effect on wave dissipation than their roughness effects, consistent with the findings of the study by van Zanten *et al.* (2014).

Commentary on results

In this study:

- The modelling of coastal flooding has shown that due to the low elevation of many parts of Grand Cayman, large areas of the island are subject to significant inundation in the storms simulated. This is demonstrated particularly for Category 5 storms but also large areas of the island are flooded in Category 3 events. Flooding is extensive in the southern areas of Georgetown (including South Sound) and Severn Mile Beach region and to the west and east of the central lagoon. Inundated areas bridge across from the south coast across Grand Harbour and Bonnie View Estates into the lagoon region.
- The model has highlighted the importance of the shelf width regarding its dissipative effects on waves. The model results clearly show that in locations where the shelf is wider, the longer propagation distance to shore allows for a larger reduction in wave height after the initial abrupt breaking at the shelf edge.
- In the degraded scenario, simulating the reduced friction of the coral reefs associated with coral die-back, an increase in wave heights ranging from 0.2m to more than 0.4m over the reef for Category 5 storms is observed. This translates to a maximum increase in flood levels by 0.25m up to 200m inland.
- In the severe degraded scenario, where erosion/loss of 1m of the reef structure was represented in the model in addition to reduced friction from coral, increases in significant wave heights of up to 1.3m are observed over the reefs, which translate to increased inundation levels of up to 0.75m for some buildings close to shore. This highlights how the reefs' contribution to local depths have a larger effect on wave dissipation than their roughness.
- An assessment of the current coastal flood extents would be further enhanced through incorporating the results into the higher resolution inland model. This would allow local small scale topographic features to influence the flood extent, which are currently not taken into account in the coarser scale grid, and has the potential to highlight greater flood impact.
- Whilst the increase in maximum inundation levels in the degraded scenario appear low, the significance of this should not be underestimated. The ill health and damage to live coral provides a key indicator to what could be instore for the future. If coral reefs are not protected and do not remain in good health the live coral can die and without the continued regeneration of the reef over the long term the reef will erode. Whilst this impact of this may not be seen immediately, the analysis observed in the severe degraded scenario provide an indication of the increased flooding as a result of reef erosion.

5.3 Economic valuation

The application of the toolkit highlights that the coastal protective value of reefs is represented in the national accounts and therefore changes to reefs would be expected to directly affect the GDP of the Cayman Islands. Although expenditure on repair and replacement is reported as economic activity, the underlying disadvantage is that it substitutes for activities which would be more desirable overall. As events occur irregularly and infrequently, budgeting for them is difficult and may increase overall costs above the long-term average. Business losses which are uninsured can be associated with flows in the national accounts but by definition relate to activities which do not occur and so are omitted from the national accounts. Insurance payments which offset business losses will result in financial flows to business owners but are different in structure and would have different effects on the local supply chain and some costs of losses, such as unemployment, would result in government expenditure.

These types of effect can be represented using standard methods, some of which are also applicable to the use of the Total Economic Value framework, and the results are inherently comparable with other values represented in the national accounts. Similarly, the results can also be used as part of a TEV framework, but it is also clear that these results are only a partial representation of the value of reefs.

The values below are compared with government reporting on sectoral performance. The results are presented for the three scenarios and are shown for two sensitivities reflecting variation in the level of physical impacts.

The scenarios aim to capture two causes of change in flooding. The first is the marginal change from the different resistance to water flows over the coral reef caused by the change in roughness of the reef related to coral health. The second is the representation of change in the structure of the reef. These are different physical processes and their interaction with the economy is over different timescales. The two are also interlinked. Healthy coral is rougher but also is the living agent that produces the reef structure.

Changes in the structure of the reef have a greater effect on flooding than even extreme changes in roughness. Economic valuation is based on the assessment of marginal changes with sudden effects, where the economy cannot adapt, seen as having greatest impact on the economy, further emphasised by societies greater concern with effects which are sooner rather than later[29]. Coral health can change very rapidly, within a year, while changes to reef structure are significantly slower, though sometimes is caused by sudden destructive events.

The estimates in the results inform the understanding of the impacts on coastal protection of changes in roughness which lead to smaller but potentially more immediate effects and changes in reef structure which lead to slower but more significant impacts. The relevance of these two depends on the perspective and importance attached to long term and short-term impacts and associated changes over time in the economy.

A simple approach is used here where changes are compared assuming that there has been no adaptation by society, so that even larger changes in reef structure are represented as sudden changes to the current economy. This seems like an overestimate because it neglects the fact that the economy may be able to adapt at low cost but, even if adaptation is possible over longer timescales, other effects would be relevant. In the Cayman Islands, a lack of healthy reefs is likely to lead to a general loss of habitability, and not unrealistically to a general if slow erosion. Over the longest perspective, the fundamental relationship between the Cayman Islands and its reefs means that any long-term degradation leading to loss is an existential issue. The framework for assessing long term change extends beyond economics to sustainability. While not estimated in this study, the existence value would be informed by asking the question "how much would you pay to ensure future generations would experience a world in which the Cayman Islands had continued with healthy reefs'. Such values would not be currently represented and would require reference to the TEV framework. As such values are not included, the assessment of reef destruction might be considered more an underestimate than an overestimate.

