JNCC – UK Overseas Territories Report Series

Model development to assess the vulnerability of the Cayman Islands to storm surge and inland flooding and the role of natural capital in mitigating the impacts – Phase 2

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Project details

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Summary

Purpose of this report

The Cayman Islands are highly dependent on the natural environment for economic and social well-being and experience the threats and risks common to many islands in the Caribbean. Tourism is fundamental to the economy with visitors drawn to the climate, facilities, renowned beaches, coral reefs and unique biodiversity. The extreme effects from Hurricane Ivan in 2004 demonstrated widespread vulnerability to natural hazards and led to serious impacts on the population, built infrastructure, natural capital assets and the economy. The natural environment of the Cayman Islands plays a key role in protecting built infrastructure and human well-being and, unless safeguarded, risks being damaged, inadvertently or deliberately, by human activities.

In this context, the Joint Nature Conservation Committee (JNCC), supported by the UK Government's Conflict, Stability and Security Fund (CSSF), is supporting the Cayman Islands Government in assessing the role and economic value of the Cayman Islands' natural capital in the protection of built infrastructure from coastal and inland flooding. This information will be used by the Cayman Islands Government in developing plans, policies and procedures which increase resilience to natural disasters and enhance on-island capability in preparing for and recovering from the impact of storm events.

In Phase 1 of support (Wood, 2021; Contract C20-0302-1509), inland and coastal flood models were developed and used to estimate the economic value of the flood protection service provided by key natural capital assets in the Cayman Islands. The purpose of this report is to provide a summary of the outcomes from improvements to inland and coastal models which are used to quantify flood extents under extreme weather events and understand how flood protection is changed under different hypothetical scenarios for the state of natural capital on the islands. These results have been used to update the assessment of the value of the flood protection service provided by the Islands' natural capital assets. This report identifies nature-based flood mitigation solutions, locations where they could be implemented, and a series of short-term environmental indicators to support disaster resilience. Finally, analytical tools have been developed to enable and assist staff in the Government of the Cayman Islands to undertake analysis and assessments in the future alongside capacity building activities.

Inland flooding

The updated results from the new computer modelling of inland flooding provide a significant improvement in accuracy and confidence. Flood extents now match considerably better with anecdotal observations of flooding on island. Results generated using industry-leading TUFLOW hydraulic models, now incorporate a high-resolution dataset (using LiDAR – Light detection and ranging) and more refined representation of the high infiltration rates.

The updated results provide a significantly improved depiction of flood risk at small scales using new representation of local topographic features such as road embankments and individual real estate developments. The modelling shows reductions in peak flood depths across limestone areas resulting from the better representation of infiltration rates. The general trends from running the models for the degraded natural capital scenarios remain the same as those from Phase 1 in that changes to peak flood depth are relatively minor in general due to the low-lying nature of the Islands and that both flood depth reductions and increases are observed. In some locations, improved conveyance of surface water to the sea is observed because of the lower vegetation roughness now used in the modelling.

However, associated increases in flow velocities can increase soil erosion and sediment load within the flood water, which is then transported into the marine environment and leads to deposition on coral reefs and reef degradation.

The higher resolution modelling provides understanding of flood implications at a detailed level and so provides key information for land-use planning, infrastructure development and hazard management while also supporting policy development and decision-making.

Coastal flooding

The representation of offshore conditions in the Cayman Islands developed for Phase 1 of the project based on the industry-standard SWAN computer modelling has had three significant enhancements. Storm surge offsets have been adjusted for Category 1, 3, and 5 storms and better represent the larger waves that penetrate further inland. The inclusion of sea grass results in decreased wave heights in areas with denser seagrass coverage, an effect which applies particularly in the North Sound. The inland (TUFLOW) and offshore (SWAN) models are now coupled which improves the overall representation of the influence of coastal conditions on inland areas. It shows inland floodwaters backing-up due to storm surge at the coast and combines these with modelling of the infiltration process and the small-scale topographic features along the coastline.

The updated models now indicate a slightly reduced flood extent across the Islands. In the new model, the baseline results for Grand Cayman indicate that the south-west portion of George Town and the coastline developments fringing the North Sound are at particular risk of coastal flooding. The impact of natural capital degradation on coastal flooding is anticipated to be most significant across Grand Cayman, given the abundant coverage of surrounding reefs. The largest relative impact on the degraded natural capital is seen for the lower magnitude higher frequency storm events. The reduced roughness levels and eroded reef represented in the severe degraded scenario has the greatest impact on inland flood inundation. Widespread depth increases of 0.10 m to 0.50 m are anticipated across the southwest portion of George Town, and notable increases to flood extent are predicted which results in an increased number of properties inundated. This demonstrates the importance of maintaining coral reef health and sea grass beds.

Economic valuation

The model results were used to assess the economic value provided by natural capital for flood protection. The valuation methodology represents the difference in costs arising from flooding modelled in the baseline (with natural capital in its current condition) and the flooding expected in hypothetical scenarios where natural capital follows a progression from 'degraded' to 'severely degraded'. The values are represented using the costs estimated for business interruption and damage to buildings and contents when flooded. The value of maintaining (protecting) the current natural capital condition is that the additional costs in the degraded and severely degraded conditions are avoided.

If natural capital is severely degraded, the losses from coastal flooding are estimated to be CI$75.0 million, equivalent to 30% of the value added by hotels and restaurants sector to the Cayman Islands economy annually. If natural capital is protected, losses are only CI$7.6 million, so saving CI$67.4 million. The properties and businesses in the George Town area of Grand Cayman account for almost all of this (CI$74.6 million out of CI$75.0 million if severely degraded, and CI$7.3 million out of CI$7.6 million if protected).

These results are based on observed historical frequencies unadjusted for potential climate change impacts. In addition, no sea level rise effects have been included.

Tool development and capacity building

A key objective of this project was to use methods and develop toolboxes that would allow Government staff to understand and investigate the effects of coastal and inland flooding. In the Cayman Islands, the interactions between the overall geography, local topographic features, natural capital condition and the economy is particularly significant. Policy development, physical change and financial incentives have both independent and combined effects, and all may affect practical decisions over land uses, infrastructure planning and the achievement of wider environmental end economic sustainability targets.

A week-long workshop programme was delivered to staff across the Departments of Environment, Hazard Management and Land and Surveys. Sessions included walk-through of the methodologies and process flow required to undertake an economic assessment as well as detailed training on use of the SWAN, TUFLOW and economic model toolboxes. The workshop included detailed discussions on environmental indicators to be used in the short-term and the potential for nature-based solutions. The workshops equipped staff to investigate the economic impact of flooding in relation to future scenarios of natural capital status and extreme weather events.

Nature-based Solutions

Nature-based Solutions (NbS) aim to deliver benefits such as decreased flood risk or better water quality by recognising and enhancing the ecosystem services provided by natural capital along-side or in place of traditional engineering-based solutions. A list of 28 priority NbS were identified for the Cayman Islands, including policy-level changes as well as specific technical proposals.

Discussions were held with the Department of Environment to identify targets for NbS solutions and relevant geographic areas. For the mitigation of coastal flooding, maintaining and restoring the condition of offshore and coastal natural capital such as reef, mangroves and sea grass was recommended. For the mitigation of inland flooding, the application of smaller scale NbS in urban developments, either retrofit, or as part of new development was discussed. It was identified that there is a need for the awareness of NbS and the benefits they can provide to be increased across government departments. This is a key step to enhance their uptake and would provide multiple benefits to a range of different stakeholders.

Environmental indicators to monitor impact of short-term shocks

The use of indicators which provide consistent environmental monitoring is strongly related to the development of effective environmental policy. In the context of understanding the impacts on the environment from short-term shocks such as hurricanes, four priority headline environmental indicator categories were identified through stakeholder consultation: 'air', 'land', 'freshwater' and 'marine, estuarine and coastal'. Across these four headline indicator categories a total of 17 environmental indicators have been developed including specific quantitative metrics as well as methodologies for establishing the frequencies at which monitoring and when monitoring should be conducted. Baseline monitoring of these indicators should be established or enhanced where it exists already and protocols for monitoring immediately after hazard events should be established.

Contents

1. Introduction

1.1. Context

The Cayman Islands are highly dependent on the natural environment for economic and social well-being and experience the threats and risks common to many islands in the Caribbean, including the UK Overseas Territories. Tourism is a dominant economic sector with visitors arriving by sea and air, drawn by the renowned beaches, coral reefs and unique biodiversity.

The extreme effects from Hurricane Ivan in 2004 provided explicit demonstration of widespread vulnerability to natural hazards and led to serious impacts on the population, built infrastructure, natural capital assets and the economy. The natural environment of the Cayman Islands plays a key role in protecting built infrastructure and human well-being and, unless safeguarded, risks being damaged, inadvertently or deliberately, by human activities.

In this context and building on a continued and extensive 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 in assessing the role and economic value of the Cayman Islands' natural capital in the protection of built infrastructure from coastal and inland flooding. This information will be used by the Cayman Islands Government in developing plans, policies and procedures which increase resilience to natural disasters and enhance on-island capability in preparing for and recovering from the impact of storm events.

In Phase 1 of support provided by WSP in 2021 (under contract Wood, 2021; C20-0302-1509), inland and coastal flood models were developed and used to estimate the economic value of the flood protection service provided by key natural capital assets in the Cayman Islands. The work in Phase 2 is reported here, and comprises:

- Further verification and refinement of the physical flood models based on comparison with evidence of historic floods and on further stakeholder consultation.
- Updating the assessment of the economic impact of natural capital in mitigating coast and inland flooding.
- Development of tools to enable staff in the Government of the Cayman Islands with the ability to undertake analysis and assessments in the future.
- Identification of nature-based flood mitigation solutions and locations where they can be implemented.
- Development of short-term environmental indicators to support disaster resilience.
- Capacity building activities.

1.2. Structure

The purpose of this report is to provide a summary of the outcomes of this work and has the following sections:

- Section 2 provides a summary of work undertaken in Phase 1.
- Section 3 highlights the updates made to the inland and coastal flood models.

- Section 4 provides and discusses the outputs from the flood modelling and the results of the economic assessment.
- Sections 5 is an overview of the tools developed and made available to the Government of Cayman Islands.
- Sections 6 and 7 introduce the short-term environmental indicators and nature based solutions.
- Section 8 presents final conclusions.

2. Background

In 2021 WSP undertook a study (Wood, 2021) with the objective of assessing the role and value of natural capital in mitigating the impacts of natural disasters on built infrastructure in the Cayman Islands. Specifically, this related to the provision of protection from coastal and inland flooding because of extreme weather events.

2.1. The role of natural capital in flood protection

Vegetation is dense across much of the Cayman Islands, with high levels of dry forest and woodland inland and mangrove forests on the coast. Vegetation intercepts rainwater before reaching the ground which enables evaporation and provides temporary storage, holding back water and reducing the peak flows that cause the greatest flooding.

Around the coasts, reefs dissipate destructive storm energy by forcing deep-water waves to break in the shallows and by friction from the roughness of healthy corals, while seagrass and mangroves reduce water movement by reducing wave heights and currents.

2.2. Assessment framework

The assessment framework was implemented in three stages. Firstly, coastal and inland flood models were built to identify geographic areas and assets (both natural and built) that were at risk of flooding during extreme weather events. Secondly, the models were run under different scenarios of natural capital state to understand how the flood extent and depth changed. Thirdly, these flood results were used as input into economic analysis to provide a valuation of the flood protection service provided by the Islands' natural capital assets.

2.3. Inland and coastal models

Hydraulic models of the water catchments inland were developed for each of the three islands using the TUFLOW modelling product to simulate the response to storm events and degraded vegetation. Natural capital degradation was simulated through a scenario where all vegetation – forest, shrubland, mangrove forest and mangrove shrubland – was assumed to revert to grassland leading to a lower level of rainwater interception, greater flooding, and faster moving water.

Coastal flooding was assessed using the SWAN spectral wave model to estimate offshore wave conditions propagating over the shelf and shallow coastal areas. 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 in the level of degradation of coral reefs and mangroves by adjusting their respective frictional coefficients and, in a severe degradation scenario, by reducing the height of the coral reefs by 1 m to simulate reef erosion.

2.4. Valuation approach

The approach to economic valuation was based on estimating the additional costs to society that would result from degradation and are avoided if degradation can be prevented. The flood models were used to identify the additional infrastructure (buildings) that are flooded in the degraded scenarios compared to the baseline. Depth damage functions from a standard source were applied to assess damage impacts and additional business losses estimated.

The differences between the baseline and degraded scenarios relate to the protection value provided by natural capital.

2.5. Flood results

The results of the inland modelling showed that there is widespread surface water flood risk across the three Islands characterised by extensive ponding of floodwater in the low-lying 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.

The coastal model highlighted those waves exceeding 13 m offshore break at the shelf surrounding the islands, but waves of up to 4 m do reach the coast. 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 0.4 m over the reef which leads to a maximum increase in flood depth of 0.25 m for some buildings. In the severely degraded scenario, wave heights are increased by 1.3 m at the reefs leading to increases in flood depth of up to 0.75 m for some buildings.

2.6. National value of natural capital in providing flood protection

Estimates of the value of protection provided by natural capital on Grand Cayman for the degraded and severe degraded scenarios were made to 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 $33 million and $87 million, 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 $2 million and $3 million.

3. Methodology

3.1. Inland flooding

The inland hydraulic models developed for Phase 1 of the project have been refined and updated following a review of datasets and a series of results verification workshops held with the Government of the Cayman Islands. The following sub-sections detail the updates made.

3.2. Topography

A detailed Digital Terrain Model (DTM) covering the Cayman Islands of approximately 0.5 m resolution was supplied by the Cayman Islands Land and Survey Department (LSD) for Phase 1 of the project. Initial review of the data suggested that this was potentially a Digital *Surface* Model (DSM) given the highly variable topographic surface which was assumed to represent the vegetation canopy rather than a bare-earth Digital *Terrain* Model (DTM) which is required for the direct rainfall modelling. Hence, the lower resolution WorldDEM data was used to define the topography within the models for Phase 1.

However, discussions with the Cayman Islands LSD have since established that the high resolution DTM data is in fact correct and is representative of the bare earth surface which is naturally variable given the underlying and exposed limestone formations as seen in Figure 1. The high resolution DTM data has subsequently been incorporated into the inland models for Phase 2 of the project. The DTMs have been resampled to 1 m resolution to improve data manageability, and a fixed grid approach has been adopted using a reduced cell size (relative to Phase 1) of 5 m. This is deemed to be appropriate for the scale and scope of the island-wide models.

Figure 1: Exposed limestone geology (supplied by JNCC, February 2022).

3.3. Infiltration

Following the results verification workshop held via MS Teams in November 2021, it was highlighted that the assumed rainfall-runoff was potentially too high over the bluff on Cayman Brac in particular. The bluff is known to be of limestone formation and highly fissured, hence the modelled depths and extents shown in Phase 1 of the project were thought to be an overestimate and unrealistic.

The infiltration rate in the Phase 1 models was defined solely based on the United States Department of Agriculture (USDA) soil texture dictated by the global International Soil Reference and Information Centre (ISRIC) soils data. This defined Clay and Clay Loam soils as dominant across the islands, which typically conforms well with the soil groups identified in local studies (Ahmad 1996). However, further research has established that soil coverage is in fact sparse across the islands, and the exposed limestone typically has a high porosity with limited drainage issues (Smith Water International Ltd 2015). Therefore, the infiltration parameters have been updated based on the underlying geology rather than soils.

Two geological formations are prevalent across the islands – ‘Ironshore formation’, and 'Bluff Group' (consisting of Cayman formation and Pedro Castle formation). Ironshore formation typically dominates the low-lying coastal regions where infiltration rates are typically poor, and subject to high groundwater levels influenced by the tide. The Ironshore formation is known to develop a hard crust of calcium carbonate following repeated precipitation and is subject to increased soil accumulation. In contrast, the Bluff Group formation generally dominates across elevated land, and is highly fissured and jointed with no known surface water drainage issues. The formation has high secondary porosity in the form of skeletal molds, open joints, and fissures (Jones *et al*. 2004). Central portions of both Little Cayman and Cayman Brac are underlain by bluff formation, whilst the eastern and southern portions of Grand Cayman are dominated by the bluff formation.

Spatial geology data (Jones 2019, 2000) has been digitised within GIS to be input into the model, as seen in Figure 2. Given the higher soil prevalence and known drainage issues across the Ironshore formation, the underlying USDA soil texture has been set as 'Clay Loam' within the model, representative of the dominant soil classification across the islands. However, across the Bluff Group formations, the geology data has been associated to a 'Sand' USDA soil texture. This is assumed to provide the best representation of infiltration across the exposed Bluff Group formation which is known to have high infiltration rates and no flooding issues.

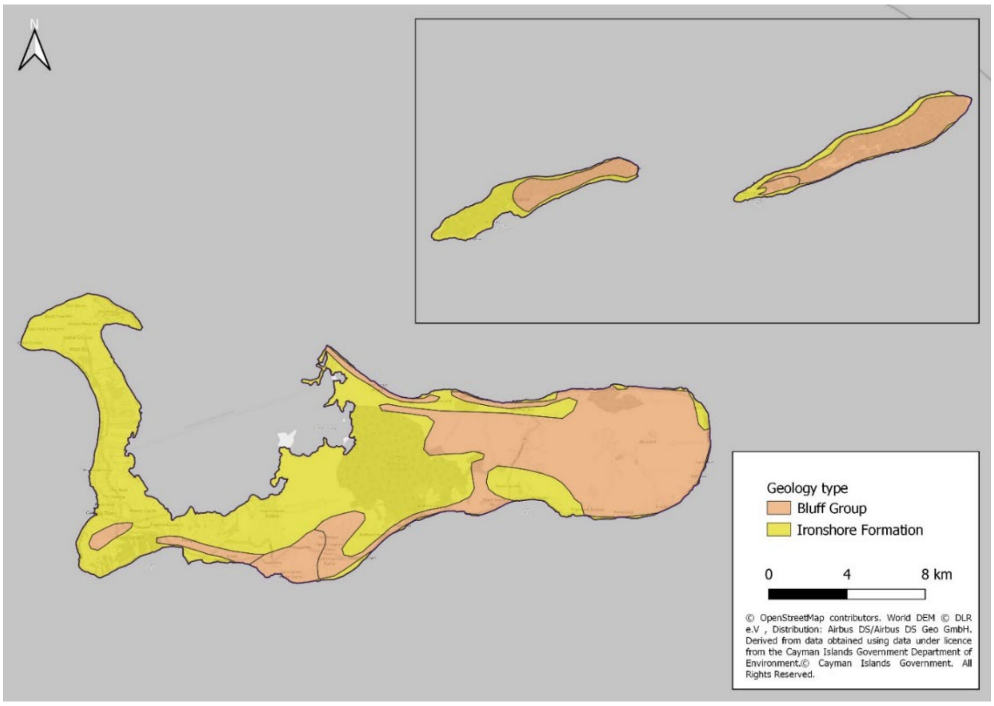


Figure 2: Cayman Islands geology (Jones 2000; Jones 2019).

