Using radar based terrain mapping to model the vulnerability of 5 UK OTs

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1. Introduction

This work is part of an ongoing project to build capacity and knowledge in the Overseas Territories (OTs) on the potential use and applications of new types of Remote Sensing (RS) to enable better understanding of the environment and the role it plays in supporting the economy of the islands. In addition the project considers how to enhance the skills of those in the OTs in analysing the data using open source analysis techniques, which are accessible with minimal costs.

Fundamental data about the spatial distribution of key environmental variables for the OTs, such as elevation and land cover, are often not available, out of date, or incomplete in their coverage. Where it is available, it is often at an inappropriate scale for mapping and monitoring. This project considers the latest RS data, including terrain data, and how this can be used by the government agencies in the OTs to implement mapping and modelling of risks in regards to climate events and how the natural capital on the islands is helping protect against future climate change. These types of data can be used to model and map the effect of a variety of risks to the islands, which are likely to impact on the natural capital, and in which the natural capital also plays a role in the mitigation of such risk.

This project forms part of a suite of projects by JNCC, which will integrate satellite data, Geographic Information Systems (GIS), and economic assessments of environmental goods and services (derived from natural capital) with the following objectives:

i. Establish the Total Economic Value (TEV) of the terrestrial and marine natural environment to each of the ten listed OTs;
ii. identify the priority natural capital assets and measurable attributes (Natural Capital Metrics) to monitor changes in value through time;
iii. integrate natural capital valuations into national mapping (GIS) to define the spatial distribution of these natural assets (Value Mapping) and to promote the integration of such valuations into planning and policy making to improve long-term economic growth.

1.1. Aims

This project researched the different RS terrain data available and, where applicable, developed suitable modelling methodologies which:

- Produced contour, slope, and terrain maps for five islands; Anguilla, Turks and Caicos Islands, British Virgin Islands, Montserrat, and Tristan da Cunha
- Developed models using readily available software of the vulnerability (susceptibility) of manmade capital to natural hazards:
    - Areas most prone to coastal flooding from sea level rise due to climate change, likely impact of storm surge following an extreme storm event;
    - Erosion risk;
    - Risk of inland flooding from extreme storm events;
- Carried out an economic analysis to demonstrate both the methods and the value of natural capital in protection of manmade capital.

An important consideration has been to develop training material in the techniques, which will allow the OTs to implement the methods themselves. This will enable them to undertake scenario work and to use this type of data for monitoring.

1.2. Background

1.2.1. Risks and natural capital in the OTs

The OTs in the Caribbean and in the northern part of the south Atlantic are small island communities. Due to the land resource being finite, they are particularly vulnerable to climatic events, such as storms and hurricanes, and the consequences of a changing climate. In addition, the developed zones, or in some cases the whole islands, are low lying, with an economy heavily reliant on the coastal zone for both tourism and business sites. Fishing and the marine environment play a very large role in the economies. The communities are, therefore, very reliant on an environment that is particularly vulnerable to storm events, flooding, and sea level rise, all of which could be an effect of climate change.

Natural capital can be defined as the stocks of natural assets found within the Earth's critical zone[1], which include living things, vegetation, and animals together with the geology, soil, air, and water. It is from this natural capital that humans derive a wide range of services, often called ecosystem services, which make human life possible. In these small island communities the natural environment can play an extremely important role in regulating the effects of disasters. The natural capital is often under-regarded and, therefore, undervalued and can lose out in in land management decisions because of lack of evidence and/or lack of knowledge of its importance.

This project investigates how basic land cover and terrain datasets can assist with the knowledge base and show the importance of the environment in terms of ensuring resilience into the future and maintaining and enhancing the islands economic viability.

The small island communities are also characterised by having a limited population and many officials have a heavy and extremely varied work load. Any mapping and modelling solution that needs to be implemented on the islands has to be readily accessible and straightforward to understand and use. The growing maturity of open source software, accessible without the need for expensive licence fees, is a great benefit to the islands with their limited resources. This project has, therefore, when possible[2], used open source software to build the models, so that they are repeatable and useable by staff on the island.

1.2.2. Remote sensing background

Advances in RS data provision have been rapid over the last five years, with new satellites being launched with a superior sensors configuration. This is providing a wide range of different types and scales of data sets suitable for a range of mapping and modelling projects. RS has the advantage that large areas can be covered at one time. This is particularly useful when mapping and modelling environmental risks. This project was specifically looking at the level of detail possible from the WorldDEM radar sensor. This is an active sensor which works by sending an active pulse of radio waves to the surface and utilising the time to return to give a surface height.