Tables 5.7 – 5.9 show valuations for Grand Cayman. The tables have four columns and include two sensitivity cases as the physical effects related to run-up are a remaining source of uncertainty. In the left-hand columns, the results for individual storm events are shown. In the right-hand columns, the values for each event are weighted by their expected frequency. This shows the importance of reef protection to lower category storms.

The structural changes are greater and are shown in the results for the scenario described as 'Severe degradation' (Table 5.7). These show the effects from a one metre loss in height of the reef crest two sensitivities are shown with aggregate values of $33m and $87m annually. We estimate that these figures would be proportionally higher if reefs were further eroded.

The effects of changes in roughness are shown in the two other scenarios of further degradation (Table 5.8) and further enhancement (Table 5.9). The enhancement is a 20% change over the current state and the

[29] As inbuilt to economic evaluation through the underlying general concept of discounting.

degradation is a 40% change below it. The results are in a similar proportion and reflect again a similar linearity. Degradation, for the two respective run-up sensitivities, leads to values of $2m and $3m annually while enhancement leads to an improvement of a value of ~$1m change.

For comparison, quantitative values of previous estimates[27] are:

- In the estimate for the BVI, complete reef loss, represented by full strength storms reaching the cost led to annualised costs estimated of the order of $70m per year, approximately equivalent to the profits in the bar and restaurant sector.
- In an estimate for the Cayman Islands, based only on damage from category 5 storms, the value of coastal protection was estimated as $5.1m (Wolfs, 2017).
- The annual value added (reported as GDP in 2018) for the Bars and Restaurants sector in the Cayman Islands was $231m.

Important to the context of these comparisons are that:

- The geography of the BVI allow modelling of a 'no-reef' scenario, but in Cayman Islands, a no-reef scenario would lead to flooding overall.
- Also due to the geography, in the BVI, flood damage was related to simply whether properties flooded or not, while in the Cayman Islands, as most properties flooded, such changes were very few and the flood damage was instead determined in relation to the depth of flood.
- The importance of protection in lower category floods was omitted in the $5.1m estimate from Wolfs Company as it was based only on a Category 5 storm.

Table 5.7 Annualised avoided costs of business losses and damage to property ($m) from coastal flooding: severe degraded scenario, Grand Cayman.

Storm Category	Event ($m)		Annualised ($m)	
	100% runup*	200% runup*	100% runup*	200% runup*
Category 1 North	71.8	195.2	6.0	16.3
Category 1 South	54.0	170.7	4.5	14.2
Category 1 South West	91.8	229.0	7.7	19.1
Category 3 North	136.4	310.1	4.5	10.3
Category 3 South	74.0	244.4	2.5	8.1
Category 3 South West	146.5	294.6	4.9	9.8
Category 5 North	101.5	319.6	1.0	3.0
Category 5 South	92.6	306.4	0.9	2.9
Category 5 South West	127.8	344.6	1.2	3.3
Total			33.1	87.1

*Wave runup values were assumed to range from 100% to 200% the offshore significant wave height above the still water level

Table 5.8 Annualised avoided costs of business losses and damage to property ($m) from coastal flooding: degraded scenario, Grand Cayman, Gran.

Storm Category	Event ($m)		Annualised ($m)	
	100% runup*	200% runup*	100% runup*	200% runup*
Category 1 North	6.8	10.1	0.6	0.8
Category 1 South	4.9	5.8	0.4	0.5
Category 1 South West	5.4	1.2	0.5	0.1
Category 3 North	8.2	6.9	0.3	0.2
Category 3 South	3.8	14.9	0.1	0.5
Category 3 South West	1.8	15.3	0.1	0.5
Category 5 North	7.3	17.1	0.1	0.2
Category 5 South	17.6	26.9	0.2	0.3
Category 5 South West	28.3	7.0	0.3	0.1
Total			**2.4**	**3.2**

*Wave runup values were assumed to range from 100% to 200% the offshore significant wave height above the still water level

Table 5.9 Annualised avoided costs of business losses and damage to property ($m) from coastal flooding enhanced scenario, Grand Cayman.