Sensitivity testing has confirmed that applying a sand soil texture results in minimal surface water accumulation, typically limited to the minor depressions within the exposed limestone caves and joints. An additional sensitivity test has been run to assess the impact of the soil change from 'Clay Loam' (as used in Phase 1) to 'Sand'. The updated high-resolution model has been run with a global soil setting of Clay Loam, and the results of which are discussed further in Section 5.

3.4. Assumptions

A key assumption of the models is the representation of infiltration which has been established based on anecdotal information only (particularly for the bluff group). The infiltration rate is known to be high across the bluff group based on available literature and discussions with the Cayman Islands Government. However, limited data or research is available regarding the quantifiable rate of infiltration. The sensitivity of the model to this parameter has been assessed and discussed further in Section 4.1.3. Given the uncertainty in this parameter, it is recommended that infiltration testing be carried out to further establish the infiltration rates across the various geology types and could be incorporated into a future iteration of the model.

In defining the 'degraded' natural capital scenario within the model, a broad scale hypothetical scenario has been used to simulate the conversion of mangrove land covers (among others) to a grassland land cover (representing minimal vegetation cover). In the baseline model, mangrove landcovers have been parameterised as fully impermeable assuming a waterlogged state and hence no infiltration occurs to the underlying soil. It is assumed that where mangrove has been converted to grassland, the resultant landcover is free draining and dictated by the underlying soil type and geology. In instances where the underlying geology is the bluff group, this leads to significant infiltration losses in the degraded scenario and depth reductions relative to the baseline, as discussed further in Section 4.1.2. Further iterations of the model could incorporate a more targeted approach in specific areas such as South Sound basin, where a conversion of mangrove to an 'urban' land cover may be deemed more appropriate given the encroachment of recent developments.

3.5. Future applications

The incorporation of the high-resolution LiDAR data into the models for Phase 2 of the project significantly improves the accuracy and confidence in the model results. The outputs from the island-wide model have a wide range of applications in land-use planning, hazard management, emergency response and public awareness. However, given the scale and original scope of the models, there are several considerations to bear in mind if using the model results for more detailed, site-specific purposes. These relate to:

- Cell size.
- Representation of drainage infrastructure.
- Representation of buildings.

Such aspects could be refined and incorporated in future iterations of the model for more focused modelling studies that could be used to support a variety of purposes.

The cell size of 5 m is relatively high resolution for the purposes of large scale, island wide flood modelling. However, some additional minor cell size convergence (the fact that model results converge on a common answer as cell size decreases) may be observed in urban areas in particular using lower cell sizes below 5 m (BMT 2021). Using cell sizes of 5m and above has the potential to underestimate flood hazard particularly on small-scale urban flow paths. Should it be desired to produce more detailed flood extents and hazard maps for urban areas using a lower cell size, it is recommended that a cut-down version of the supplied models is made (especially for Grand Cayman given the size) to improve model run times and the manageability of results. Typically, negligible cell size convergence is seen in direct rainfall urban models using a cell size of below 2 m, and hence there are limited benefits of using a finer cell size for the additional run time.

The models are 2-dimensional (2D) only given the scope of the project with no incorporation of drainage infrastructure. Some caution should be used when reviewing results at a fine scale, especially in urban regions or adjacent to road embankments where there are likely to be relief culverts to aid the passage of floodwater. There is the potential that in such areas, the model results over-predict the risk of flooding. Further development of the model to incorporate 1-dimensional (1D) elements is recommended for any more detailed, site-specific studies.

The representation of buildings within the model has been parameterised with the use of a high Manning’s n roughness value only, which is considered industry standard for the purposes of broad-scale modelling. It has been assumed that the buildings have been entirely removed from DTM, and that the underlying elevation represents the true ground level. In accordance with the points raised above, a more refined representation of buildings could be incorporated for improved representation of flood risk in site-specific urban studies. Industry standards recommend the use of topographic modifications to raise building levels above the maximum expected flood height (Smith & Wasko 2012).

3.6. Coastal flooding

The SWAN model developed in Phase 1 (Wood 2021) was used for modelling the propagation and transformation of the wave field under three different hurricane category wind speeds and directions. Following discussions with the Government of the Cayman Islands, the model was updated to consider the following three improvements.

3.7. Representation of storm surge

Information on historical coastal flooding observations was provided by Simon Boxall (personal communication, Hazard Management Cayman Islands) and through discussion it was determined that the initial assumptions of 0.5 m, 1.0 m, and 1.5 m of water level offset due to storm surge for Category 1, 3, and 5 (respectively) winds were underestimated. Thus, the water level offset was increased to 1.0 m, 1.5 m, and 3.0 m for each respective hurricane wind scenario. This provided a higher storm surge level with which the waves can penetrate further inland, more closely resembling the flood maps generated for Hurricane Ivan.

3.8. Inclusion of seagrass

The effect of seagrass on wave energy dissipation and wave heights was incorporated through the addition of a vegetation parameterization (Suzuki *et al.* 2012) in the SWAN model. The energy of waves propagating through vegetation is dissipated by calculating a bulk drag coefficient which is dependent on the diameter, density, and height of the vegetation. In the SWAN model the energy is dissipated due to the work done by the waves on the vegetation. In addition, the vegetation energy dissipation considers the wave frequency and wavelength, as well as the total integrated energy at each grid cell. Thus, the dissipative effect of vegetation considers the dynamic effects of the wave field as it propagates and transforms while moving over the seagrass areas.

Locations of seagrass in the SWAN model grid were determined based on the benthic habitat coverage maps. These cells were then specified a seagrass density of 400 plants/m^2 following the approach of Zhu *et al.* (2021).

Figure 3 provides a map of the SWAN seagrass coverage for the Grand Cayman domain. During model computations, the vegetation energy dissipation parameterisation is applied to the cells defined as seagrass. In this way the localized dissipative effect of seagrass is distinct from that of reefs and mangroves.

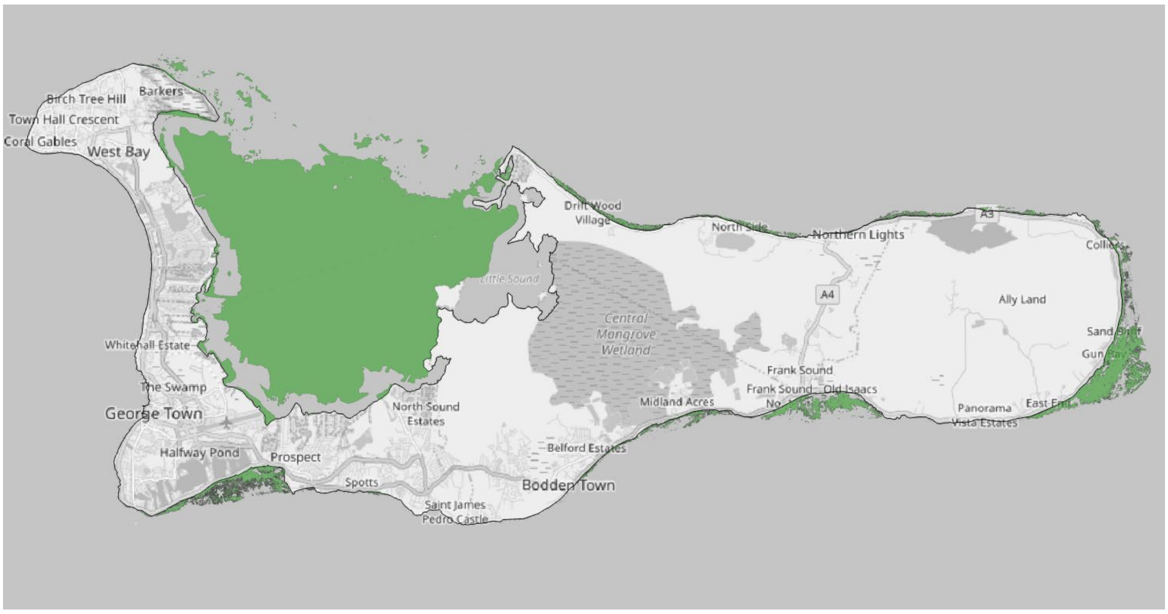


Figure 3: Location of SWAN seagrass cells for the Grand Cayman Islands domain.

3.9. Improved topography

The models for Little Cayman and Cayman Brac were updated to incorporate the land elevations from high resolution DTM detailed in Section 3.1.1.

3.10. Model scenarios

For completeness and to avoid referring to the Phase 1 work, the scenarios modelled were 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.
- **Severe degraded** – building on the degraded run, hypothetical 1 m loss 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.
- **Enhanced** – where natural capital is represented in full health.

Table 1 summaries the model parameterisation. It is noted that the Manning's n values used to represent mangroves differs between the TUFLOW and SWAN models. However, this is justified given the original research behind the Manning's n parameter by Chow (1959), to represent energy loss in open channels. The guidance provided by Chow (1959) is relevant for the parameterisation of inland hydraulic models such as that developed for this project using TUFLOW. However, the guidance is not directly applicable to wider applications in coastal modelling such as this, hence different values are recommended (Joyce *et al.* 2019) for the SWAN model to provide a reasonable representation of reality.

Table 1. Coastal modelling scenario definitions. Note: Where n is the Manning's roughness coefficients (Joyce *et al.* 2019) which are subsequently converted to Madsen's roughness lengths for model input.

Scenario	Coral Reefs	Mangroves	Seagrass
Baseline	n = 0.176	n = 0.32	400 /m^2
Degraded	n = 0.110	n = 0.20	400 /m^2
Severe degraded	n = 0.110 Loss of 1 m depth along reef cells	n = 0.20	400 /m^2
Severe degraded – no seagrass	n = 0.110 Loss of 1 m depth along reef cells	n = 0.20	none
Enhanced	n = 0.22	n = 0.4	400 /m^2

3.11. Coastal inundation modelling

The outputs from the updated SWAN wave model have been processed to form synthetic storm surge boundary conditions which are then applied to the high-resolution inland TUFLOW models. The coastline of each island has been segmented based on the wave height results, to apply spatially varying tidal conditions along the coast considering the variable wave heights along the coastline.

Near-shore wave height data has been sampled and an average calculated for each boundary segment and incorporated with a storm surge allowance to form a maximum surge level. The surge level has been used to scale a base tidal curve, assuming a symmetrical storm surge shape and duration of 6 hours. Example timeseries are shown in Figure 4 for boundary segments on the south-west corner of George Town for a Category 5 south-west storm.

Given the magnitude of some of the surge levels applied, the TUFLOW cell size has been increased to 10 m to improve model stability. Initial test runs through the model resulted in some instabilities particularly along the coastline in locations of significant (> 5 m) flood depth. The TUFLOW manual (BMT 2018) notes caution in instances where the flow depth is larger than the cell width, as this may start to violate the assumptions of the 2D shallow water equations. Sensitivity testing of results indicates that an increased cell size typically has minimal impact to modelled flood depths and extent. Given the nature of coastal flooding mechanisms (typically a well-defined extent) and in contrast to direct rainfall modelling (sporadic and patchy extents), the representation of small-scale topographic features is less critical to the output flood extent and depth.

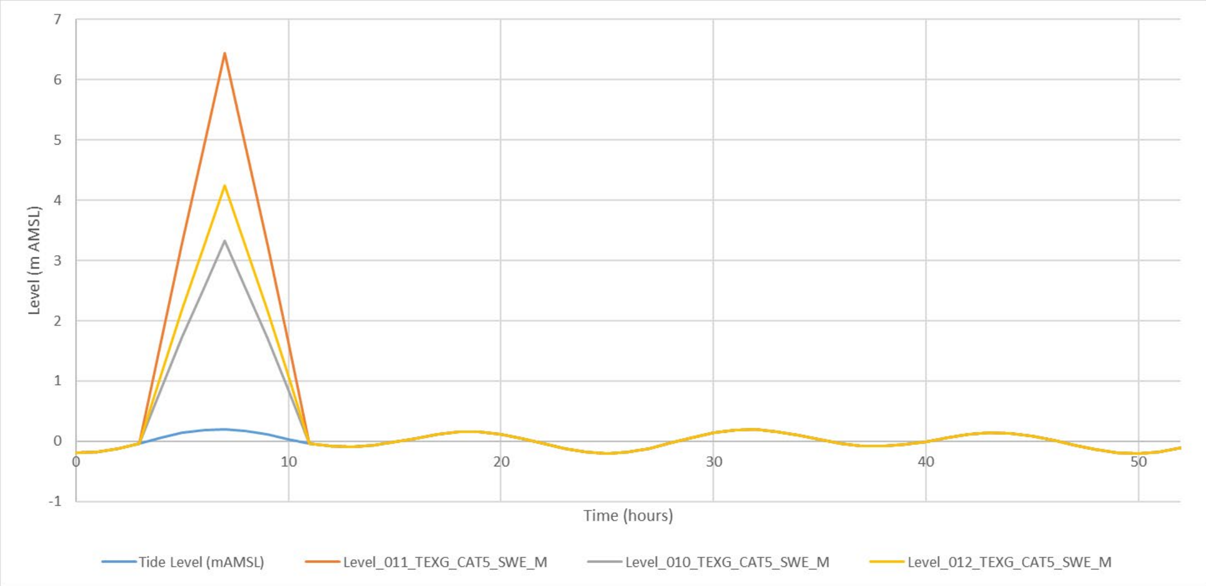


Figure 4: Example of a synthetic storm surge timeseries. An example time series of water surge levels (in metres (m) above mean sea level) which is used as boundary conditions to the TUFlow model to calculate coastal inundation. This particular case is for water levels (at a segment of shoreline) caused by a Category 5 south-west hurricane, assuming an offshore storm surge level of 3 m (See section 3.11). The time series are derived from a base tidal time series and the estimated increased water levels due to the offshore storm surge and waves breaking nearshore and are the calculated for each coastal segment'.

3.12. Economic valuation

This section of the report covers the methodology used for the estimates of economic values resulting from the updated modelling. In summary, the approach adopted was to use the methods used for the Phase 1 economic valuation (Wood 2021) but apply them to the updated Phase 2 modelling results for flooding

The geographical scope of the Phase 1 estimates was also widened to include Little Cayman and Cayman Brac in addition to Grand Cayman. In the results section below, estimates are presented for each island individually as well as for the three combined.

The revised estimates (for Grand Cayman) are surprisingly close to the previous estimate, particularly for the severely degraded scenario. This correspondence is despite a variety of changes which together have offsetting and complementary effects. It does not reflect underlying accuracy in the previous estimate.

The comparators used for the Phase 1 estimates remain valid references for the revised Phase 2 estimates and maybe used as before. They are:

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

In line with the Phase 1 methodology, the Phase 2 economic estimates reflect, firstly direct damage to property, and secondly losses from business interruption.

In more detail, the revisions to the Phase 2 economic estimates arise from:

- More detailed results for the physical representation of flooding, which has particularly benefited from coupling the coastal and inland models together and from using a higher resolution DTM.
- More recent updated values for property construction costs (which are used to derive the damage to property).
- More specific identification of the types of property flooded, and the probable levels of loss that result from the different use categories (based on input from Cayman Islands experts).

While the definition of the expected frequency of storm direction and intensity remains the same as for the Phase 1 estimate, the results for Little Cayman and Cayman Brac are based on storms only from the north, due to the limitations on modelling runtimes, and these results are used as proxies for storms from the south and south-west. In Grand Cayman, all storm directions are modelled individually.

4. Results

This section summarises the results from the updated inland and coastal flood modelling what are then used as input into the economic valuation.

4.1. Inland flooding

Inland flood depth results for baseline and degraded scenarios for Grand Cayman, Cayman Brac and Little Cayman can be found in Appendix A. A full list of related figures is provided below:

- Figure A.1 – Grand Cayman 4% AEP Baseline Flood Depth
- Figure A.2 – Grand Cayman 1% AEP Baseline Flood Depth
- Figure A.3 – Little Cayman 4% AEP Baseline Flood Depth
- Figure A.4 – Little Cayman 1% AEP Baseline Flood Depth
- Figure A.5 – Cayman Brac 4% AEP Baseline Flood Depth
- Figure A.6 – Cayman Brac 1% AEP Baseline Flood Depth
- Figure A.7 – Grand Cayman 4% AEP Severe Degradation Depth Difference
- Figure A.8 – Grand Cayman 1% AEP Severe Degradation Depth Difference
- Figure A.9 – Little Cayman 4% AEP Severe Degradation Depth Difference
- Figure A.10 – Little Cayman 1% AEP Severe Degradation Depth Difference
- Figure A.11 – Cayman Brac 4% AEP Severe Degradation Depth Difference
- Figure A.12 – Cayman Brac 1% AEP Severe Degradation Depth Difference
- Figure A.13 – Grand Cayman 1% AEP Infiltration Sensitivity Test Depth Difference
- Figure A.14 – Little Cayman 1% AEP Infiltration Sensitivity Test Depth Difference
- Figure A.15 – Cayman Brac 1% AEP Infiltration Sensitivity Test Depth Difference

4.2. Baseline

4.2.1. Grand Cayman

The updated Phase 2 peak flood depth results for Grand Cayman are shown in Figures A.1 and A.2 in Appendix A. In accordance with the Phase 1 results, the island is characterised by extensive shallow flooding across the low-lying portions of the island, particularly across the central mangrove wetland. The updated results provide a much-improved representation of flood risk across the urban regions of George Town, capturing surface water flood risk at a street level and incorporating the small-scale hydraulic impacts of road embankments which was previously missed.

Typically, reduced flood depths are anticipated across the eastern portion of the island because of the increased infiltration rate incorporated into the Phase 2 model updates, given that the eastern portion of the island is primarily underlain by bluff formation limestone. Across the western portion of the island (for which the infiltration rate remains the same between Phase 1 and Phase 2 given the underlying Ironshore formation), the Phase 2 results typically anticipate increased flood depths relative to the Phase 1 results. Depth increases are typically in the range of 0.1 m to 1 m, and generally coincident with low-lying depressions and wetlands, for which the high resolution DTM provides a significantly improved representation and captures the lowest elevation values. This can be seen most noticeably at South Sound basin, Matilde ponds and across the numerous low-lying wetlands and ponds on West Bay. Within the coarse resolution WorldDEM, such depressions are poorly represented and hence the subsequent surface water flooding is generally shallow and widespread in contrast to the updated Phase 2 results.