Two common types of digital elevation models (DEM) can be derived from the WorldDEM; Digital Surface Models (DSM) and Digital Terrain Models (DTM). DSMs represent the first-return surface features of an area, and includes any protruding objects, such as trees, shrubs, and buildings. A DTM represents the bare-Earth and underlying terrain of the Earth’s surface, i.e. without any vegetation or man-made structures. In this study most use was made of the DTM. Using the example of Anguilla, which had some good height data already available for comparison and

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[1] Earth's critical zone is defined as *“heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources”* (National Research Council, 2001).

[2] Where dependencies on proprietary software exists, the base data layers produced by this software will be made available, enabling the island to repeat the analysis.

quality assurance purposes, the DTM, in combination with other data, was used to demonstrate how vulnerability and risk modelling can be undertaken.

1.2.3. Economic value of flood risk reduction as an ecosystem service

Ecosystem services are defined as the benefits that people derive from ecosystems and biodiversity. Following The Economics of Ecosystems and Biodiversity (TEEB) approach, ecosystem services can be supporting, provisioning, regulating, and cultural. Within the ecosystem services taxonomies, the group of regulating services help society deal with processes such as erosion or changes in water flows, and with extreme events, such as floods and storms. The value of ecosystem services for flood risk reduction reflects an anthropogenic value; i.e. it refers to their importance for people.

The economic value of flood risk reduction as an ecosystem service is defined as an indirect use value. Indirect use means that the benefits obtained from the service are received without active extraction of ecosystem products. Many ecosystems provide natural protection from the threat of floods, such as mangroves, coral reefs, and forested areas. Two key valuation methods of regulatory services include 'replacement cost' (RC), and 'avoided damage costs' (CA), the second of which is most frequently used and adopted in this approach. Both techniques are market-based techniques, as the valuation is based on actual prices as reflected in markets.

2. Data sourcing

To start the process of assessing vulnerability within the OTs, the sourcing and purchasing of radar satellite data, suitable for generating a digital terrestrial elevation model of the five listed OTs, was undertaken. These data are under an appropriate licensing agreement, which will permit use of the derived terrain maps by JNCC and its OT partners in development of vulnerability maps, vulnerability models, or other related uses.

The primary source of data was the Airbus WorldDEM™ DTM & DSM bundle 12 m grid. These data have a pixel spacing of 12 m with vertical accuracy of < 4 m and horizontal accuracy of < 6 m, suitable for the derivation of vulnerability metrics. A multi-user licence was purchased[3] to allow OT to use derived products. The AOIs were carefully elected and optimised to reduce the amount of no data whilst maintaining Airbus minimum order parameters for WorldDEM™. The total order, encompassing: Anguilla, British Virgin Islands, Montserrat, Turks & Cacios, and Tristan da Cunha, was 1,452 km^2.

In addition to Airbus WorldDEM™, Airbus Pléiades (PL) multispectral 4 bands (Blue, Green, Red, and Near Infrared) at 2 m and Panchromatic (50 cm) were purchased in a separated bundle, for the purpose of visual comparison and for future development of modelling following this contract. Radiometric and ortho-corrections will be required. Note that PL is ordered by the km^2 rather than per scene. The total order, encompassing: British Virgin Islands, Montserrat, Turks & Cacos, and Tristan da Cunha, was 2012 km^2.

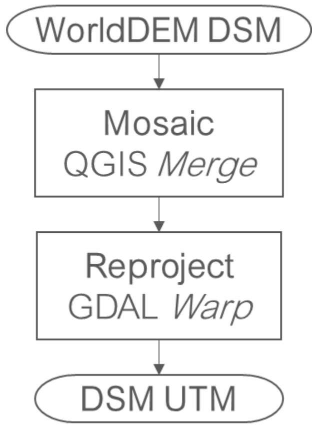
The Caribbean islands are typically affected by cloud cover making it difficult to achieve a cloud free scene from one acquisition date. Airbus allow for this by permitting scene selection to generate a composite image made up of multiple acquisition dates to form a relatively cloud free scene e.g. BVI / TCI. Environment Systems staff selected the optimal scenes based AOI coverage to negate the effect of cloud cover whilst also maintaining periodic continuity in the image composite (i.e. scenes that do not have a wide date range and where possible keep the date range within season).

[3] Standard Licence: Five users are permitted (20 % uplift for more than five).