Storm Category	**Event ($m)**		**Annualised ($m)**	
	100% runup*	**200% runup***	**100% runup***	**200% runup***
Category 1 North	-1.1	-1.7	-0.1	-0.1
Category 1 South	-0.9	-1.2	-0.1	-0.1
Category 1 South West	-0.1	-2.5	0.0	-0.2
Category 3 North	-1.2	-2.3	0.0	-0.1
Category 3 South	-9.8	-11.7	-0.3	-0.4
Category 3 South West	-1.0	-4.5	0.0	-0.1
Category 5 North	0.0	-10.2	0.0	-0.1
Category 5 South	-2.5	-3.4	0.0	0.0
Category 5 South West	-0.2	-7.7	0.0	-0.1
Total			**-0.6**	**-1.3**

*Wave runup values were assumed to range from 100% to 200% the offshore significant wave height above the still water level

Further detail on calculation methods

The aggregate valuation for each scenario is based on the reinstatement costs from direct damage to real estate and building contents and on the value of business disruption. In many assessments, often only the first (direct damage) is taken into account, though more recent studies have included business disruption. The valuation methodology used here closely follows that used in the BVI (Wood, 2019) and input prices and assumptions stated below which are not explicitly referenced are taken from this source.

As mentioned above, other types of economic impact related to flooding are not assessed quantitatively and for this reason the aggregate estimates here are lower than had these been included. Studies considering flooding do not often include these other aspects and they may not be relevant in other circumstances, but here their omission here in a study of reef value to coastal protection will lead to an undervaluation of the effects. These underestimates relate to items identified only qualitatively in the national accounts (such as spending on flood protection programs) as well as items not in the accounts (such as the existential values).

The damage and repair costs are based on the widely used US government (FEMA) depth damage functions which assess damage as a proportion of the costs to reinstate the property (estimated at an average cost of $300/ft2). The damage costs rise to a maximum of 90% of this figure for the deepest floods in the flooding zone nearest the shoreline and a 50% in zones without direct shoreline effects. For a shallower flood depth of 6 feet the values are approximately 65% and 30% respectively.

Business disruption is calculated as leading to loss of function for 1 year for all property types based on experience recorded elsewhere in the Caribbean, except that for residential and government buildings disruption is estimated for a shorter period of 6 months. The value of disruption for most types of property is based on the rental rate in the residential sector, as businesses would expect to earn at least this (or they would be better simply renting out their property), except that it is higher for bars and restaurants for which an explicit estimate for this sector exists. Unit rates are $38/ft2, a value estimated for the Caribbean rental market in the BVI and $130/ft2 for bars and restaurants.

These direct impacts are recognised as being associated with wider indirect economic impacts in supply chains and from induced spending in these supply chains and elsewhere. The standard representation of these effects is used based on an economic multiplier which increases the magnitude by a of 1.65.

5.4 Opportunity maps

The annualised avoided costs of business losses and damage to property has been mapped spatially and associated to a reef segment to express the relative significance of the reef in terms of flood protection offered. The reefs surrounding Grand Cayman have been segmented and associated to an inland region, delineated primarily based on the topographic catchment. However, given the low-lying nature of Grand Cayman, there is some uncertainty with this process given that coastal flooding propagating inland has the potential to span several topographic sub-catchments, depending on the wind direction. As such, the flood risk protection offered by the reef segments may in fact extend beyond the regions delineated for the purposes of this assessment.

Figure 5.13 and Figure 5.14 below demonstrate the potential annualised avoided costs of business losses and damage with respect to the degraded and severe degradation scenarios. The maps highlight the relative importance of the reefs spatially, showing that those on the west coast and north coast in particular hold significant value in terms of flood risk protection. Given the low-level of development in the eastern portion of the island, the potential degradation of reefs here is shown to result in negligible increase to annualised costs of business losses and damage.

In accordance with the degradation scenarios, Figure 5.15 below shows that greatest benefit in terms of damages avoided would be seen on the west coast of George Town if the coral reefs underwent enhancement. In particular, a short segment of reef to the northwest of George Town and a segment to the southwest are shown to offer greatest value in terms of damages avoided. Similarly, the reefs surrounding the eastern portion of the island are shown provide negligible benefit in terms of damages avoided in the event of enhancement, given the relatively low-level of development.