A comparison between the DTM and water levels within the South Sound basin is shown in Figure 5 below for reference. As seen, the updated high-resolution DTM provides an improved representation of the basin and captures the lowest elevations and surrounding developments which are missed within the lower resolution WorldDEM. As a result, the flood depths within the basin are generally greater than in the Phase 1 results, whilst flood depths across the surrounding elevated land are generally reduced.

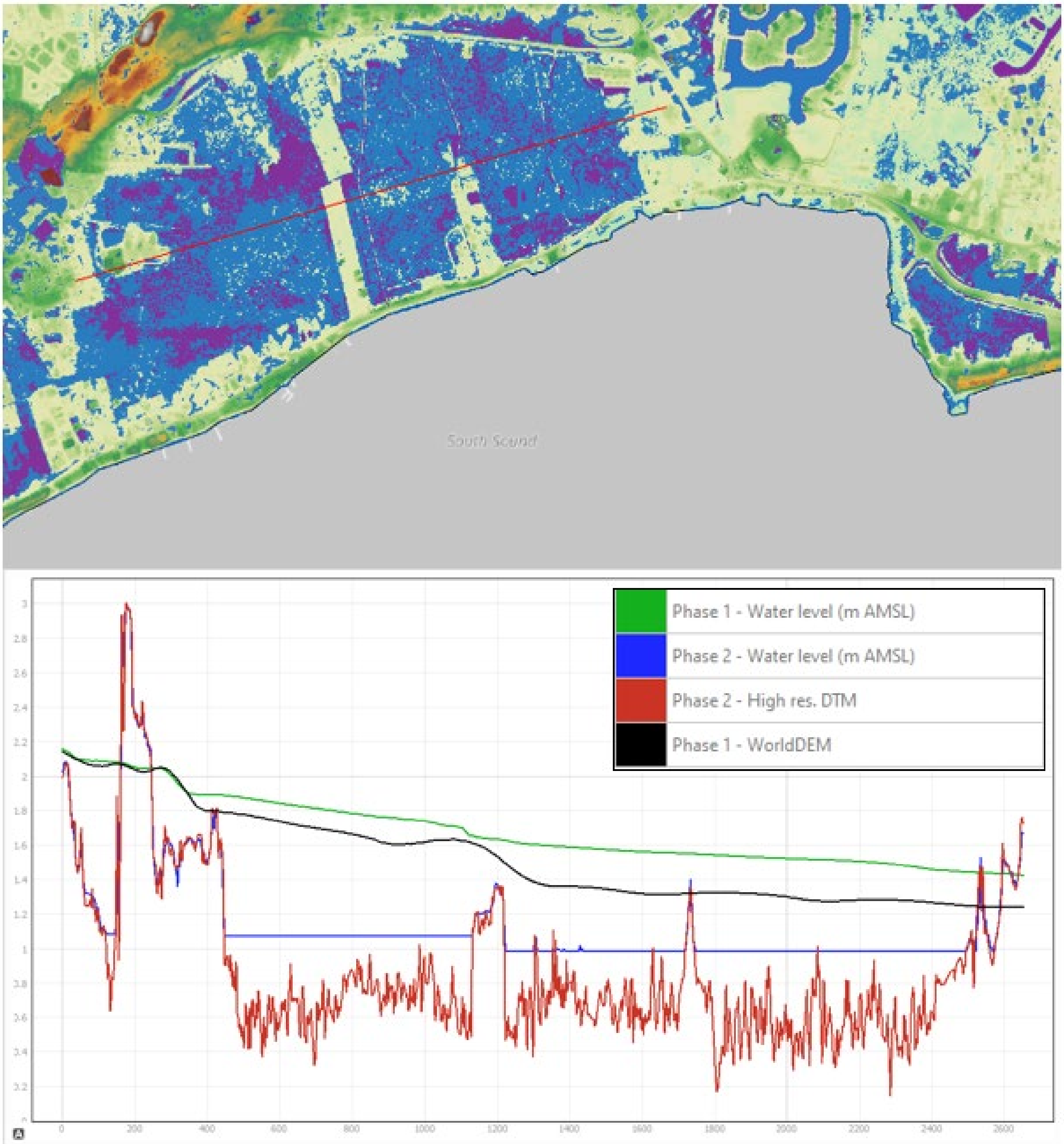


Figure 5: South Sound Basin updated flood depths.

4.2.2. Little Cayman

The updated Phase 2 peak flood depth results for Little Cayman are shown in Figures A3 and A.4 in Appendix A. Similarly, to the Phase 1 results, the island is characterised by extensive shallow flooding across the low-lying regions of the island, with more extensive flooding indicated across the low-lying wetlands and lakes. The updated topography and finer model resolution provide a more accurate representation of the small-scale flooding mechanisms, particularly across the urbanised regions.

The Phase 2 results typically show reduced flood depths, most noticeably across the eastern and central portion of the island given the underlying Bluff formation and increased porosity that has been incorporated into the Phase 2 model. Some depth increases are shown, most noticeably along the low-lying coastal regions on the north coast and western portions of the island because of the updated topography providing an improved representation of the low-lying elevations.

4.2.3. Cayman Brac

The updated Phase 2 peak flood depth results for Cayman Brac are shown in Figures A.5 and A.6 in Appendix A. The Phase 2 results indicate surface water flood risk across the low-lying coastal regions of the island, particularly along the north coast and adjacent to the airport in accordance with the Phase 1 results. However, because of the updated infiltration parameterisation to reflect the underlying geology, negligible surface water flooding is anticipated across the central bluff. Surface water flooding across the bluff is generally limited to isolated depressions and typically shallow (< 0.25 m). The high infiltration rates (reflecting the porous nature of the underlying bluff formation limestone) prevent the establishment of any surface water flow paths that were anticipated as shown in the Phase 1 results.

As one would expect, there are significant depth reductions relative to the Phase 1 results across the central bluff given the minimal surface water flooding anticipated in the Phase 2 results. Across the low-lying coast regions, differences between the Phase 1 and Phase 2 results are solely due to the changes to the topography layer given that the infiltration parameterisation remains unchanged where the Ironshore formation is dominant. Both depth increases and reductions are anticipated across the low-lying coastal land, generally of up to 1 m. Depth increases are most significant across the north coast of the island because of the updated topography providing an improved representation of the low-lying land between the coastal road and bluff, not captured within the Phase 1 WorldDEM topography.

4.3. Degraded

4.3.1. Grand Cayman

The associated depth difference results for the degradation scenarios on Grand Cayman are shown in Figures A.7 and A.8 in Appendix A. The impact of the degradation scenario is broadly like the findings of the Phase 1 modelling, with both depth increases, and depth reductions anticipated. However, depth reductions appear to be more dominant in the Phase 2 results, particularly over the eastern portion of the island and most significant in areas of mangrove conversion to grassland.

This can be explained by the updated representation of infiltration, and in particular the higher infiltration rate modelled for areas underlain by bluff formation as in the eastern portion of Grand Cayman (Appendix A).

Within the baseline model, mangrove-based land covers have been parameterised such that the underlying soil is impervious to represent waterlogged land, and as a result there is no infiltration losses of surface water to the ground. However, the degraded scenario has been parameterised to represent a conversion to grassland, for which the underlying ground is assumed to be freely draining (representative of the underlying geology) given the assumed land drainage that would be required. Hence, in areas where mangrove has been converted to grassland, depth reductions are typically anticipated because of infiltration losses outweighing the reduction in rainfall losses. Given the low-lying nature of the island and the fact that surface water tends to stay in situ (rather than flowing downstream via a drainage network), any detrimental impact in terms of increased runoff due to reduced surface runoff and reduced rainfall losses is typically negligible.

The degraded natural capital scenario represents a hypothetical island-wide land use change. However, based on recent development trends as observed in areas such as South Sound Basin, a more targeted approach in mangrove regions may be more appropriate, representing a change to an ‘urban’ land cover.

4.3.2. Little Cayman

The associated depth difference results for the degradation scenarios on Little Cayman are shown in Figures A.9 and A.10 in Appendix A. In accordance with the Phase 1 results, both depth increases, and reductions are anticipated in response to the land cover changes modelled. Depth increases are typically shown across the western portion of the island in low-lying wetlands and lakes because of the increased surface runoff, and typically in the region of 0.05 m to 0.2 m in magnitude.

Depth reductions are typically in the region of 0.05 m to 0.35 m, and most apparent where mangrove forest and mangrove wetland is simulated as being converted to grassland as observed on Grand Cayman.

4.3.3. Cayman Brac

Depth difference maps between the baseline and degradation scenarios for Cayman Brac are shown in Figures A.11 and A.12 Appendix A. Given the high infiltration rates across the bluff (and in contrast to the Phase 1 results), no depth difference is anticipated as there is negligible surface water flooding and runoff generated in both the baseline and degraded scenarios.

Both depth increases and reductions are shown across the low-lying coastal regions of the island, though depth increases are typically dominant across the north coast of the island in the region of 0.05 m to 0.3 m. Given the limited upstream catchment along the coastline, the depth increases anticipated can be attributed primarily to the reduced rainfall losses in the degraded scenario (associated with the conversion of forest and shrubland to grassland), resulting in increased rainfall reaching the ground level. Some minor depth reductions of less than 0.05m are anticipated along the north coast of the island because of faster runoff to the surrounding land and sea, given the reduced friction.

More significant depth reductions in the region of 0.05 m to 0.15 m are anticipated along the southwest coastline. As observed on Grand Cayman and Little Cayman, this can be attributed to the conversion of mangrove (assumed to be impermeable) to grassland, resulting in an increased infiltration rate and hence a reduction in surface water flood depths despite the reduced rainfall losses.

4.4. Infiltration sensitivity test

A sensitivity test has been run for each of the island-wide models using the 1% AEP event, to assess the sensitivity of the model results to the updated infiltration representation discussed in Section 4.1.2. Depth difference maps are shown in Figures A.13 to A.15 (Appendix A) showing the difference between the peak flood depths of this test relative to the updated baseline results.

The results indicate that the models are highly sensitive to the infiltration parameterisation, with widespread depth increases anticipated of up to 1.5 m across the bluff formation geology. The sensitivity of the model results to the infiltration parameters highlights the limitations of the model without additional or detailed infiltration data available. The geology types shown in Figure 2. have been associated to a USDA soil texture based on anecdotal information regarding surface water flooding and drainage characteristics only. Detailed infiltration testing across the various geology types is recommended which would greatly improve the confidence in the model results.

4.5. Coastal flooding

4.5.1. SWAN results

The main effects of incorporating the seagrass energy dissipation and increasing the storm surge water level offset were:

1) a localized decrease of wave heights at the vicinity of seagrass model cells, and
2) further inland penetration of waves (larger than Phase 1) due to the increased water level over which waves can propagate.

Figure 6. shows the wave energy dissipation caused by seagrass for the degraded reef scenario under Category 5 hurricane winds from the North. Notice that the dissipative effect is localized, with the major effect happening in the North Sound, which is also where most of the seagrass coverage is located. Without the inclusion of seagrass into SWAN, as in Phase 1, the resulting effect of decreased wave heights would be missing from the model results.

Figure 7. illustrates the combined effect of seagrass energy dissipation and the higher storm surge water level offset. In this case, the model scenario is degraded reefs (50% reduction of Manning's n) under Category 5 hurricane wind forcing from the North. The Figure shows the difference of the resulting SWAN wave heights when including seagrass and the updated higher storm surge water level offset (Phase 2) minus the SWAN wave heights when using the Phase 1 configuration. In the North Sound, where most of the seagrass energy dissipation occurred, the wave heights decreased by about -1.5 m. In the areas where seagrass overlaps with the shelf edge, such as at the entrance of North Sound, the dissipative effect is even stronger to about a -2.0 m in wave height difference. In addition, the effect of increased storm surge water level offset is shown by the positive differences of up to +1.5 m in the inland areas of Grand Cayman. This means that waves can further penetrate inland, allowing larger waves to reach farther into the island.

For the severely degraded scenario, the Category 5 from south-west provides the best illustration of the combined effects of seagrass and water level offset increase (Figure 8). In this case, the increase in water level causes wave heights to increase by about 1.0 m over the reef line (which in this scenario is deepened an additional meter), with the subsequent effect of larger waves penetrating inland. These larger waves that penetrate inland are over 1.0 m higher than those in Phase 1. Thus, the increase in the water level offset, combined with the deepened reef line defined for the severely degraded scenario, results in a wave height increase of more than 1.0 m over both the reef line and inland. This effect under the severely degraded scenario is most pronounced for the South and South-west wind forcing cases, as they are the ones for which the reef lines have the largest dissipative effects.

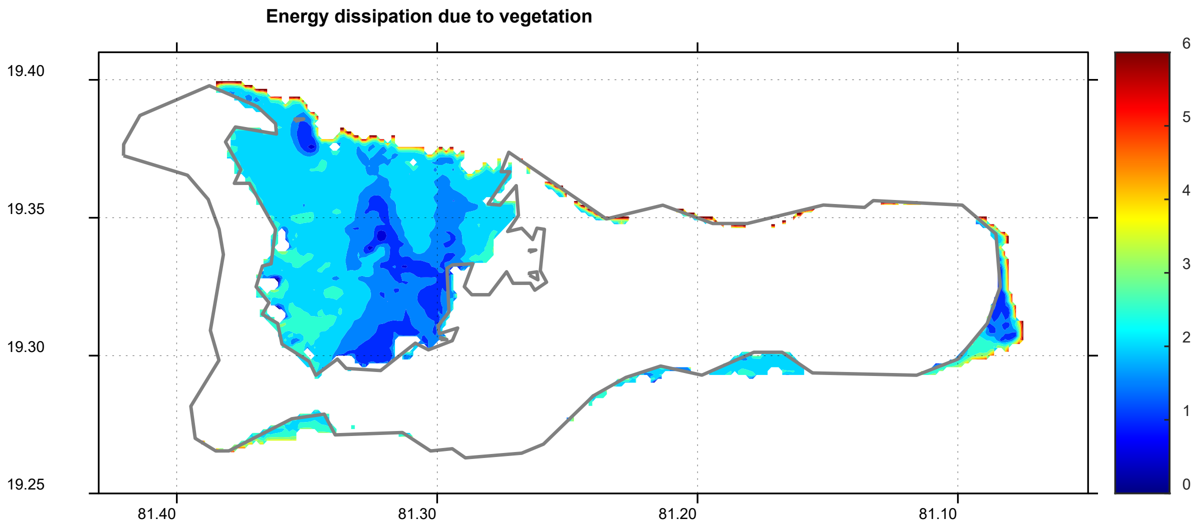


Figure 6: Energy dissipation (shown as ln(energy dissipation)) due to seagrass (vegetation parameterization) in the SWAN model. This solution is for the scenario of Category 5 hurricane winds from the north. Notice that the dissipative effect is localized at the seagrass grid cells. Units are W/m^2.

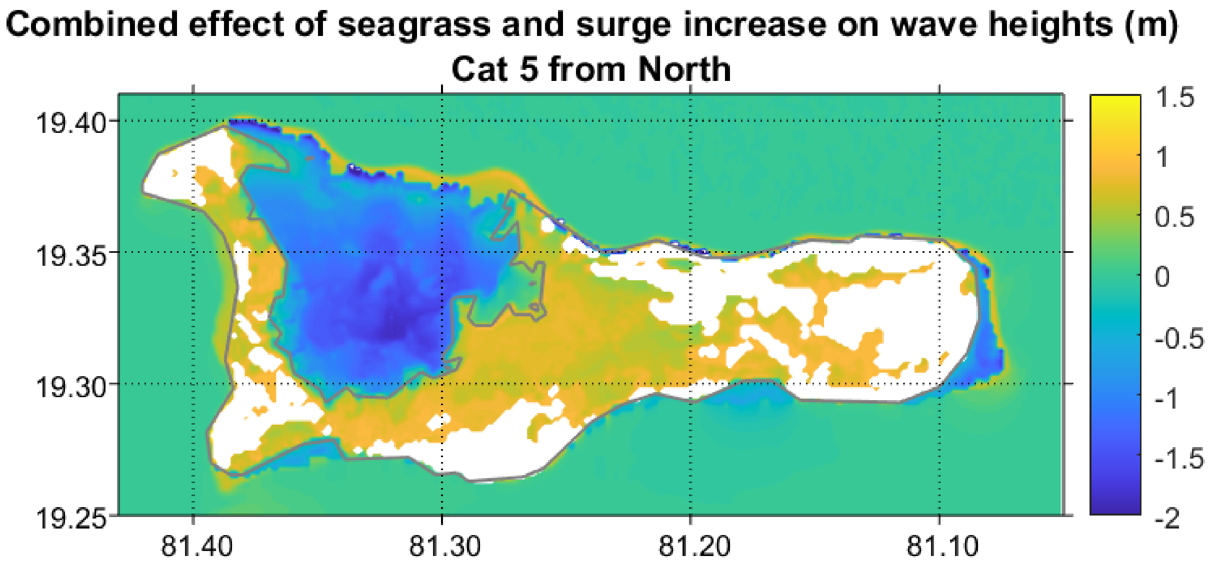


Figure 7: This figure illustrates the combined effect of including both seagrass energy dissipation and an increase in the storm surge water level offset in the SWAN model for the degraded reef scenario. Shown is the difference in wave height (m) between Phase 2 and Phase 1 model configurations for the scenario of Category 5 hurricane winds from the north.

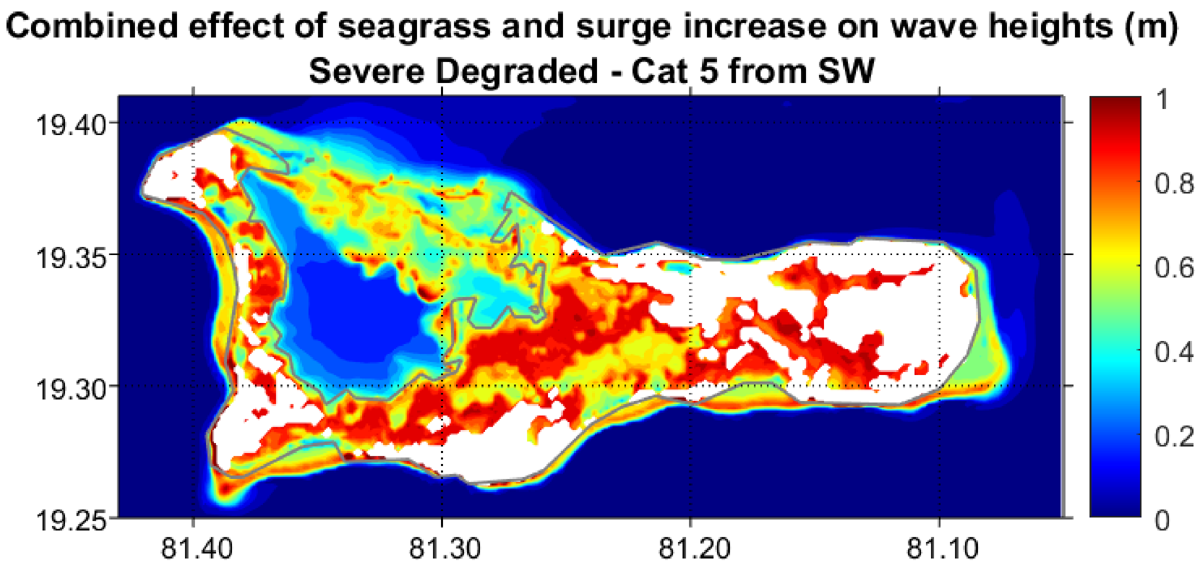


Figure 8: This figure illustrates the combined effect of including both seagrass energy dissipation and an increase in the storm surge water level offset in the SWAN model for the severely degraded reef scenario. Shown is the difference in wave height (m) between Phase 2 and Phase 1 model configurations for the scenario of Category 5 hurricane winds from the north.

4.5.2. Coastal inundation – baseline

Coastal inundation results for baseline and natural capital scenarios for Grand Cayman, Cayman Brac and Little Cayman can be found in Appendix B. A full list of related figures is provided below:

- Figure B.1 – Grand Cayman Category 1 Baseline Composite Flood Depth
- Figure B.2 - Grand Cayman Category 3 Baseline Composite Flood Depth
- Figure B.3 - Grand Cayman Category 5 Baseline Composite Flood Depth
- Figure B.4 – Little Cayman Category 1 Baseline Composite Flood Depth
- Figure B.5 – Little Cayman Category 3 Baseline Composite Flood Depth
- Figure B.6 – Little Cayman Category 5 Baseline Composite Flood Depth
- Figure B.7 – Cayman Brac Category 1 Baseline Composite Flood Depth
- Figure B.8 – Cayman Brac Category 3 Baseline Composite Flood Depth
- Figure B.9 – Cayman Brac Category 5 Baseline Composite Flood Depth
- Figure B.10 – Grand Cayman Category 1 (south-west) Enhanced Depth Difference
- Figure B.11 – Grand Cayman Category 1 (south-west) Degraded Depth Difference
- Figure B.12 – Grand Cayman Category 1 (south-west) Severe Degradation Depth (and Extent) Difference
- Figure B.13 – Little Cayman Category 1 (south-west) Enhanced Depth Difference
- Figure B.14 – Little Cayman Category 1 (south-west) Degraded Depth Difference
- Figure B.15 – Little Cayman Category 1 (south-west) Severe Degradation Depth (and Extent) Difference

- Figure B.16 – Cayman Brac Category 1 (south-west) Enhanced Depth Difference
- Figure B.17 – Cayman Brac Category 1 (south-west) Degraded Depth Difference
- Figure B.18 – Cayman Brac Category 1 (south-west) Severe Degradation Depth (and Extent) Difference

4.5.3. Grand Cayman

Baseline maximum depth results for each of the three wind directions considered have been combined to form a composite maximum depth grid. These are shown in Figures B.1 to B.3 in Appendix B.

Flooding within George Town in the Category 1 storm is typically less than 1 m, and generally confined to the within 1 km of the coastline. The results indicate that the south-west portion of George Town and the coastline developments fringing the North Sound are at particular risk of coastal flooding. Minimal inundation is anticipated across the entire eastern portion of the island.

Widespread flooding of up to 1.5 m is anticipated across much of George Town in the Category 3 storm, and floodwaters from both the North Sound and south-west coastline breach across the narrow sections of the Town. In the Category 5 storm, the vast majority of George Town is anticipated to be inundated with floodwaters exceeding 2 m. Some floodwater ingress is anticipated along the eastern portion of the island at Frank Sound on the south coast, and Old Man Bay on the north coast.

The TUFLOW model outputs typically anticipate a reduced flood extent in the central eastern portion of the island relative to the SWAN outputs (as mapped in Figure 7 and Figure 8). The SWAN model uses a static storm surge level, such that all areas of land that sit below that level is assumed to be inundated. In contrast, the TUFLOW model incorporates a temporal element to the storm surge, and hence the peak surge is only applied for 1 hour in duration. The topographic representation within the TUFLOW model is of significantly higher resolution to SWAN (10 m versus 150 m), and therefore represents small scale topographic features along the coastline that influence the propagation of floodwater inland.

Furthermore, the representation of infiltration within the TUFLOW model will account for significant losses to the underlying soils, which is not captured within SWAN and can further explain some of the differences in flood extent observed.

4.5.4. Little Cayman

Baseline maximum depth results for each of the three wind directions considered have been combined to form a composite max depth grid. These are shown in Figures B.4 to B.6,(Appendix B). The results indicate that the low-lying portions of the northern coastline of the island are at most risk from coastal flooding, with anticipated flood depths typically in the region of 0.5 m to 3 m. More significant flood depths are anticipated in Category 3 events and higher within some of the coastal wetlands and ponds along the north coast.

The anticipated flood extent is typically confined to a narrow band following the coastline in events up to a Category 3 storm, though the flood water is anticipated to breach into some of the western central portions of the island in the Category 5 storm event.

4.5.5. Cayman Brac

Baseline maximum depth results for each of the three wind directions considered have been combined to form a composite maximum depth grid. These are shown in Figures B.7 to B.9 in Appendix B.

Results indicate that the northern coastline in the south-west and north-east corners of the island are at highest risk of coastal flooding, with flood depths of up to 2 m in the Category 1 storm. Given the topographic nature of the island, the anticipated flood extents are confined to the narrow strip of low-lying coastal land that surrounds the bluff. Minimal flooding is anticipated across the south coast of the island, with significant floodwater ingress anticipated in the Category 5 storm only. Widespread flooding typically exceeding 2.5 m is anticipated across the entire northern coastline in the Category 5 event.

4.5.6. Coastal inundation – scenarios

Depth difference maps are included in Appendix B for the hypothetical natural capital scenario for each island (Figures B.10 to B.18). Only the worst-case wind direction for each island has been presented and considering only the Category 1 storm since the relative impact of natural capital has been observed to be greatest for lower magnitude events. Depth (and extent) difference outputs for additional Category storms have been included in the result deliverables for reference.

The inland inundation peak depth differences show typically minor differences for the enhanced and degraded scenarios parameterised through a Manning’s n change only. Typically, negligible changes are anticipated to the flood extents (hence these are not mapped), and depth differences are typically localised to the coastline and of less than 0.10 m. The anticipated impact to peak flood depth is typically seen to diminish with increasing event magnitude, highlighting that the flood protection offered by the reef systems is most significant for more frequent, lower magnitude storms.

For the severe degradation scenario which includes a 1 m loss of reef structure, the anticipated impact to inland flood inundation is more significant. Widespread depth increases of 0.10 m to 0.50 are anticipated on Grand Cayman, and notable increases to flood extent are predicted. These are most notable within George Town in the lower magnitude Category 1 storm, given that the increased flood extents will results in an increased number of properties inundated.

The severe degradation results across Little Cayman and Cayman Brac show reduced impact to peak flood depths and extent relative to Grand Cayman. Negligible impact is predicted to the peak flood extents, and anticipated depth increases are typically less than 0.10 m.

4.6. Economic Valuation

4.6.1. Overview

The results are developed using the same economic basis as the previous Phase 1 estimates.

Important features of the scope of the estimates are 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.
- Business losses reflect a loss of economic activity and would result in reduced financial flows with associated losses such as in government tax revenues.
- Damage to property is estimated as the costs of repair and restitution.

Other potential economic impacts are not included.

Results are presented as annual averages, taking account of the frequency of storms of different intensities and the different levels of damage from storms from different directions. The most important of these parameters is the frequency of storms. These results are based on observed historical frequencies unadjusted for potential climate change impacts. In addition, no sea level rise effects have been included.

4.6.2. Results

Note that the results are reported here in Cayman Islands Dollars [CI$] while in Phase 1 results were reported in US Dollars [$]. In May 2022, the exchange rate was 1.19 US Dollars to the CI$.

The annual average economic loss to the Cayman Islands in the severe degraded scenario is estimated at approximately CI$75 million (See Table 2). It is shown in the table as CI$74,984,535 so that the much smaller values for Little Cayman and Cayman Brac can be shown in the same units in the subsequent table.

The CI$75 million is the average additional loss in every year arising from severe reef degradation over and above the average level of losses that arise in the baseline without degradation. The average reflects the combined effect of multiple storms of different categories and from different directions and is weighted by their frequency, to account for the fact that, while a more severe storm causes greater damage, it also occurs less often. For this reason, the effects of smaller more frequent storms can comprise a greater part of the annual average.

The level of loss is estimated using the methodology described above. In summary, the value includes the more direct effects that would be experienced and is calculated with reference to an economy in the current state. It does not include, for example, longer term effects such as reputational damage leading to lower demand for property on the Islands.

In the degraded scenario, rather than severely degraded, the annual average economic loss to the Cayman Islands is estimated at approximately CI$7.6 million. The difference between severe degradation and degradation is significant and is an indicator, even excluding additional long-term effects, of potential non-linearities in the economic response and of the sensitivity to change in the natural environment.

Table 2. Annual average value of economic value of loss for Cayman Islands in the severe degraded scenario – total (Source: WSP).

Scenario	Number of properties flooded	Area flooded (building footprint) (m^2)	Property Loss (CI$)	Business Interruption Loss (CI$)	Total: Property Loss + Business Interruption Loss (CI$)
Degraded	67	15,0010	3,442,560	4,203,337	7,649,656
Severely degraded	612	145,139	4,582,340	40,398,851	74,984,535

Table 3 shows the results for the three main islands. The economic activity and levels of investment are consistent with their size and show the dominance of Grand Cayman as a location where most of the economic losses are experienced.

Table 3. Annual average value of economic value of loss for Cayman Islands for the degraded and sever degraded scenarios – results by island (source: WSP).

Island	Scenario	Number of properties flooded	Area flooded m^2 (building footprint)	Property Loss [CI$]	Business Interruption Loss [CI$]	Total: Property Loss + Business Interruption Loss [CI$]
Grand Cayman	**Degraded**	64	14,487.4	3,244,283	4,060,312	7,304,595
	Severely degraded	609.	144,452.3	34,357,525	40,214,642	74,572,167
Little Cayman	**Degraded**	0.2	35.5	7,459	10,454	17,928
	Severely degraded	0.2	35.5	8,097	10,454	18,570
Cayman Brac	**Degraded**	2.7	486.9	190,818	132,572	327,133
	Severely degraded	3.2	651.2	216,718	173,755	393,798

The two tables that follow present results for the severely degraded and degraded scenarios for Grand Cayman only. They show the importance of the more frequent and lower category storms to the annual average. In the severely degraded scenario, the most significant contributor is the Category 1 storm from the south-west which accounts for CI$20 million of the total of CI$75 million (See Table 4). The Category 1 storms together account for CI$41 million of the total of CI$75 million, over 55% of the total, while the category 5 storms account for just 8%. This shows how, from an economic perspective, while the coastal protection provided by reefs functions as insurance against extreme events, it also contributes even more significantly to ongoing levels of protection required on a regular basis.

Table 4. Annualised avoided costs of business losses and damage to property (CI$ million) from coastal flooding: severe degraded scenario, Grand Cayman (source: WSP).

Storm Category	Event [CI$ million]	Annualised [CI$ million]
Category 1 North	138.3	11.5
Category 1 South	113.9	9.5
Category 1 South-west	240.1	20.0
Category 3 North	305.4	10.2
Category 3 South	284.1	9.5
Category 3 South-west	229.2	7.6
Category 5 North	212.0	2.0
Category 5 South	225.1	2.1
Category 5 South-west	219.8	2.1
Total		**74.6**

In the degraded scenario, the difference between contributions from different storm categories is even more marked though not appreciably so. Category 1 storms contribute more to the annual average (56%), while Category 5 storms contribute less (6%) (See Table 5).

Table 5. Annualised avoided costs of business losses and damage to property (CI$ million) from coastal flooding: degraded scenario, Grand Cayman (source: WSP).

Storm Category	Event [CI$ million]	Annualised [CI$ million]
Category 1 North	8.2	0.7
Category 1 South	8.7	0.7
Category 1 South-west	32.3	2.7
Category 3 North	31.3	1.0
Category 3 South	33.4	1.1
Category 3 South-west	19.1	0.6
Category 5 North	13.1	0.1
Category 5 South	17.6	0.2
Category 5 South-west	12.8	0.1
Total		**7.3**

4.6.3. Comparison with Phase 1 Results

The two tables above (Tables 4 and 5) follow a similar format to tables presented in Phase 1 and shown in Figure 12. Note that the Phase 1 tables are in US Dollars ($).

The latest Phase 2 results for the severely degraded scenario have a result of CI$74.6 million which is numerically close to the Phase 1 result using the 200% runup of $87.1 million (equivalent to CI$73.2 million). This close correspondence is considered largely serendipitous and should not be taken as justification for sufficiency of the Phase 1 approach. The Phase 2 result is based on a significantly more accurate approach and supplants the wide range (from $33.1 million to $87.1 million) required in the Phase 1 approach.

For the degraded scenario (not shown in a figure), the Phase 1 results had a range of $2.4 million to $3.2 million (CI$2.0–2.7 million) which is appreciably lower when compared with the latest Phase 2 result (CI$7.3 million).

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

Figure 9. Previous (Phase 1) results for the severely degraded scenario for Grand Cayman.

Phase 1 also included comparisons with previous Cayman Islands references which are further updated and contextualised with these Phase 2 results here:

- In an estimate for the Cayman Islands, based only on damage from category 5 storms, the value of coastal protection was estimated as CI$4.6 million (Wolfs, 2017, with values converted to 2020 prices, also including Little Cayman and Cayman Brac). This is broadly similar to the CI$6.2 million estimated for category 5 storms in the severely degraded scenario modelled in the Phase 2 work (just for Grand Cayman) but does not include the much greater contribution of reefs to coastal protection for category 1 and category 3 storms (totalling CI$68.4 million).
- The annual value added (reported as GDP in 2018) for the Hotels and Restaurants sector in the Cayman Islands was CI$256 million (in 2020 prices, after conversion from the CI$231 million noted in 2015 prices). The CI$74.6 million of economic value for coastal protection provided by the reefs is therefore equivalent to approximately 30% of the annual value added in the hotels and restaurants sector.

5. Tool development and capacity building

Capacity building is a key objective of this project. It is important that staff of the Government of Cayman Islands can investigate, model and value the impacts of future scenarios of extreme weather events or changes to natural capital on flooding, to support the evidence base for policy development and implementation.

By their very nature, coastal and inland flood models can be complex and benefit from specialist modellers to set up, run and interpret the results to ensure robust outcomes. Recognising the complexities of the TUFLOW and SWAN models that have been used for this valuation assessment, toolboxes have been created within the ESRI ArcGIS environment to provide the non-specialist a more straightforward way to configure and run the models and view the outputs. Accompanying training manuals have been developed and training workshops delivered. This section provides a summary of these capacity building aspects.

5.1. Model toolboxes

The following sub section outlines the structure and functionality of the ESRI ArcGIS toolboxes and related python scripts created to assist the future running of TUFLOW and SWAN models.

5.1.1. Toolbox setup

The toolbox and scripts have been supplied in a pre-defined structure and can be stored at any user defined location on a local machine. All scripts are stored relative to this location, with the toolbox folder containing the following files:

- .tbx Main ArcGIS toolbox (ArcMap 10.x version)
- .py ArcGIS python processing codes linked to the toolbox (see Figure 10)

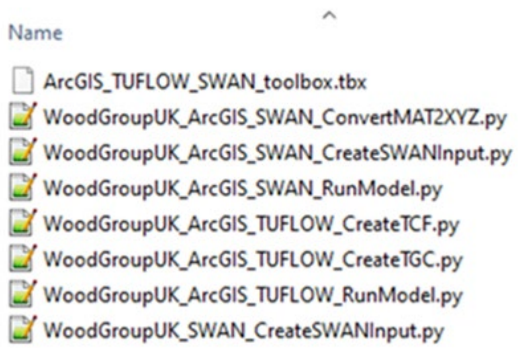


Figure 10. ESRI ArcGIS Toolbox folder structure example.

The ArcGIS toolbox must be added to the local ArcMap installation by:

- Opening a new or existing ArcMap project and then accessing the ArcToolbox menu.
- Right mouse click on the ArcToolbox menu and click “Add Toolbox”
- Select the location of the “TUFLOW SWAN Modelling Tools” toolbox and click “Open”

The toolbox will then be added and accessible for future ArcMap sessions. A series of additional steps are required to install and setup the tools for subsequent use. These are outlined below.

5.2. TUFLOW model setup

Each of the TUFLOW models supplied under the contract includes a Global settings file called “WoodGroupUK_TUFLOW_GLOBAL_SETTINGS_DEFAULT”.set. An example of the files is shown below (see Figure 11).

```
#TCF Settings
806717 Cayman Islands Natural Capital Assessment
806717
Cayman Brac
Cayman_WGS84_Projection.prj
UK_Projection.mif
0
1
GRID XMDF
CONSERVATIVE
0.44
0.000
2d_loc_cayman_brac_001_L.shp
20400,3800
2d_code_cayman_brac_001_R.shp
C:\\TUFLOW\\TUFLOW.2020-10-AA\\2020-10-AA\\TUFLOW_iSP_w64.exe

#TCF Guidance- Order of inputs
2-Project Name -$TCF_PROJECT$
3-Job Number - $TCF_JOBNO$
4-Location - $TCF_LOCATION$
5-SHP Projection -$TCF_SHPPROJ$
6-MI Projection - $TCF_MIPROJ$
7-Start_time - $TCF_STARTTIME$
8-Timestep- $TCF_TIMESTEP$
9-Map Output $TCF_MAPOUTPUT$
10-Hazard Land USe - $TCF_LANDUSE$
11-IWL - $TCF_IWL$
12-WETDRYDEPTH -$TCF_WETDRYDEPTH$
13-TGC GRID LOCATION - $TCG_GRIDLOCATION$
14-TGC GRID SIZE - $TCG_GRIDSIZE$
15-TGC GRID ACTIVE - $TCG_GRIDACTIVE$
16-TUFLOW EXE LOCATION
```

Figure 11. Example of Global setting file used by the TUFLOW tools to determine pre-set parameters and location of key executable files.