Figure 5.13 Degraded scenario economic impact

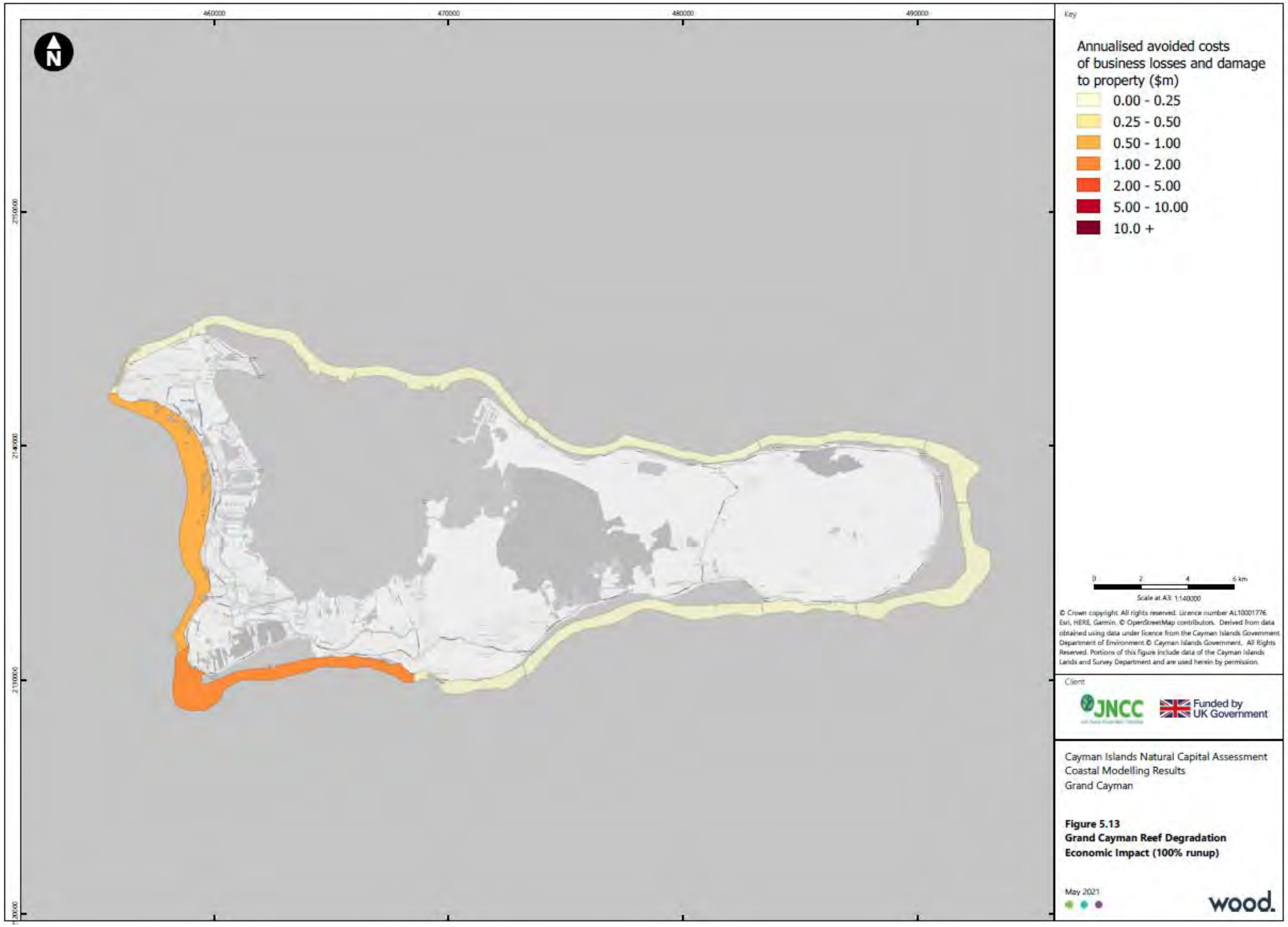


Figure 5.14 Severe Degradation