As outlined later this file is used by the TUFLOW tools to determine pre-set parameter values and location of key executable files. This file may need to be edited if any of the core model values are changed. This includes the location of the main TUFLOW executable – see line 16, Figure 11. It is recommended that a backup of this file is created before any values in the file are edited.

Each of the TUFLOW models supplied under the contract also includes two TUFLOW template files. These files are called “TCF_template.tcf” and “TGC_template.tgc” . These files are used as part of the TUFLOW tools and must be stored under a sub folder of the main TUFLOW modelling directory called \templates. These files should not be edited.

5.3. SWAN model installation and setup

The installation of SWAN consists of two main Phases. The first stage consists of installing a series of supplied SWAN executable files to local machine in the following order:

- ww_ifort_redist_msi_2018.1.156
- setup-SWAN-41.31A-omp.exe

Please note that later versions of SWAN are not compatible with the models developed.

The second part of the install process is setting of local SWAN environment variable on the modelling machine. This is achieved by accessing "Environment Variables" on local machine sand add a new SWAN variable with path set to location of the SWAN installation used in stage 1. Further details on this can be accessed at: [SWAN GIS Running Simulations - TUFLOW FV Wiki.]

5.3.1. TUFLOW ArcGIS toolbox

The ESRI ArcGIS TUFLOW SWAN toolbox contains three processing tools to assist users run the TUFLOW model (see Figures 13, 15 & 16). These tools are:

- Tool A – Create TGC file
- Tool B – Create TCF file
- Tool C – Run Model

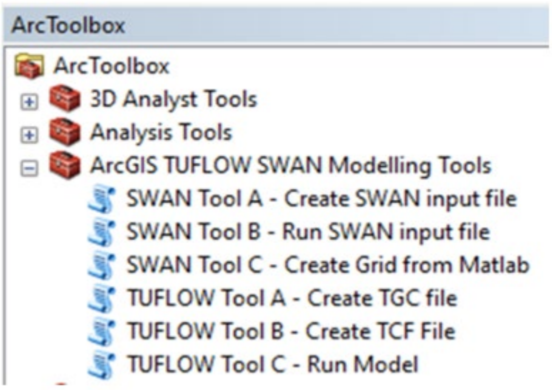


Figure 12. A screenshot of the ESRI ArcGIS TUFLOW and SWAN toolbox showing all the processing tools.

Each tool has a form which enables users to select and edit parameter values. Some of these values are set to default values.

These defaults can be edited by right mouse clicking on the tool and selecting "Properties" and then the "Parameters" tab". Access the required parameter and then alter the default value. The change will be saved in the toolbox and will save time in running future models.

5.3.1.1. TUFLOW Tool A - Create the TGC file

The interface of Tool A enables users to select the folder location of the required TUFLOW model. This folder must include all the input files needed to run the TUFLOW model (see Figure 13).

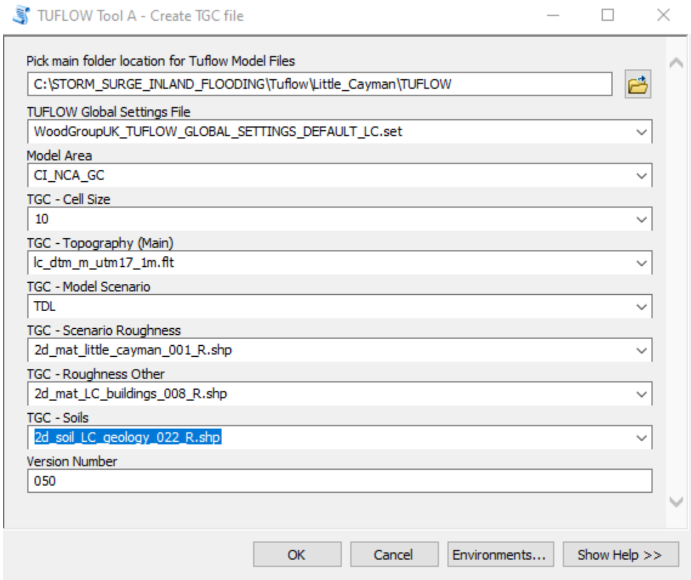
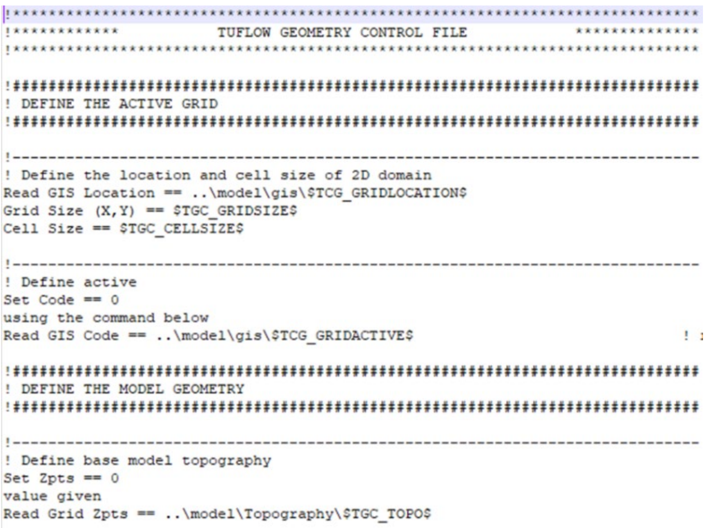


Figure 13. A screenshot showing the interface of TUFLOW Tool A which enables the creation of the TGC file (geometry control file with extension .tgc).

The ArcGIS form enables users to enter and/or select from dropdown lists, values for inclusion in the output TGC file (TUFLOW geometry control file).

After the user selects OK, the related python code is used to retrieve the TGC template (stored under the templates folder), run a python search / replace routine and then save a new TGC file. The new TGC file will be saved in the “model” sub-folder of the current model folder. The next step in the process is to run Tool B.

The screenshot (Figure 14) illustrates a portion of the TGC template. This file is stored in the templates sub-folder of the active model.



```
!*****************************************************************************
!************             TUFLOW GEOMETRY CONTROL FILE              **************
!*****************************************************************************

!#############################################################################
! DEFINE THE ACTIVE GRID
!#############################################################################

!-----------------------------------------------------------------------------
! Define the location and cell size of 2D domain
Read GIS Location == ..\model\gis\$TCG_GRIDLOCATION$
Grid Size (X,Y) == $TGC_GRIDSIZE$
Cell Size == $TGC_CELLSIZE$

!-----------------------------------------------------------------------------
! Define active
Set Code == 0
using the command below
Read GIS Code == ..\model\gis\$TCG_GRIDACTIVE$                              ! :

!#############################################################################
! DEFINE THE MODEL GEOMETRY
!#############################################################################

!-----------------------------------------------------------------------------
! Define base model topography
Set Zpts == 0
value given
Read Grid Zpts == ..\model\Topography\$TGC_TOPO$
```

Figure 14. Screenshot of the TUFLOW Geometry control file template used to define the grid and geometry of the model.

Tool A operates by replace the variables (e.g. $TGC_CELLSIZE$) in the template with the values entered or selected by the user.

The TUFLOW TCF and SWAN templates are setup and used in a similar manner.

5.3.1.2. TUFLOW Tool B – Create the TCF file

The interface of Tool B follows a similar structure to Tool A allowing users to enter and/or select from dropdown lists required values for inclusion in the output TCF file (see Figure 15). This includes selection of TGC (.tgc) files created using Tool A.

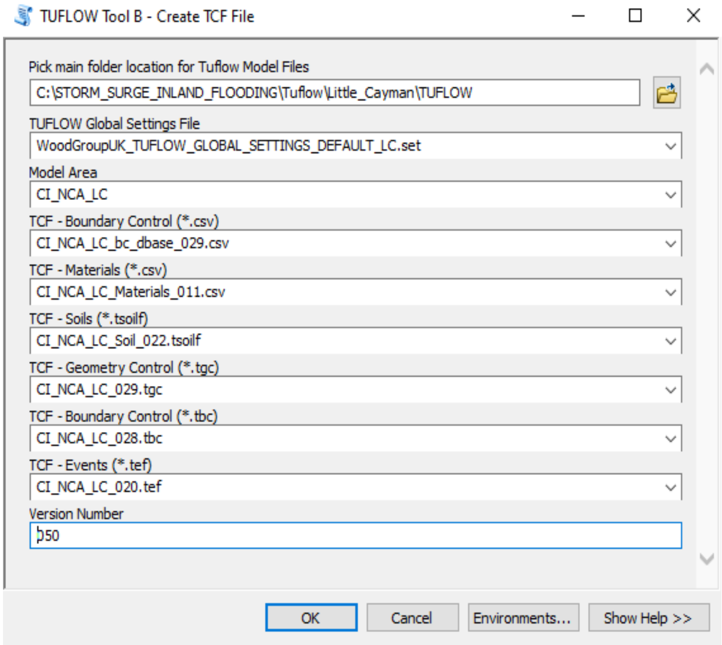


Figure 15 A screenshot of the interface of the TUFLOW Tool B which is used to create a new TCF file which will be used in Tool C to run the model.

After the user selects OK, the related python code will retrieve the TCF template (stored under the templates folder), run a python search / replace routine and create a new TCF file for use in Tool C – Run model.

The new TCF file will be saved in the “runs” sub-folder of the selected TUFLOW model folder.

The next step in the process is to run Tool C.

5.3.1.3. TUFLOW Tool C – Run model

The interface of Tool C also follows a similar structure to Tools A and B and allows the user to run one or more TUFLOW model runs.

The interface allows users to pick a TCF file created using Tool B or prepared manually.

The tool also allows the user to pick either tidal (TDL) or rainfall (RFL) as the primary source (Scenario 1) – see Figure 16. This selection will alter the remaining options presented to the user and enable the selection of additional model run parameters.

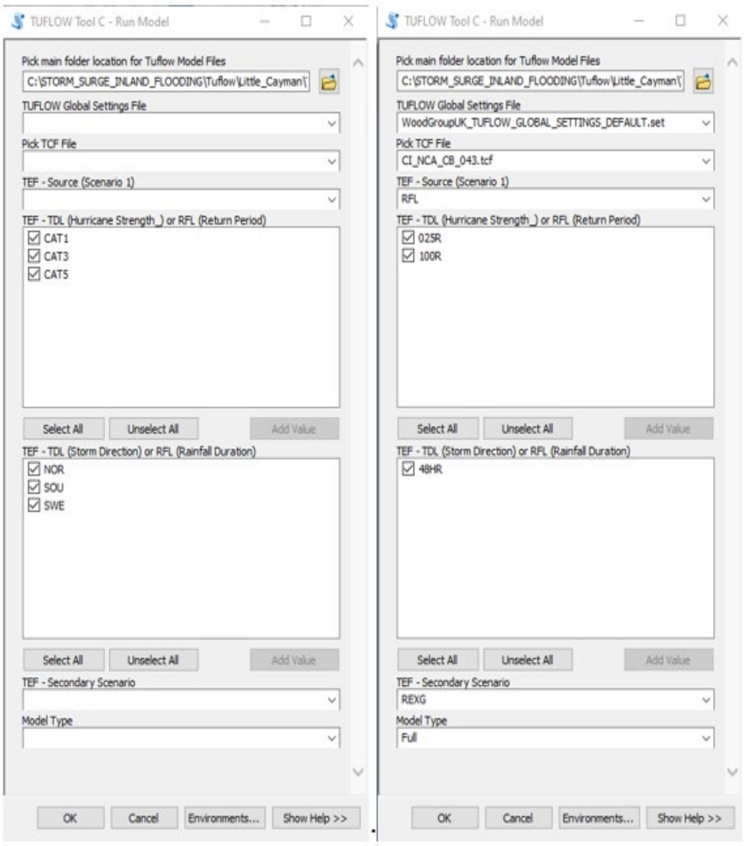


Figure 16. A screenshot showing the interface of TUFLOW Tool C used to run the TUFLOW model.

On selection of OK, the tool will create a TUFLOW batch file based upon the selections and run this using the TUFLOW executable – as set in the Global Settings File.

The output batch file will be written to the “runs” sub-folder of the current model folder location.

5.3.1.4. SWAN ArcGIS toolbox

The ESRI ArcGIS 10.x TUFLOW SWAN Modelling Tools geoprocessing toolbox includes three SWAN processing tools, namely (see also Figure 17, 18 & 20):

- SWAN Tool A – Create SWAN input file
- SWAN Tool B – Run SWAN input file
- SWAN Tool C – Create Grid from Matlab

Please note that running Tool B requires the installation of the SWAN executable and setting of appropriate environmental variables – see earlier section of the report. This may require administrative level permissions dependent on your local IT policies.

5.3.1.5. SWAN Tool A – Create SWAN input file

The interface of the SWAN Tool A (see Figure 9) follows the principles of the TUFLOW model.

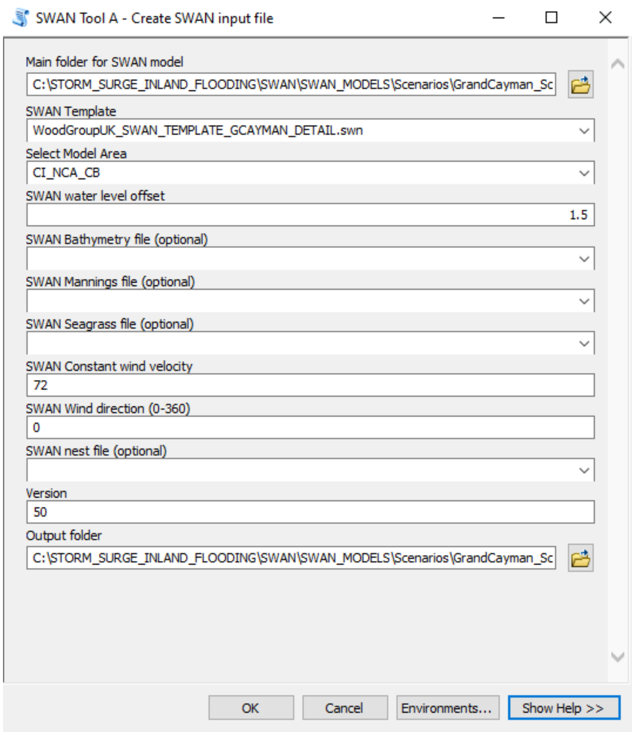


Figure 17: A screenshot of the interface of the SWAN Tool A of the ESRI ARCGIS toolbox used to create the SWAN input file.

The first setting in the model is the most important and requires the selection of a valid SWAN template file. This is located by default in the same location as the ArcGIS toolbox but can be altered if required.

The tool also allows users to enter various values for inclusion in the new SWAN input (.swn) file. Please note that the values are not subject to detailed validation and should be reviewed before progressing

After the user selects OK, the related python code is used to retrieve the SWAN template, run a python search / replace routine and then save a new SWAN input (.swn) file.

The new input file will be saved in the folder defined at the bottom of the form. This is the same folder as the location of the template file

5.3.1.6. SWAN Tool B – Run SWAN input file

The interface of the SWAN Tool B (Figure 18) consists of two user parameters. The first enables the user to pick a local folder containing a SWAN input file and the associated model files needed to run the SWAN model. The second user parameter enables the user to pick a single SWAN input file (.swn) which will be run.

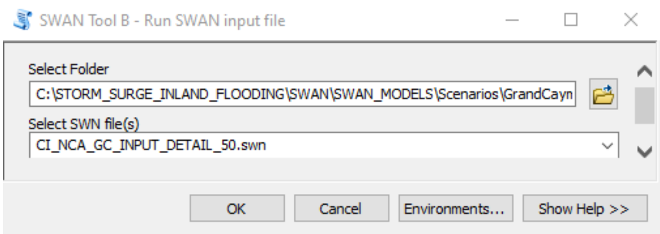


Figure 18. A screenshot of the Tool B of the ESRI ArcGIS SWAN toolbox.

After the user selects OK, the code will generate a batch file to run the selected SWAN input (.swn) file using the SWAN executable. The location of the executable is defined using an environment variable set on the modelling computer.

The SWAN model will then start to run and develop the Matlab (.mat) output – see Figure 19 for example. This output files (.mat and .prt) will be saved in the same folder location selected in the tool interface.

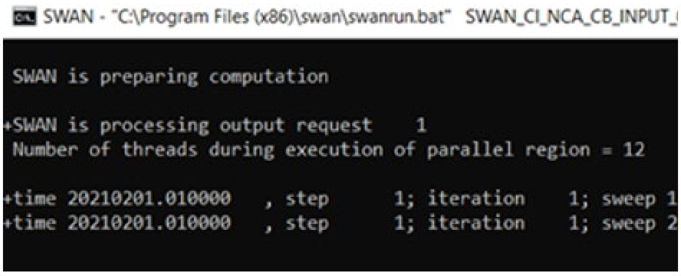


Figure 19. A screenshot of the SWAN model run to create the .mat (Matlab) output.

5.3.1.7. SWAN Tool C – Create Grid from Matlab

The Tool C interface (Figure 20) enables the user to create a final ESRI grid file of wave heights from the MATLAB (.mat) output created from running the SWAN model using Tool B.

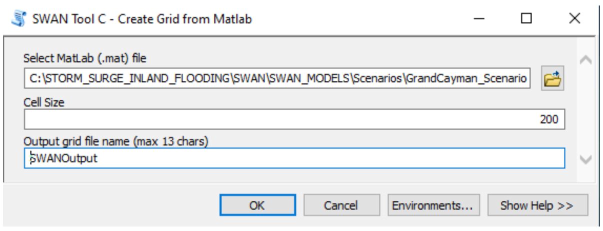


Figure 20. A screenshot of the Tool C of the ESRI ArcGIS SWAN toolbox.

The key processing steps delivered by Tool C are:

- Converts the selected Tool B MATLAB file into a three column (lat, long, wave height) csv file.
- Creates points from the .CSV file using the geographic WGS 84 projection system and reproject the points to the projected WGS84 projection system.
- Creates a final ESRI grid from the projected points. The cell size of the grid is determined by the value entered in the form.

The output GIS grid is saved in the same folder location at the input MATLAB (.mat) file.

5.3.1.8. Economics ArcGIS toolbox

The economics toolbox is split into two elements:Model Aworks out the flood damage per structure, and Model B uses the output to work out the econometric metrics of impact. The damage calculation represents flooding effects on individual structures (buildings) for each inland and coastal flood event. The tool accepts as input:

- the building footprints, with attributes for the number of stories, and building use/function.

- flood depth rasters based on either coastal or inland flooding scenario.
- high vulnerability zone definition (A-Zone).