scenario economic impact

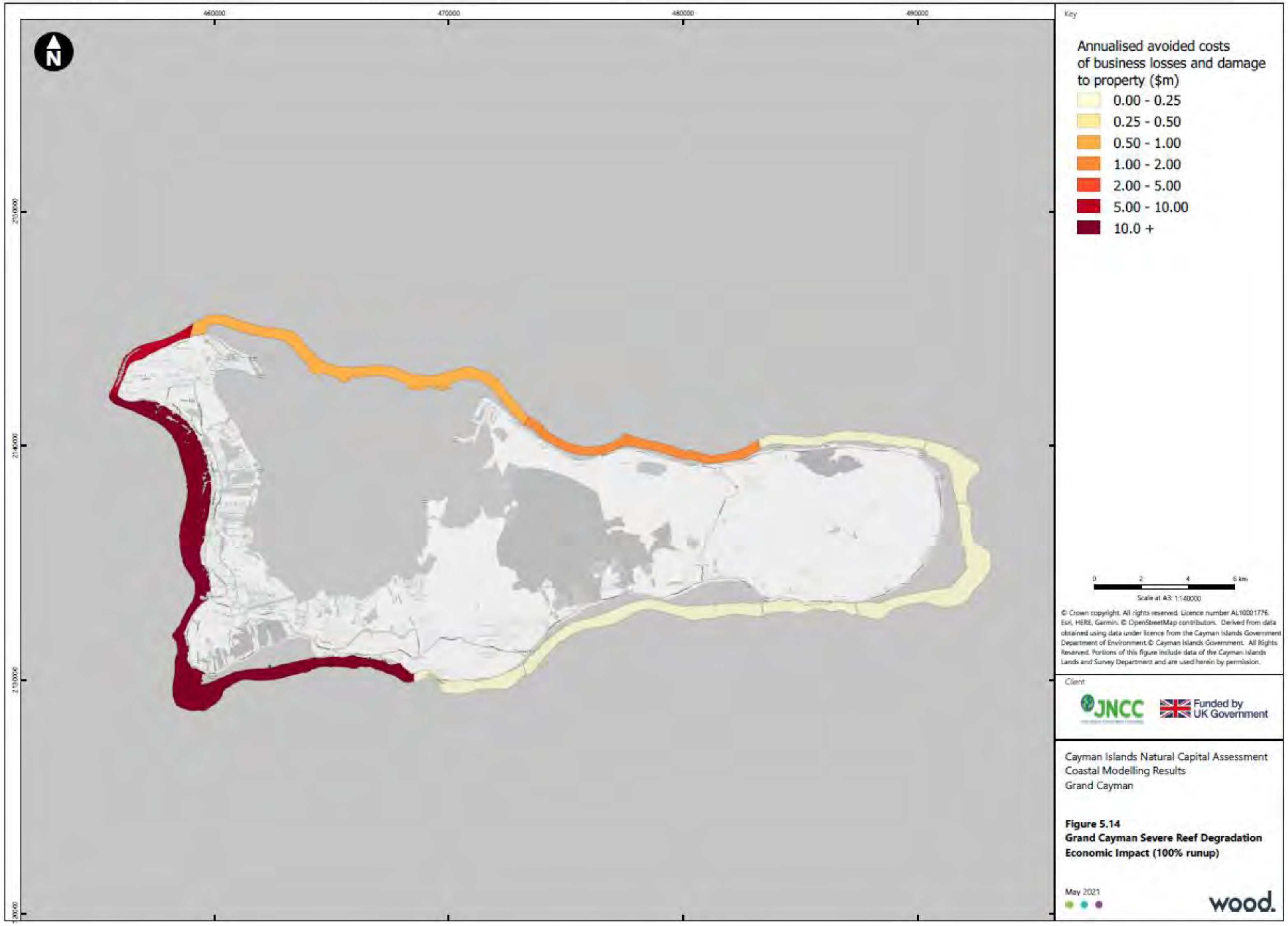
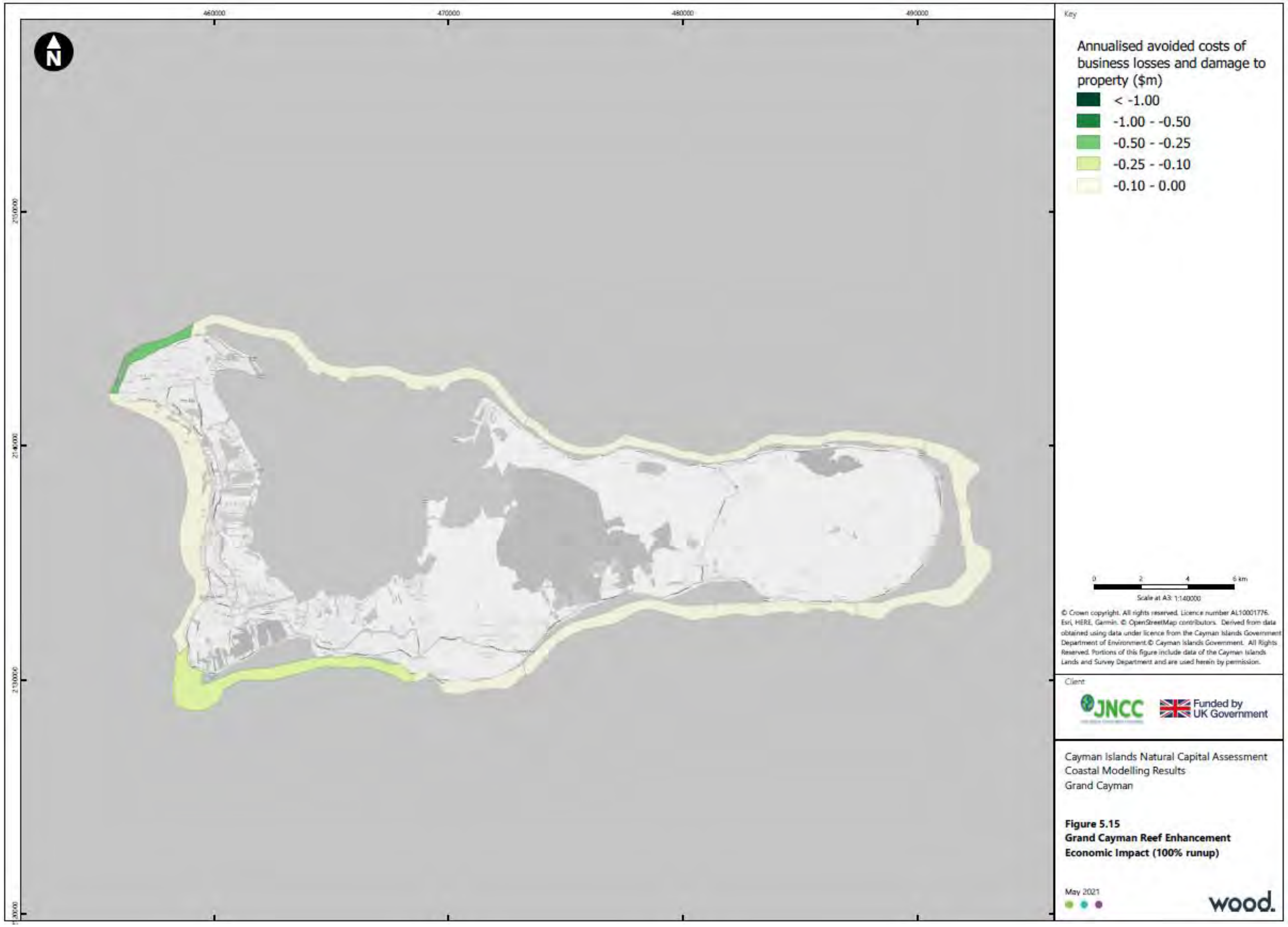


Figure 5.15 Enhanced scenario economic impact



6. Conclusions

6.1 Inland flooding

The vegetation on the Cayman Islands, provide natural capital benefits which include a flood protective function. Vegetation is dense across much of the Islands, with high coverage levels of dry forest and woodland among inland areas and mangrove forest in tidal regions. The protective benefit of vegetation results from interception and evaporation of rainwater before it reaches the ground surface and holding back water temporarily, mitigating peak flows that cause the greatest flooding by slowing the passage of water through the catchment.

The effects of degraded vegetation were assessed in this study using hydraulic models developed for all three islands to simulate the catchment response to storm events. In the main scenario, simulating the effects of natural capital degradation, all vegetation - forest, shrubland, mangrove forest and mangrove shrubland - was assumed to revert to grassland leading to less interception of rainwater, greater flooding, and faster moving water. In an additional scenario with 'selective degradation' for Grand Cayman, reversion to grassland is assumed for just dry forest and woodland and tidal mangrove habitats. The model represents physical effects using a parameter for the proportion of intercepted rainfall and a parameter for the friction affecting water flows (Manning's n roughness coefficient). The results of the modelling showed that:

- There is widespread surface water flood risk across the three Islands characterised by extensive ponding of floodwater in the low-lying (<1m AMSL) regions. Owing to the Islands low elevations, there are few recognised surface water flow paths and surface water flooding is typically widespread and of low velocity. Extensive property flooding is observed in both the 4% AEP and 1% AEP storm events with increased peak flood depths as one would expect, although increases in flood extent are limited.
- In the degraded scenarios, the anticipated result of exacerbated peak flood depths in the lower lying areas was not typically observed, with both depth reductions and increases observed. Due to the low-lying nature of the Islands, changes to peak flood depth are relatively minor in magnitude, as the impacts of increased peak flows tend to be borne over a wider area.
- In some instances, and despite the reduced rainfall losses, the associated reduction in roughness values are shown to improve conveyance of surface water to the sea. In these cases, the degraded scenario results in reduced flood depths. This, however, does not necessarily indicate an improved or favourable position with regard to flooding as a result of environment degradation.
- An increase in surface water flow velocities were observed in the degraded scenarios. This has the potential to increase soil erosion and sediment load within the flood water and resultant transportation into the marine environment. Increased sediment delivery and deposition on coral reefs can further accelerate reef degradation and highlight, albeit qualitatively, the positive impact of natural capital.
- Improved flood modelling results would be achieved using higher resolution DTM, rather than the coarser scale WorldDEM dataset that was used. This would be particularly beneficial as due to the low overall elevation of the Islands, water flows are dominated by small scale changes in topography, which would be better represented in the higher resolution dataset. As such, an improved understanding of individual flood vulnerability would be provided.
- Due to the very small scale differences in flood depths observed in the inland model results between the baseline and degraded scenarios, economic analysis at this stage was not undertaken.

6.2 Coastal flooding

Coral reefs and mangroves provide natural capital benefits which include protection from coastal flooding. The shallow water over reefs forces large deep-water waves to break, dissipating their energy and the roughness of the reefs causes further energy loss from friction as water flows over them. The vegetation in mangroves act as a source of friction against moving water, resulting in a reduction of wave heights.