The calculation tool outputs the damage as a proportion of rebuild cost from the inputs of the flood depth in each building, its number of stories, and a factor for the greater vulnerability nearer the coast. The calculated damage is subsequently valued using market prices.

Model A is implemented using a custom ArcGIS Pro project is setup and an ArcMap 10.8.1. The ArcGIS Pro project contains the following for all three islands in WGS 1984 UTM Zone 17N projection:

- Maps – map window with input data
- Toolboxes: Default toolbox *(Local_Econ.tbx)* which contains the *WSP economic damage model.* Figure 10 illustrated the model builder tool used to process the input data and define the output location. The process is the same for ArcGIS 10.8 except for coding of Python 3 elements for some of the tools in ArcGIS Pro and Python 2.7 in ArcMap.

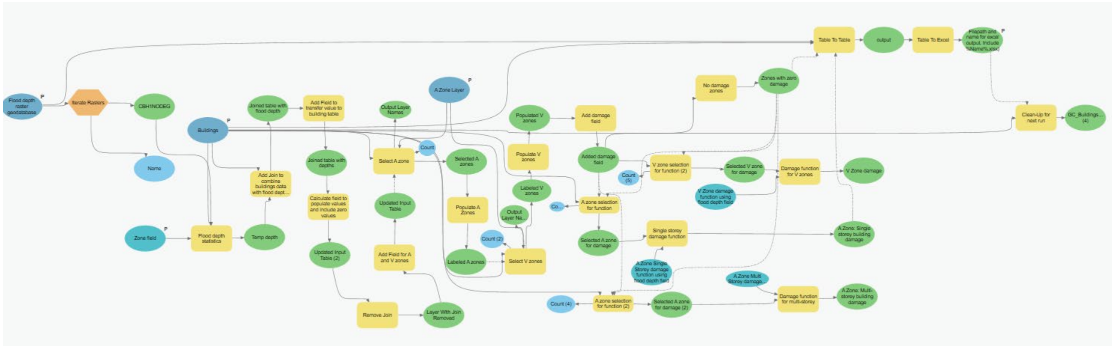


Figure 21. Illustration of WSP economic damage model process in Model Builder for ArcGIS Pro 2.8.

The model is run from a geoprocessing interface and is illustrated in Figure 22. with inputs based on Cayman Brac. The tool uses inline variable substitution to define the filename of the output excel file. The excel output is then used as input to Model B.

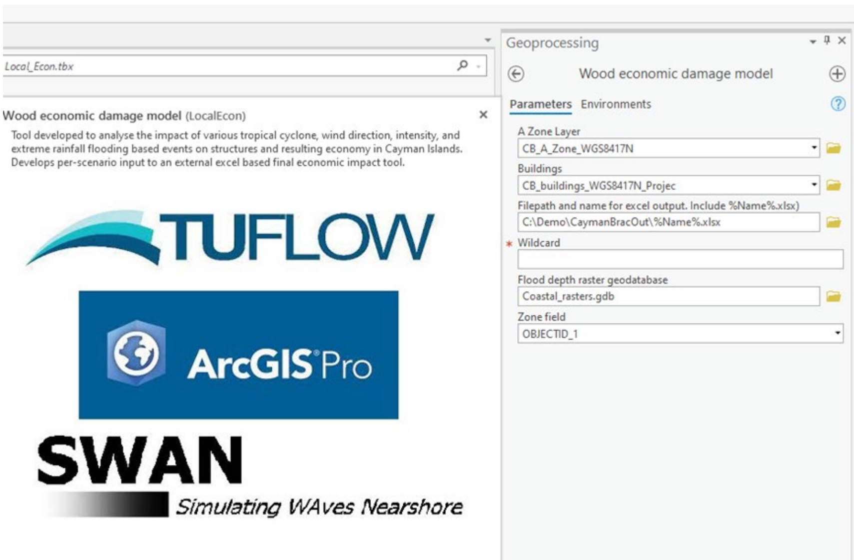


Figure 22. Illustration of the opening of the tool in ArcGIS Pro, with input for Cayman Brac.

5.4. Training manuals

To support the training and future use of the inland and coastal modelling toolboxes accompanying training manuals have been developed (see Appendix C). The objective of manuals is to provide future model users with:

- An overview of the existing model sources and elements, in addition to general modelling theory and background.
- Descriptions of how to undertake possible model updates in the event of new data or should there be the desire to assess a specific scenario using the model.
- An overview of the functionality of the WSP TUFLOW SWAN Toolbox developed.

5.5. Workshops

A five-day, six-session workshop programme was delivered in the offices of the Department of Environment on Grand Cayman via a combination of virtual and face to face delivery. The overall aim of these workshop sessions was to support capacity building and specific objectives were to provide:

- A full overview of the objectives of the project and summarise in simplistic terms the methods adopted to value the role of natural capital in flood protection.
- An overview of the inland and coastal modelling results for verification purposes.
- A detailed guide to the inland and coastal models, the ArcGIS Toolboxes, and how they can be used to run different modelling scenarios.
- The approach to taking the flooding modelling scenario outputs and to undertake a natural capital valuation using the ArcGIS Toolbox A and Excel Toolbox B.
- A facilitated discussion to identify potential locations where nature-based solutions could be implemented and what nature-based solutions could be considered.
- A further review and finalisation of short-term environmental indicators.

Over 10 different representatives attended the workshop sessions during the week from the Department of Environment, Hazard Management and Land and Surveys.

6. Nature-based solutions

The purpose of this activity is to identify natural measures which could be implemented to mitigate coastal and inland flood risk. Nature-based solutions (NbS) make use of natural processes and ecosystem services for functional process such as decreasing flood risk or improving water quality and can be used along-side or in place of traditional engineering-based solutions.

Section 6.1 discusses the first sub-task, which required the development of a prioritised list of potential NbS that could be applied in the Cayman Islands. Section 6.2 encompasses the second sub-task where the opportunity maps generated from the modelling developed in Activities 1 and 2 (themselves further derived from the opportunity maps from Phase 1) were used to identify locations appropriate for implementing a small number of possible NbS.

6.1. Prioritised list of nature-based solutions

A comprehensive review of relevant literature was undertaken to compose a long list of NbS, which included the recent Wolfs Company report on implementing nature-based flood protection and WWFs Natural and Nature Based Flood Management (A Green Guide) (for a full list of sources see Appendix D). Overall, 46 nature-based solutions were identified during the literature review and can be found in Appendix D.

The long list of NbS were screened using Red-Amber-Green (RAG ratings (1 to 3) to determine suitability for implementation in the Cayman Islands. The RAG rating criteria, as presented in Table 6 below, was developed using the IUCN Global Standards for nature-based solutions, in addition to the WWF's report on 'Creating the Conditions to Enable Nature-based Solutions', the EU's 'Nature-based solutions for flood mitigation and coastal resilience' and the Wolfs Company report.

Table 6. Nature-based solution screening criteria.

Screening category	Criteria	Red (1)	Amber (2)	Green (3)
Applicability	Is the NbS relevant to the Cayman Islands? I.e. are the conditions required for the NbS present (such as habitat, geological, topographical, etc.)	Not applicable		Applicable
Scale	Potential scale the proposed NbS could be applied over.	Select locations	Local	Landscape/ seascape
Cost	Potential costs associated with the NbS, qualitatively assessed on assumptions of resource requirements, maintenance, land acquisition, etc.	High	Medium	Low

Screening category	Criteria	Red (1)	Amber (2)	Green (3)
Benefit	Potential extent of flood regulation benefits provided by the NbS option.	Minimal	Moderate	Major
Readiness	Readiness for implementation of NbS. Based on how straight forward the implementation of the NbS would be. For example: Consistent with current policy/ legislation, and environmental goals? Complements existing efforts?	Not easily implemented	Neutral	Easily implemented
Time to realise benefit	Time for ecosystem service benefits to be active, following implementation/ construction.	> 10 yreas	< 5 years	Immediately
Additional ESS benefits	Would the NbS provide any additional benefits, as well as flood regulation? For example, carbon sequestration, groundwater recharge, biodiversity, water quality regulation, etc.	None	Limited additional benefits	Definite additional benefits

The characteristics of the island's habitat and topography, as identified through the modelling activities, were key in ascertaining the applicability of the NbS. In the cases where NbS were identified as being 'Not Applicable', then these potential options were screened out completely on the basis that they would not be suitable for implementation. This was typically due to habitat or topography requirements which were not present across the Islands; for example, perennial watercourses, agriculture, or slopes (leading to high velocity runoff). Flooding pathways are typically not well defined (surface water typically accumulates in situ) in the Cayman Islands and therefore there is limited potential for many of the 'upstream' nature-based solutions that target specific flow paths.

Those that were 'Applicable' were scored either 1 (red), 2 (amber) and 3 (green) for each screening category, using the criteria detailed in Table 6. The scores were based upon the information gathered during the literature review. Finally, the scores were aggregated and then the NbS ranked most suitable (highest aggregated score value) to least suitable (lowest aggregated score value). The findings of the screening activity are summarised below.

6.1.1. Summary of results

The outcome of the screening concludes a short-list of 28 potential nature-based solutions for flood risk mitigation, which could be applied in the Cayman Islands. Of these short-listed nature-based solutions, eight can provide regulation benefits against both coastal and inland flood sources; whilst there are six that can be applied for coastal flood regulation only, and a further 14 which could be specifically used for inland flooding regulation. A summary of the short-listed NbS solutions is provided in Table 7 below; note that the NbS options are listed in order of most suitable to least suitable, based on the outcome of the screening exercise.

The short-listed solutions which were identified to be most suitable are marine and terrestrial protected areas; this is due to the applicability in terms of habitat and scale, in combination with potential benefits and alignment with the Cayman Government ambitions. However, it is recognised that marine protected areas are already in place and offer significant protection to existing coral reefs and mangrove areas.

In terms of coastal flooding, it was identified that setbacks and land-use planning would also be highly suitable for implementation across the Cayman Islands. Both these solutions are non-physical and would require change/development to policy and legislation. Meanwhile, it was found that infiltration, attenuation, and recovery solutions were more suitable solutions to regulate inland flood risk. These include potential solutions such as channel and rills, infiltration trenches, rainwater harvesting and rain gardens. To achieve a resilient and holistic flood management approach it is likely that a combination of these solutions should be applied; potentially alongside engineering based solutions, such as canals, dikes, and levees.

Table 7. Summary of the 28 short-listed Nature-based Solutions.

Nature-based Solution	Inland or coastal flood regulation?	Summary
Marine Protected Areas	Coastal	Establishing Marine Protection Areas improves the resilience of reefs and coastal ecosystems, which subsequently restores and maintains the ecosystem services they provide; by reducing the disturbance caused by human activities (such as fishing). Caymans Coral Reefs have been under protection for since the 1978 Marine Conservation Law and subsequently the formation of Marine Protected Areas since 1986 which include the Marine, Replenishment and Environmental Zones. Existing programmes such as Reef Renewal Cayman Islands currently work to protect and restore reefs across the Islands. There is potential opportunity to enhance the work already being undertaken.
Terrestrial Protection Areas	Inland	Terrestrial Protection Areas protect existing habitat of significant value, which would be applicable where a habitat provides significant flood regulation benefits, such as mangroves, wetlands, and woodlands. These can be implemented in conjunction with Marine Protected Areas, to offer holistic conservation of the landscape and natural processes. Protecting terrestrial habitat also conserves the numerous ecosystem services they provide. The Cayman Island has already implemented Terrestrial Protection Area schemes across the Grand Cayman, Little Cayman and Cayman Brac, totalling and area over 4,000 ha (as of 2018). The Cayman Government has published its ambitions to increase the protected terrestrial areas under the National Conservation Law (NCL).
Channels and rills	Inland	Channels and rills are often used at the start of a SuDS system, as they are shallow open channels (often vegetated) which receive and convey runoff from the adjacent land. They also slow down flows and provide storage for sediment and contaminants. This is a potential NbS that could be applied in rural and urbanised areas of the Cayman Islands. It would provide extremely localised flood regulation benefits, but if applied strategically across the landscape or in development designs can be effective.

Nature-based Solution	Inland or coastal flood regulation?	Summary
Infiltration Trenches	Inland	Infiltration trenches are typically shallow excavations lined with rubble, stone, or rip rap. They receive runoff from adjacent land, which is typically urban areas or transport infrastructure, which is allowed to infiltrate naturally to the underlying soils. Infiltration trenches provide extremely localised benefits, as they draw water from directly adjacent land, which would likely be beneficial in areas experiencing problems of water accumulation.
Swales and rain gardens	Inland	Swales and rain gardens are infiltration devices that intercept surface water runoff and allows attenuated water to infiltrate naturally, recharging the groundwater. Subsequently they reduce the risk from surface water flooding locally. The swales are often vegetated to encourage transpiration, which also offer biodiversity benefits. Individual swales and rain gardens provide extremely localised benefits, as they draw water from directly adjacent land, which would likely be beneficial in areas experiencing problems of water accumulation. It is understood that this is an approach already applied in some instances across the Cayman Islands.
Watershed protection legislation	Inland	Watershed protection legislation enables the conservation of the watershed area, as designated by the governing authority. The policies set out the land-use and activities requirements within the conservation areas. The protection of the watershed area under policy will ensure that the area is not degraded and managed to regulate flooding downstream/slope. Protection of watersheds would require that the activities within the protected areas do not have a detrimental effect on flood risk elsewhere. This could also be aligned with Plan Caymans ambitions for land use and natural resource policies. As well as in environmental and water resource polices, where relevant.

Nature-based Solution	Inland or coastal flood regulation?	Summary
Land use planning	Both	Incorporating flood management into land use planning will ensure that the resulting management approach is holistic and integrated. This is on the basis that land use planning considers the requirements and opinions of relevant stakeholders, so by incorporating flood management into this process it will encourage effective implementation and support of plans/strategies at local, island and national levels. Plan Cayman is an existing land use planning strategy, which could be developed to include flood management priorities and requirements
Setbacks	Coastal	Coastal setbacks provide a buffer area between the coast and any coastal developments. The aim is to provide room for the sea level to rise without causing increased risk to property and development within its lifetime. This also enables the natural erosion processes within the beach ecosystems which enables wide natural beaches. This NbS will require changes to policy and building regulations, however, it has been highlighted as a preferred NbS by the Cayman Island Government. The development of the policy and resourcing to implement may take time to establish, however, it is a suitable approach to flood management across the islands.
Rainwater harvesting	Inland	Rainwater harvesting involves collecting and storing rainwater at source. Water can be harvested from roofs or drainage systems at a local level. Harvesting the rainwater can reduce the volume of surface water run off within urban areas. Water tanks or butts often have small capacities, so fill up quickly during storm events. However, they are typically inexpensive to install and take up little space, so are practical for use in urban areas. Rainwater harvesting would provide extremely localised benefit in the Cayman Islands. Due to the minimal costs and land take, retrofitting into urban areas is feasible. However, as these features provide very limited storage capacities, they are likely to be overfilled quickly in extreme storm events.

Nature-based Solution	Inland or coastal flood regulation?	Summary
Attenuation ponds and detention basins	Inland	Attenuation ponds or detention basins are SuDS features which receive and hold surface water runoff. The ponds/basin allow the water to infiltrate naturally and support an aquatic or semi-aquatic biodiversity. Ponds and basins require high land-take, as such there can be significant costs associated with land acquisition, in addition to not using land for development. Ground investigations are also required for suitability. This option has numerous additional benefits including groundwater recharge, biodiversity, water supply and quality regulation. Due to the geographical nature of the Cayman Islands, attenuation ponds and detention basins will offer somewhat limited flood regulation potential, which provides localised management of surface water flooding. This option has potential to be implemented at island-scale but should be strategically located to provide optimum benefit and to ensure infiltration is acceptable. It should be noted that SuDS schemes are less applicable to the Cayman Islands, as due to the low-lying nature of the islands, hence surface water remains in-situ.
Reef restoration	Coastal	Reefs provide coastline protection from tidal flooding as they dissipate the waves energy, velocity, and height before they reach the shoreline. Many reefs have become degraded (because of unsustainable harvesting, pollution, and diseases) or removed completely due to changes in natural processes. Despite high costs associated with creating new reefs or restoring existing reefs, the approach is cost effective due to the high costs associated with the damage caused by coastal flooding. The reefs also provide multiple additional benefits including seafood provision, biodiversity benefits, water quality regulation and particularly for oyster reefs, the filter nitrogen pollution which can be fatal to marine life. Reef Renewal Cayman Islands works to protect and restore reefs across the Islands. Potentially there is opportunity to enhance the work already being undertaken.

Nature-based Solution	Inland or coastal flood regulation?	Summary
Wetland restoration	Both	Wetlands can store flood waters or intercept flows reducing velocity of flash floods/storm surges. Restoration and improving existing wetland enables the provision of optimum flood regulation, which can be maintained through appropriate management and protection of the habitat. Wetlands offer a range of additional ecosystem service benefits including recreation, water purification and food provision. The National Trust of the Cayman Island undertakes conservation of some existing wetlands (including swaps and marshes). There is potential to align with these efforts.
Mangrove forest restoration	Both	Mangroves stabilise coastlines by trapping sediments in their root systems. The mangroves also provide flood management as they reduce the impact of coastal flooding, by reducing wave height and velocity. And provide additional benefits including climate regulation, water purification and food provision. The Cayman Island Mangrove Rangers are currently undertaking projects, protecting the remaining mangrove forests. There may be potential to align efforts to restore historic forests. Mosquitoes were a key reason for the removal of mangroves initially, which may limit where they can be restored. It is noted that mangroves will take time to establish and provide the optimum benefits, so there will be a delay between creation and benefits"
Seagrass restoration	Coastal	Seagrasses are valuable ecosystems that inhabit shallow coastal waters. In summertime, their dense canopies can significantly slow tidal currents and lower wave energy, thereby reducing sediment resuspension and improving light environments for seagrass growth. There appears to be existing projects to restore seagrasses in the Cayman Islands, however limited information is publicly available.