Coastal flooding was assessed using the SWAN spectral wave model. The SWAN model is used to estimate offshore wave conditions which are propagated over the shelf and shallow coastal areas, where the effects of natural capital are accounted for in order to assess the resulting flood inundation onshore.

The model was run for representative Category 1, 3 and 5 tropical storms originating from the three different compass directions as indicated by historical conditions. The model scenarios represented change from degradation and enhancement (regeneration) of coral reefs and mangroves by adjusting their respective frictional coefficients and, in the severe degradation scenario, by reducing the height of the coral reefs by 1m to simulate reef erosion. In order to estimate overall flood depths in buildings, the significant wave heights calculated by the model are also supplemented by a height allowance for storm surge. The model results show that:

- Waves exceeding 13 metres offshore break abruptly as they approach and interact with the steep underwater shelf surrounding the islands. Nevertheless, waves of up to 4 metres still propagate across the narrow shelf and reach the coast.
- A large decrease in wave height occurs at the narrow shelf edge in locations where the shelf is wider due to the longer propagation distance to shore and illustrates the importance of the shelf width regarding its dissipative effects on waves.
- Due to the overall low elevation of Grand Cayman, 'coastal' flooding extends to large areas of the island in severe storms (Category 5) but also in those less severe (Category 3).
- In the degraded scenario, the frictional reduction from the loss of live coral reef component and mangrove die back leads to increases in wave heights of up to 0.4m over the reef (according to location), which leads to a maximum increase in flood depth of 0.25m from some buildings up to 200m inland in a Category 5 storm.
- In the severely degraded scenario, with 1m of reef erosion (and so water which is deeper by 1m at the reef crest), wave heights are increased by 1.3m at the reefs leading to increases in flood depth of up to 0.75m for some buildings up to 200m inland. Although reef depth shows a greater impact on waves than roughness, the first is a long term effect linked to reduced coral and mangrove health in the short term. A reef with fewer live corals is both less rough and has a reduced capacity to maintain the physical reef structure through new growth. Mangroves are similarly linked to both short term and long term impacts.
- The opportunity maps in the results show that flood risk protection has significant value along the west, south-west and north coasts. In particular, a short segment of reef to the north-west of George Town and a segment to the south-west are shown to offer greatest value in terms of damages avoided.

Improved understanding of infrastructure flooding could be obtained by using the coastal model outputs as inputs to the higher resolution inland flood model as a boundary condition. This would provide an enhanced representation of the flooding mechanisms as coastal floodwater propagates inland and flood maps. In addition, future studies could investigate the depth-induced effects of the reefs and how they might be impacted by degradation for scenarios considering sea level rise for different time horizons.

The ill health and damage to live coral/mangrove provides a key indicator to what could be instore for the future. If coral reefs are not protected and do not remain in good health the live coral can die and without the continued regeneration of the reef over the long term the reef will erode. Whilst the impact of this may not be seen immediately, the analysis observed in the severe degraded scenario provides an indication of the increased flooding as a result of reef erosion in the longer term.

Economic valuation

A valuation of the benefits of the coastal flood protection provided by the natural capital of reefs and mangroves is estimated for Grand Cayman using an economic toolkit developed in this project. The toolkit is based on a 5 step process and aims to establish a valuation framework which maximises comparability of economic analysis. Coastal flood protection acts to reduce economic losses as a result from storm events and the level of value reflects the calculated losses that would have occurred without this protection.

The estimate here includes, firstly the costs of repairing damage to real estate and building contents, and secondly, the losses from business disruption. In principle, a range of other costs may occur ranging from mental health damage to loss of reputation as a tourism venue but common practice is to consider only restitution costs[30]. The addition of business losses is increasingly also considered and is included here. The effect of this partial representation of costs is that the estimates here, as well as in other studies of flooding, are intrinsically low[31].

Estimates of the value of protection from natural capital have been made for the degraded, severe degraded and enhanced scenarios and include two levels of sensitivity to address the uncertainty related to representing the physical process of wave run-up on resulting inland flood levels.

- In the severe degraded scenario, the annual economic losses to the Cayman Islands, from the need to replace and repair property and from lost business, are estimated between $33m and $87m, with the range reflecting uncertainties relating to wave run-up.
- In the degraded scenarios, the reduced friction from degraded reefs and mangroves would result in annual economic losses to the Cayman Islands of between $2m and $3m, while enhancement would lead to reduced annual economic losses of $1m.