Nature-based Solution	Inland or coastal flood regulation?	Summary
Mangrove establishment	Both	Mangroves stabilise coastlines by trapping sediments in their root systems. The mangroves also provide flood management as they reduce the impact of coastal flooding, by reducing wave height and velocity. Mangroves also provide additional benefits including climate regulation, water purification and food provision. Mosquitoes were a key reason for the removal of mangroves initially, which may limit where they can be established and must be taken into consideration. The mangroves will take time to establish and provide the optimum benefits, so there will be a delay between creation and benefits. It is also noted that the Species Conservation Plan for Mangroves would apply to any mangrove habitat created or restored, which supports the species named in the plan. As such, this NbS could aid the Government in achieving their Mangrove conservation objectives.
Building codes	Both	Urbanisation of the coastline, wetlands or floodplains can increase flood risk to the development itself or elsewhere. By enforcing building codes and regulations it is ensured that coastal developments do not contribute to flooding and erosion and are themselves protected from the risks posed by natural hazards. There are existing building codes enforced in the Cayman Islands, but these do not address flood risk or resilience. The addition of flood resilience requirements, relating to location, land cover, green infrastructure, etc., could be included in these codes. Resources will be required to develop and enforce these codes, which will extend the time to realise the benefits. There are potential for additional ESS benefits which could arise from habitat protection or green infrastructure.
Green roofs	Inland	Vegetation covering roofs or drainage areas are known as Green Roofs. Rainfall is intercepted, stored, and discharged at reduced rates from the roofs. This reduces the runoff within urban areas and subsequent flow velocities. This is a potential NbS that could be applied in urbanised areas of the Cayman Islands. It would provide extremely localised flood regulation benefits, but if applied strategically across the landscape or in development designs (as part of a SuDS scheme) can be effective.

Nature-based Solution	Inland or coastal flood regulation?	Summary
Urban trees	Inland	Trees provide a variety of services which support flood regulation such as enhanced infiltration, rainfall interception and slowing of overland flows. In addition to air quality regulation, carbon storage and biodiversity. Urban trees provide similar benefits but to a lesser extent. Much of the urban regions across the Cayman Islands include vegetated areas. Aerial imagery indicates that this is mainly shrub habitats, but also urban trees and minor areas of urban woodland. As these types of green infrastructure are already established, it may be more appropriate to investigate how these assets could be enhanced to improve flood regulation provision.
Wetland establishment	Both	Establishing wetlands requires the modification of current habitat to restore the natural functions and processes that support the wetland ecosystems. This approach increases wetland area and provides additional storage area to manage potential flood waters. The cost associated with re-establishment are typically higher than restoration, as the habitat must be created to begin with, which requires land acquisition as well as long-term maintenance. Wetlands can take at least 10 years to establish, so benefits would take a considerable time to be fully realised. Much of the removed wetland habitat in the Cayman Islands has been done so for development and to manage the mosquito population in urbanised areas. Mosquitoes pose a considerable health and well-being risk, due to the diseases they carry, so re-establishment of wetlands near to developed areas would be avoided to protect society.
Permeable surfaces	Inland	Much of the surface areas in urban regions is impermeable and infiltration is greatly reduced. Permeable surfaces such as paving can enable infiltration of surface water through the to the ground below. This reduces the runoff retention on the surface and subsequently surface water flooding. According to the Environment Agency permeable surfaces cost less during its life cycle than normal materials. However, additional costs such as land remediation, may make this approach more expensive. This is a potential NbS that could be applied in many urbanised areas of the Cayman Islands. It would provide localised flood regulation benefits, as surface water would be managed in-situ.

Nature-based Solution	Inland or coastal flood regulation?	Summary
Sponge cities	Inland	By creating wetlands, greenspaces and utilising floodplains throughout cities; rainfall and surface water can be absorbed before it submerges the surface within urban areas. These features can improve water attenuation and infiltration within urban areas, reducing the risk of flooding from surface water. Sponge cities are a cost-effective, long-term solution to flood management within urban areas. Additional benefits include air quality regulation, water purification, recreation, and water supply. Much of the urbanised areas of the Cayman Islands supports areas of vegetation, however, these features are not necessarily intended to mitigate flood risk or provide surface water management. There may be potential to enhance these areas for drainage and flood management purposes. The concept of Sponge Cities could also be incorporated into the requirements of new developments. Plan Cayman does include ambitions for green infrastructure, so is there potential to build upon these objectives with more specific targets relating to flood management and drainage.
Buffer strips and hedges/ boundaries	Inland	Buffer strips and hedges are margins (of typically agricultural fields or transport infrastructure) of natural habitat, which can vary from grassland, shrubland or even woodland. These areas can intercept the runoff from the adjacent land, which is stored or slowed. Limited flood risk applicability given low-lying nature of islands - rather than rainwater running off field downstream it tends to stay in situ. It would provide extremely localised flood regulation benefits. It is not typically an approach used across the Cayman Islands, so may take time to establish the approach. The features will also take time to establish and provide the optimum benefits.

Nature-based Solution	Inland or coastal flood regulation?	Summary
Lake restoration	Both	Historically lake modifications have been undertaken to drain land for agriculture or have not been sufficiently maintained. Lake restoration involves the enhancement of structure and function, by reversing the modifications or impacts. Where wetland/mangroves have been historically drained, there may be some potential for re-establishment of natural functions. Whilst there will be limited inland flood regulation benefits, there is potential for greater coastal flood regulation ESS. Also potential for provision of numerous wider ESS benefits.
Training and education of nature-based solutions	Both	Training and education of nature-based solutions for flood management, will encourage the use of these approaches when preparing for and mitigating flood risk. Strategic training, focusing on individuals, such as government agencies, local authorities, developers, non-profit organisations, enables a holistic approach nature-based solution. There are existing organisations and groups in the Cayman Islands (such as Protect Our Future and the National Trust) who offer educational programmes, typically to youth groups or schools.
Continuous cover forestry	Inland	Continuous cover forestry is a forest management approach, which avoids clear cutting extents within a woodland area. The main aim is that tree canopy is not interrupted, and the soil surface is not exposed. The protection of the soil structure and infiltration rate, as well as rainfall interception by the canopy will provide flood regulation benefits. It is expected that the costs of continuous cover forestry will be like existing approaches. Modelling outputs from this project have shown that this option is likely to have only minor flood benefit. The requirements of this option are negligible as it is mainly dependent on a change of management and resource extraction practices, and although the potential flood regulation benefits may be somewhat limited this option potential to provide numerous wider ESS benefits.

Nature-based Solution	Inland or coastal flood regulation?	Summary
Woodland re-establishment.	Inland	Strategic planning and management of woodland can reduce flooding downstream; as the woodland intercept's rainfall, slows down surface water flows and reduces erosion. Dependent on the scale of planting required, the cost of the NbS will vary. Large scale planting will inevitably be more expensive during creation and maintenance. However, it is beneficial for carbon storage, biodiversity, wood resources, water purification, erosion control, etc. Dry tropical woodlands within the Cayman Islands are under pressure from disturbance and timber extraction. As such they are classified under critical/endangered status. However, in line with the Phase 1 modelling it is suggested that there is limited applicability in terms of a flood risk perspective, due to the flooding conditions and topographical nature of the Cayman Islands. Despite this there are numerous wider ESS benefits.
Beach nourishment	Coastal	Beach nourishment is an approach to counter the effects of longshore drift or erosion, where the lost materials are replaced artificially. Often the materials are dredged from the seabed or from nearby streams, causing disruption to other habitats. It is not considered to be a cost effective approach due to the high costs of the dredging and machinery, as well as the disruption to tourism. It will also need ongoing maintenance and monitoring, which will also have cost implications. There are some considerable disbenefits associated with this option, mainly associated with the methods of material recovery (dredging and excavations) which lead to loss of habitat and biodiversity. It is also only a temporary solution which must be repeated to maintain effectiveness, so it is not considered to be sustainable.

Nature-based Solution	Inland or coastal flood regulation?	Summary
Sand dunes restoration	Coastal	Sand dunes intercept tidal flooding, dissipating waves, and tidal energy, they also release sediment to the beach during tidal flooding which rebuilds the dunes via wind transfer. Restoration of sand dunes requires stabilising and increasing the height of the dunes. Reducing the erosion of the sand through fencing, thatching or vegetation are the primary techniques for sand dune restoration. Costs are associated with reprofiling or recharge, the stabilisation works will also have moderate costs, the dunes will also require ongoing maintenance and monitoring. There is very limited area of sand dune habitat on Little Cayman and Cayman Brac, with none being observed on Grand Cayman. Therefore, the scale this NbS solution could be applied at is very limited.

6.2. Identification of areas

A series of discussions were undertaken between the project team and the Department of Environment to identify potential areas where NbS could be focused. The outputs of the flood modelling were used to direct these conversations and particularly the differences to flood extent and depth between baseline and degraded scenarios.

6.2.1. Inland

A high-level screening assessment has been carried out across each of the islands to identify potential locations for NbS implementation. This has been carried out based on the inland flood modelling results as described in Section 4.1, and review of existing land use and topography.

6.2.1.1. Grand Cayman

A key feature on Grand Cayman is the incidence of ponds and wetlands adjacent to populated areas and towns (as shown in Figure 23). Such features serve a significant role in terms of flood water storage, and therefore the protection of existing ponds and wetlands is a key NbS. Review of the inland modelling results suggests several locations where protection of existing features could provide flood attenuation benefit, amongst others. These include the Matilde ponds and wetlands (Prospect), South Sound Basin (George Town), Jacksons Pond (West Bay), Mount Pleasant, Meagre Bay, and Bodden Town.

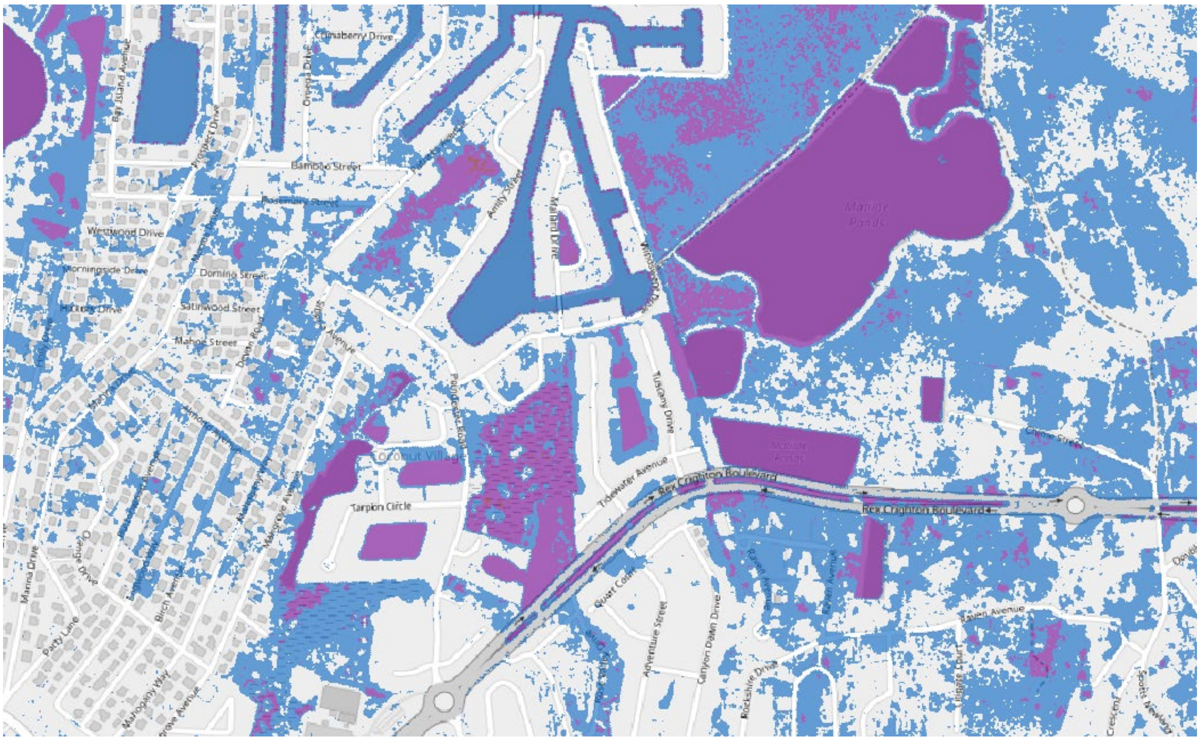


Figure 23: Existing ponds and wetlands adjacent to Prospect.

In localised regions of urban surface water flooding (Figure 24), a series of smaller-scale NbS could be implemented. These would include channels and rills, infiltration trenches, permeable surfaces and green roofs, which could be implemented to provide localised flood attenuation benefits in lower magnitude events. Review of the inland flood modelling results suggests urban regions of Prospect, North Sound, George Town, and Bodden Town would be applicable for small scale NbS.

Figure 24: Surface water flooding across North Sound Estates.

6.2.1.2. Little Cayman

Similarly to Grand Cayman, there are numerous coastal ponds and wetlands where protection could be sought. Booby Pond, Jackson Pond, Tarpon Lake and the Easterly Ponds all provide significant flood water storage in storm events, amongst other wider benefits.

The central portion of island is largely undeveloped; however, this would benefit from land-use planning regulations and building codes to ensure that any new developments avoid mapped regions of surface water flood risk. Review of satellite imagery indicates new road developments on the western side of Spot Bay Road, North of Blossom Village which intersect a region of mapped surface water flood risk (Figure 25).

Elsewhere across the island, there is typically minimal intersection between existing developments and mapped regions if surface water flood risk. However, some of the small scale NbS including channels and rills, swales and rain gardens, attenuation ponds and permeable surfaces could be applicable in localised regions of surface water flooding and drainage issues.

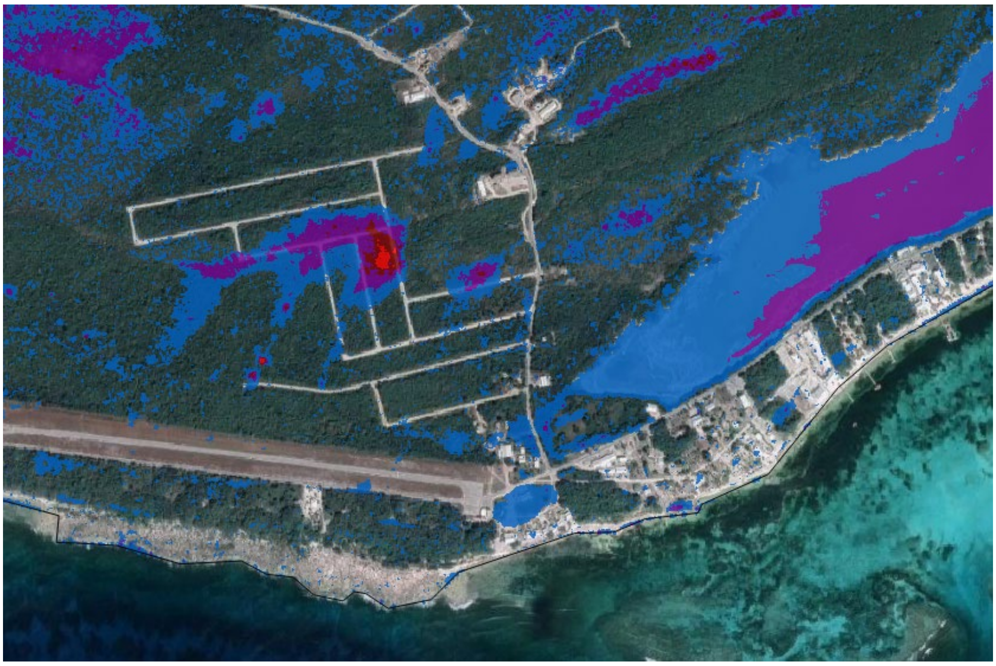


Figure 25: Spot Bay Road development.

6.2.1.3. Cayman Brac

Cayman Brac is characterised by extensive surface water flooding along the low-lying developments on the north coast, as seen in Figure 26. In such areas, the establishment of formal wetlands and infiltration trenches could provide some localised flood risk benefit to provide additional storage and draw floodwater away from existing properties and infrastructure. This could be further supplemented with land-use planning, the implementation of channels and rills, swales and rain gardens.

Elsewhere across the island, there are several existing ponds and wetlands in the south-west portion of the island which would benefit from land use planning and protection. The westerly ponds adjacent to the airport store significant volumes of floodwater during storm events.

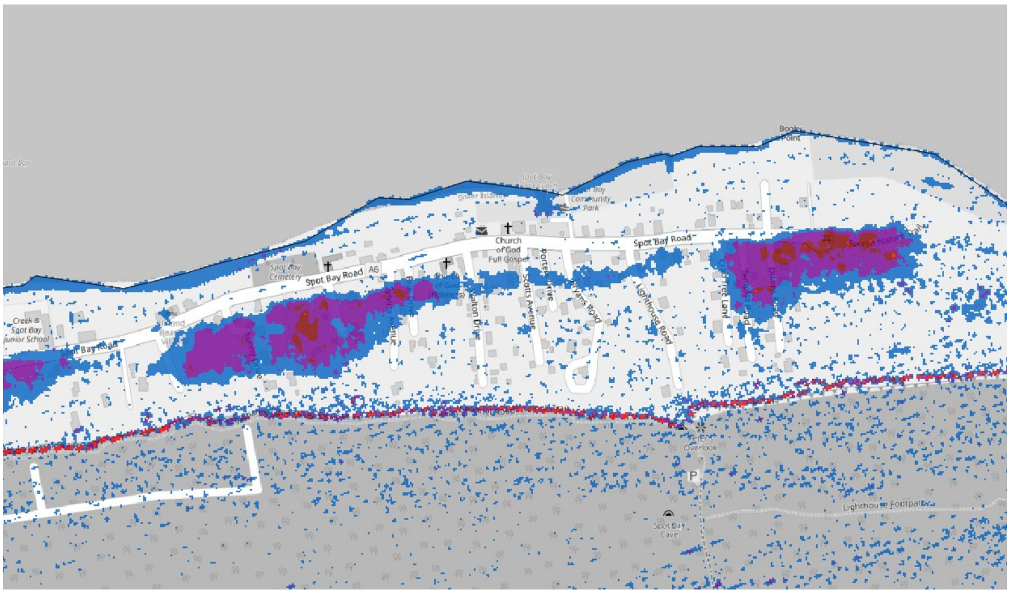


Figure 26: Cayman Brac north coast.

6.2.1.4. Coastal

Identification of potential locations where NbS could be located to mitigate coastal flooding focused on Grand Cayman where infrastructure is most extensive. The coastal flood modelling results (presented in Appendix B) were used to inform this analysis and particularly for the Category 1 events, which are reproduced and shown in Figure 27.

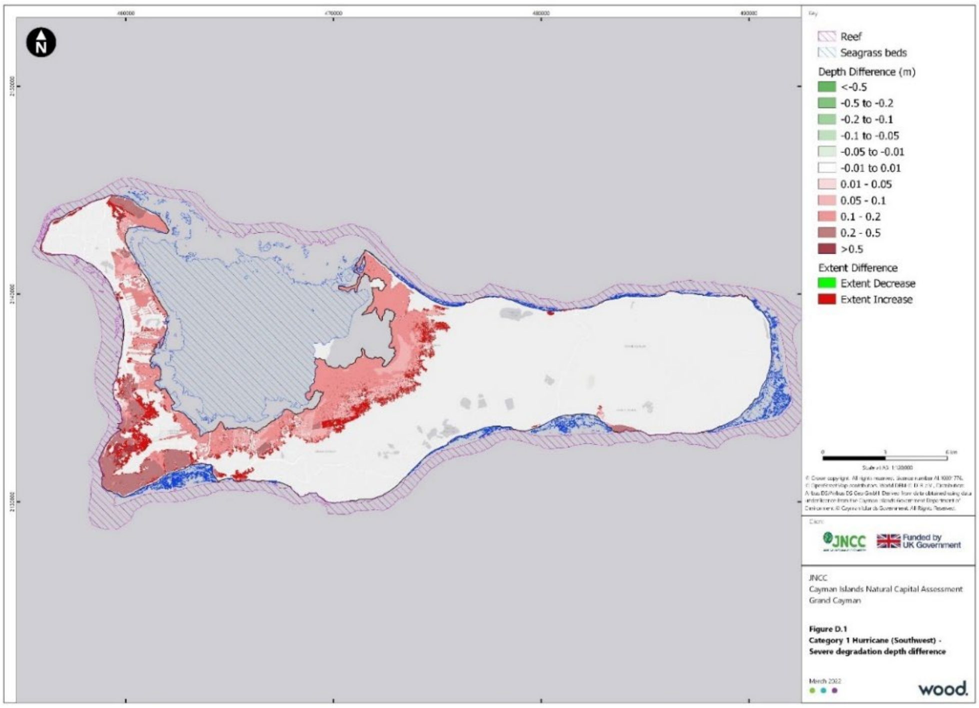


Figure 27: Grand Cayman Category 1 (south-west) Severe Degradation depth difference.

The depth difference map highlights the greatest increase in flood depths and additional flood extent from the degradation of natural capital are in areas to the south-west of George Town and around South Sound where there is also substantial infrastructure. There are also large areas to the south and east of North Sound, recognising to the east there is minimal infrastructure present. However, the existing Marine Park, Environmental and Replenishment Zones established as part of the Marine Protection Zones already offer significant protection to the coral reefs and mangroves in these areas. The health of the coral reefs are being impacted through changes in sea temperature and ocean acidification because of climate change and through disease such as stony coral tissue loss which are broad scale issues. Targeted options could be investigated such as:

- coral reef restoration to address areas of high coral ill health;
- prevention of point sources of pollution, such as the culvert in the South Sound, through the use of schemes such as wetlands which could capture pollutants;
- beach restoration such as at the southern end of South Mile Beach;
- through mitigating the impact of flooding on infrastructure by taking a climate resilient approach through changes to the current high water mark setback rules. At present site-specific considerations are not considered rather a blanket setback approach is used for generalised categories of beaches, ironshore or mangrove coastlines. The setback could be influenced by localised physical characteristics such as offshore marine environment, historic erosion rates, historic or predicted extreme water levels.

7. Environmental Indicators

7.1. Background and context

The development of indicators for the purposes of consistent environmental monitoring is strongly related to the development of effective environmental policy. The UK Government provides support to the Overseas Territories to manage their environment, and to enhance economic security and disaster resilience through a variety of policy initiatives and funding programmes. In 2018, the UK government introduced the 25 Year Environment Plan (25YEP) to develop a comprehensive set of indicators, which collectively describes environmental change. The indicators have been developed primarily for UK reporting but include the role of the UK internationally and have potential application in the Overseas Territories.

The Cayman Islands are vulnerable to extreme weather events and natural hazards, as illustrated by the effects of Hurricane Ivan. Natural disasters, such as hurricanes and storm surges have been shown to cause extensive environmental damage over very short timescales. In this context, it is advantageous to consider a range of short-term indicators which can be used in the context of damages assessment as a response to short-term shocks.

7.2. Approach

A list of Environmental Indicators developed through this activity have been designed to provide a comprehensive insight into the damages to the environment, which occur during such events, and the response that follows.

The approach taken to develop the Environmental Indicators followed three stages and utilised a set of short-term environmental indicators developed previously for the British Virgin Islands (Wood 2019) as a starting point.

The first stage sought to gain the view and opinion from different representatives of the Cayman Islands Government to gain insight to identify important indicators in the context of the Cayman Islands. A questionnaire was developed for remote consultation with stakeholders for completion. The questionnaire covered two main sections relating to:

- The current state of environmental monitoring in the Cayman Islands. Asking stakeholders what kind of environmental monitoring is currently being undertaken in the Cayman Islands, what environmental indicators they would like to see in the future and how adequate monitoring currently is.
- Short term environmental indicators. Asked stakeholders to rank the importance of 5 headline indicator areas (Marine, estuary and coastal; Land; resilience to natural hazards; exposure to harmful chemicals; and freshwater) and to identify any specific headline areas that are absent and could be included in addition to specific indicators that should be considered.

Taking feedback from the returned questionnaires, the second stage updated the draft set of short-term indicators ready for a detailed review.

In the third stage, an Environmental Indicators workshop session was held with representatives participating from the Departments of the Environment and Hazard Management reviewed the draft indicators to ensure they reflect the environmental priorities and encapsulated a targeted set of environmental pressures, assets and services. These draft indicators were reviewed for a second time during the workshop programme in the Cayman Islands undertaken in March 2022.

7.3. Results

Through the response to the remote consultation questionnaire, the following headline indicator categories were determined to be priority areas for monitoring:

- Freshwater.
- Marine, estuarine and coastal.
- Land.
- Air.

The workshop session and subsequent additional review enables the draft list of short-term Indicators to be refined. This resulted in a list of 17 short-term indicators which are summarised in Table 8. The detailed list of short-term Environmental Indicators is presented in Appendix E, where recommendations (including potential metrics, methodologies, monitoring frequencies and costs) are provided.

Table 8. Potential short-term post-disaster Environmental Indicators.

Headline Area	Potential Indicator
Freshwater	Freshwater pond and wetland extent
Freshwater	Groundwater quality
Freshwater	Stormwater flooding (also see resilience)
Marine, estuarine and coastal	Pollution loads entering marine waters (e.g. N, P, BOD, pH, Salinity and thermal pollution, turbidity, sediment (TSS), chemicals (e.g. heavy metals hydrocarbons, faecal coliform, temperature))
Marine, estuarine and coastal	Bathing water quality
Marine, estuarine and coastal	Seafood contamination
Marine, estuarine and coastal	Condition of marine areas inside and outside national parks and protected areas
Marine, estuarine and coastal	Population of key endemic and Red List species
Marine, estuarine and coastal	Coastal erosion: changes in beach area and coastal profile depth
Marine, estuarine and coastal	Coastal flooding (see also resilience)

Headline Area	Potential Indicator
Marine, estuarine and coastal	Marine litter occurrence (Clean Seas Marine Litter) – wreaks
Marine, estuarine and coastal	Marine litter occurrence (Clean Seas Marine Litter)
Land	Population of key species (to be defined)
Land	Contamination of local foodstuffs
Land	Condition of national park and protected areas
Land	Extent, condition, and connectivity of habitat (e.g. forests, wetlands, agriculture, wetlands)
Air	Concentration of key pollutants in addition to GHGs: NOx, SOx, soot, fine particulate matter (PM2.5), other.

8. Conclusions

8.1. Inland flooding

The inland TUFLOW hydraulic models developed for Phase 1 (Wood, 2021) of the project have been further refined incorporating a high-resolution LiDAR dataset and an improved representation of the high infiltration rates across the islands associated with the underlying limestone geology. The updated model outputs provide a significant improvement in terms of the accuracy and confidence in the model results. The flood extents now match with anecdotal observations of flooding on island. The outputs from the island-wide model have a wide range of applications in land-use planning, hazard management, emergency response and public awareness, and the incorporation of the high-resolution LiDAR data opens numerous further possible applications of the existing models.

The refined models have been run for both the baseline and broad scale degraded natural capital scenarios as defined in Phase 1 of the project, for events of 4% AEP and 1% AEP. Updated baseline results across the islands are markedly different to those presented in Phase 1 because of the improved DTM. The updated results provide a significantly improved depiction of flood risk at small scales, given the representation of local topography features such as road embankments and individual developments. The range of depths observed is broadly similar at an island-wide level, although significant reductions in peak flood depths are simulated where the infiltration parameters have been updated across the Bluff Group. This is most notable across the eastern portion of Grand Cayman, and the central portions of Little Cayman and Cayman Brac.

In the degraded scenarios with reduced mangrove cover, a similar trend has been observed to the Phase 1 results. The associated reduction in Manning's roughness values in some cases is anticipated to improve conveyance of surface water, resulting in reductions in peak flood depth along the flow paths. The most notable flood depth reductions are anticipated across areas know to be underlain by the Bluff Group geology in instances where mangrove has theoretically been converted to grassland. Mangrove based land covers have been parameterised as impermeable within the model assuming a waterlogged state, hence, the conversion to grassland results in a significant increase in infiltration losses which outweigh any reduction in rainfall losses associated with the land cover change. Anticipated depth increases are typically minor, given the low-lying nature of the islands rainfall typically accumulates in situ, and therefore there is limited potential for a cumulative impact of increased surface water runoff downstream to be observed.

8.2. Coastal flooding

The coastal SWAN wave model developed for Phase 1 (Wood, 2021) of the project has been enhanced through three key developments. Firstly, the storm surge water level offsets for hurricane wind scenarios have been adjusted. Secondly, the effect of seagrass on wave dissipation has been included into the model. These changes were included after valuable input from the local stakeholders regarding observed flooding during past hurricane events as well as local knowledge of the importance of seagrass on the coastal dynamics. Thirdly, the outputs from the updated SWAN wave model have been processed to form synthetic coastal flood boundary conditions which are then applied to the high-resolution inland TUFLOW models.

The respective increased water level offset of 1.0, 1.5, and 3.0 for hurricane forcing of Category 1, 3, and 5 resulted in larger waves that penetrate further inland. This is due to the additional water depth over which waves can grow larger before breaking, and a larger inland flood extent over which these waves can propagate. The inclusion of seagrass resulted in a localized decrease of wave heights in the areas with seagrass coverage, this being the densest in the North Sound region. Thus, the largest effect of seagrass energy dissipation and coastal protection is in the North Sound. The coupling of the SWAN outputs to the TUFLOW model further improves the confidence in the results due to the high-resolution topography captured within TUFLOW.

The updated TUFLOW results typically predict a reduced flood extent relative to the SWAN outputs, which can be explained by the finer resolution of the TUFLOW model, the inclusion of a temporal element to the storm surge and representation of infiltration within TUFLOW. The baseline results for Grand Cayman indicate that the southwest portion of George Town and the coastline developments fringing the North Sound are at particular risk of coastal flooding. A southwest storm direction was deemed to be the worst-case scenario to the island and provided the greatest flood extent across the urban region of George Town. Generally minimal inundation is anticipated across the entire eastern portion of the island.

Across both Little Cayman and Cayman Brac, a northern storm direction was deemed to provide the worst-case scenario to the islands. The low-lying communities along north coast of Little Cayman are anticipated to be at risk of coastal flooding in Category 1 and 3 storms, whilst floodwater is predicted to breach into the central portions of the island in a Category 5 storm. Similarly, the low-lying communities along the north coast of Cayman Brac between the Bluff and coastline are shown to be at significant risk of coastal flooding, particularly at North East Bay and West End. The south coast of the island is anticipated to remain largely unimpacted in storm events of less than Category 5.

The impact of natural capital degradation on flood risk from coastal flooding is anticipated to be most significant across Grand Cayman, given the abundant coverage of surrounding reefs. Typically, only minor impact has been predicted across both Little Cayman and Cayman Brac. The greatest relative impact is shown to be for lower magnitude events. The inland inundation peak depth differences show typically minor differences for the degraded and enhanced scenarios represented by a change in roughness parameterisation only. In the severe degradation scenario, however, the anticipated impact to inland flood inundation is more significant. Widespread depth increases of 0.10 m to 0.50 m are anticipated across the southwest portion of George Town, and notable increases to flood extent are predicted which results in an increased number of properties inundated.

8.3. Economic valuation

The economic valuation is based on the difference in costs arising from storms modelled in the baseline, with natural capital in current condition and in hypothetical scenarios where natural capital is degraded and severely degraded. The value of maintaining the current conditions is that the additional costs in the degraded conditions are avoided and this can be seen as a benefit which can be quantified in economic terms.

The costs used in the valuation cover two types:

- Costs of damage to buildings and contents, which are quantified based on authoritative and established standard methods which use the detailed flooding results as inputs.
- Costs of business interruption, which are quantified by identifying the use of a building and estimating the period of lost profits (1 year).

The first type of costs (damage) is closely linked to the flooding impacts and cover the costs of repair and restitution for building owners and occupiers. The valuation method is commonly used and reflects significant long-term research by the insurance industry on claims histories. Apart from flood depth, it uses average construction costs (per m^2) on the Cayman Islands, which are obtained from a recent review across the Caribbean.

The second type of costs (business interruption) is a generic approach assuming that businesses lose profits but can mitigate (and so do not incur) any other costs. The method is clear but is also based on averages, with business types represented by the reported building use across broad categories with, for example, all hotels treated as a single category.

In principle, a range of other types of costs may occur, ranging from mental health damage to loss of reputation as a tourism venue but common practice is to consider only damage costs. With the desire to increase the accuracy of estimates, and as the datasets improve, the addition of business interruption losses is increasingly also considered and is included here. The effect of this representation of costs is that the estimates here are partial and intrinsically low, as the types of costs not included do not currently have easily applicable methods and datasets.

The economic valuation also depends on level of degradation. The level of annual benefit for the Cayman Islands ranges from CI$7.6 million if the reefs avoid being degraded to CI$75.0 million if they avoid being severely degraded. Most of this value reflects impacts on Grand Cayman where the corresponding benefits range from CI$7.3 million to CI$74.6 million.

For comparison, the value of CI$74.6 million is equivalent to approximately 30% of the annual value added in the Cayman Islands hotels and restaurants sector and this provides an indication of the scale of the ongoing benefit provided by reefs which avoid severe degradation.

8.4. Tool development and capacity building

A bespoke ESRI ArcGIS geoprocessing toolbox has been developed to facilitate the running of the inland TUFLOW and SWAN model as well as a coupled ArcGIS toolbox and excel toolbox to undertake the economic valuation. These toolboxes allow the user to investigate the economic impact to future scenarios of natural capital status and extreme weather events.

A week-long workshop programme was delivered to staff across the Departments of Environment, Hazard Management and Land and Surveys. Sessions included a summary of the methodologies and process flow required to undertake an economic assessment, detailed training of how to use the SWAN, TUFLOW and economic models and detailed discussions on short term environmental indicators and nature-based solutions.

8.5. Nature based solutions and short-term environmental indicators

A long list of potential NbS which could be implemented in the Cayman Island was developed and following a process of screening resulted in 28 priority NbS being identified which included both policy level and target technical solutions. Discussions were held with the Department of Environment providing preliminary ideas for where NbS could be targeted and those solutions most applicable. Maintenance and where possible restoration of offshore natural capital such as reef, mangroves and sea grass was recommended. For inland flooding the application of smaller scale NbS in urban developments, either retrofit, or as part of new development was discussed. It is acknowledged that the Department of Environment can only force the application of this type of measure in urban areas so far, other key Government departments need to be bought on board to understand the benefits. For existing un-developed area where possible maintenance and enhancement of existing natural capital through NbS was recommended, but again it is understood that this relies heavily on the buy-in of landowners and as such they also need to be bought into the benefits of the implementation of NbS and the value of natural capital.

Through a process of consultation with stakeholders four headline indicator categories were identified as being of most importance for response to short-term shocks in the context of damage assessment. These are ‘air’, ‘land’, ‘freshwater’ and ‘marine, estuarine and coastal’. Across these four headline indicator categories a total of 17 environmental indicators have been defined including potential metrics, methodologies for post-damage short term monitoring and monitoring frequencies.

8.6. Recommendations

The following recommendations are made:

- The model provides a step-change in accuracy in representing the impacts of natural capital on flooding in the Cayman Islands and in methods of minimising human impacts and is available as a tool to be used on-island. As such it may provide wide benefits across communities in the Cayman Islands, informing developers and planners, as well as the general public. It is recommended to be used generally to inform all decisions where potential flooding may be an issue, which, in the Cayman Islands, is likely to be in many areas.
- The models can be used to investigate the impacts of the resilience to flooding of existing infrastructure and future development and land use change. For example, in mangrove regions such as the South Sound basin, assessment of changing land cover to ‘urban’ may be a clear method of providing information relevant to the locality and to individual developments within it.
- Introduction of the model to a range of audiences and forums in the Cayman Islands will enhance its general acceptability which will allow it to achieve the full range of possible benefits. It is recommended that workshops with different groups are conducted to introduce them to its general capabilities, showing, for example the importance of impacts on individual land plots and on the neighbouring areas. Running these workshops separately for groups such as land developers, infrastructure operators, and economic sectors as hotels would enable them to avoid conflict over use and understand the capabilities within a benign learning environment.
- Across government, the range of uses covers applications in land-use planning, hazard management, emergency response and in driving public awareness, and users may benefit from workshops with specific geographic, societal, or functional focuses. It is recommended that a potential roll-out plan is prepared to explain results and capability to government. Users from this group are likely to provide core expertise and experience within and outside government.
- On a technical level, incorporation of the high-resolution LiDAR data into the models will allow numerous potential applications at the detailed geographic level. Knowledge sharing workshops and awareness campaigns are recommended to integrate the model with policy making and management perspectives based on the rapidly growing set of datasets used across the Cayman Islands government.

- The economic benefits resulting from better knowledge of flooding are key to political decision making. It is recommended to link and confirm use of data with ministries responsible for finance and economic planning to enable results to be developed on a consistent basis with them and used in government budgeting as well as to provide a robust basis for political decisions.

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Appendices

The appendices for this report are available as separate resources. A summary is provided below:

- **Appendix A. Inland modelling results:** Inland flood depth results for baseline and degraded scenarios for Grand Cayman, Cayman Brac and Little Cayman.
- **Appendix B. Coastal modelling results:** Coastal inundation results for baseline and natural capital scenarios for Grand Cayman, Cayman Brac and Little Cayman
- **Appendix C.** Inland and Coastal Flood Model Manuals**:** Guidance manuals for the **TuFlow model** (inland flooding) and the **SWAN model** (wave model for coastal flooding.
- **Appendix D. Nature-based Solutions:** A full list of sources used in the literature review to identify nature-based solutions.
- **Appendix E. Environmental Indicators:** A detailed list of short-term Environmental Indicators.

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