6.3 Summary

Hydrological modelling of tropical storm effects on inland areas in the Cayman Islands indicates the impact of natural capital degradation on inland flood risk was small, with the already extensive flooded areas seeing only very minor changes in flood depths (both increases and decreases) as the water volumes are distributed over wide areas due to the predominantly flat topography of the islands. However, the observed increase in flow velocities in the degraded scenario is likely to increase sediment erosion, transportation and potential deposition and degrade coral reef systems offshore. The use of higher-resolution topographic data would enhance the results by allowing the differences in elevations which are small but relatively important to patterns of water run-off to be better represented. Flood modelling of the effects from waves and storm surge on coastal areas from tropical storms offshore highlighted extensive flooding to the Cayman Islands during Category 3 and 5 events with significant dependency on the undersea near shore bathymetry and associated levels of wave run-up. Natural capital degradation in the form of reef erosion loss and poor coral health reduces water friction and increases wave heights resulting in increased flooding to buildings situated within 200m from the shore by up to 0.75m (severe degraded scenario). In this scenario, the annual economic losses to the Cayman Islands, from the need to replace and repair property and from lost business, are estimated at between $33m and $87m. There would be benefits of coupling the outputs from the coastal model with the enhanced inland modelling (using the higher resolution topographic data), which would

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[30] The main driver for this is the insurance industry which is almost exclusively concerned with physical damage.

[31] Adding other elements of cost might produce a more representative estimate but this would also be more uncertain as these elements are less well researched.

provide a better representation of the coastal floodwater as it propagates inland and the impact on infrastructure.

Appendix A

Inland modelling results

Appendix A presents the inland modelling results as a series of maps, described in sections 5.1 & 6.1

It is available as a separate PDF file

Appendix B
Coastal modelling results
Appendix B presents the coastal modelling results as a series of maps, described in sections 5.2 & 6.2
It is available as a separate PDF file

wood.

Appendix C
Natural Capital Register

Table C.1 Terrestrial Landcover for the Cayman Islands taken from 2013 Landcover data (DoE)

Land Cover 2013	Area (hectares)		
	Cayman Brac	Grand Cayman	Little Cayman
Xeromorphic semi-deciduous forest	1,216.7	-	-
Coastal mohagany forest	-	-	163.4
Dry forest and woodland	-	1,418.2	1,091.2
Seasonally flooded / saturated semi-deciduous forest	-	75.4	-
Seasonally flooded mangrove forest and woodland	7.5	4,888.9	2,318.7
Tidally flooded mangrove forest and woodland	-	1,091.5	85.8
Seasonally flooded mangrove forest and woodland	7.5	4,888.9	2,318.7
Tidally flooded mangrove shrubland	-	180.8	-
Seasonally flooded mangrove shrubland	13.4	406.8	2,958.7
Seasonally flooded grasslands V.A.1.N.g	0.5	41.0	83.5
Semi-permanently flooded grasslands V.A.1.N.h	0.0	21.3	46.9
Ponds, pools, and mangrove lagoons	21.8	928.6	2,855.0
Tidal tropical or subtropical annual forb vegetation	-	-	2.6
Invasive species - casuarina	-	114.6	25.7
Salt tolerant succulents	-	17.9	-
Sparsely vegetated rock	-	90.5	-
Black candlewood	-	1.8	-
Coastal shrubland	89.6	106.1	1,570.1
Dry shrubland	682.9	2,448.5	16,724.7
Dwarf vegetation and vines	38.9	9.3	-
Dry lakebed	13.9	-	-
Shoreline	94.8	-	645.3
Man-modified	1,531.1	-	2,011.0
Man-modified with trees	-	1,705.4	-
Man-modified without trees	-	5,457.8	-
Urban	136.2	950.8	475.2
Total	3,854.8	24,844.2	33,376.6

Table C.2 Shelf Benthic Classification for the Cayman Islands taken from 2008 dataset (DoE)

Shelf Benthic Classification 2008	Area (hectares)		
	Cayman Brac	Grand Cayman	Little Cayman
Aggregated patch reef	27.8	161.6	42.7
Un colonised hardbottom	603.6	17,056.3	6,051.6
Spur and groove	1,203.5	25,107.1	9,868.3
Sand	6.0	909.7	41.1
Rubble	22.2	3,660.5	1,227.3
Reef crest	15.9	2,163.6	1,152.5
Individual patch reef	0.0	3.6	-
Colonised hardbottom	189.6	5,245.2	2,147.6
Beach rock	-	27.7	1.3
Aggregate reef	-	572.5	39.8
Total	2,068.7	54,907.9	20,572.1

Table C.3 Lagoon Benthic Classification for the Cayman Islands taken from 2008 dataset (DoE)

Lagoon Benthic Classification 2008	Area (hectares)		
	Cayman Brac	Grand Cayman	Little Cayman
Beach rock	0.3	4.4	3.1
Backreef	14.1	129.4	62.4
Vegetated sand	4.7	1,628.2	136.1
Hardbottom	24.4	901.6	126.1
Seagrass beds	14.7	6,344.9	183.1
Sediment	5.6	854.6	218.9
Lagoonal coral	-	58.2	10.3
Vegetated peat	-	746.7	-
Silt	-	253.9	-
Total	63.9	10,921.9	739.8