2.1. Image processing

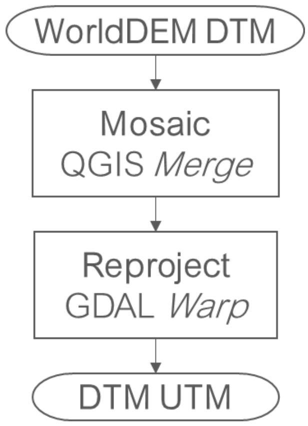
The WorldDEM™ products are delivered as single GeoTIFF datasets which cover the entire AOI ordered. To limit costs in ordered. To limit costs in some regions (e.g., British Virgin Islands), the AOI was split to cover the individual islands and individual islands and reduce the capture of shallow water areas. These areas were mosaicked into a single product into a single product before being re-projected from WGS84 into the local Universal Transverse Mercator (UTM) zone Mercator (UTM) zone (Figure 1). All DSMs and DTMs (example shown in

Figure 2) have been made digitally available to the licensees for future use.



a)

Figure 1 Work flow for producing digital surface model



b)

Figure 2 Work flow for producing digital terrain model.

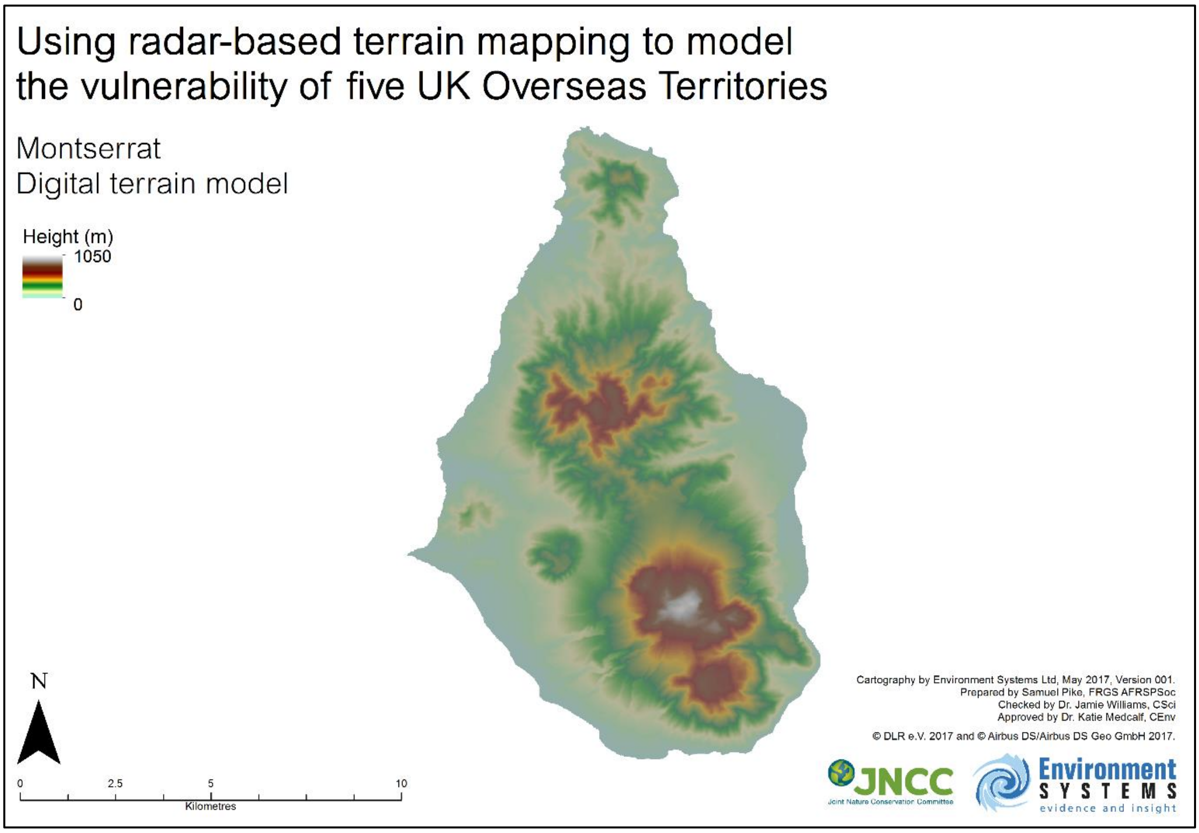


Figure 3 An example digital terrain model, created from WorldDEM™ DTM & DSM bundle 12 m grid.

Although one of the most straight forward products to produce from the satellite data, the height data can be useful for a wide range of mapping and modelling purposes on the islands. In the case of Montserrat, shown in Figure 3, the height model could be run every few years to track the growth of the island due to the presence of the active volcano. For environmental work the start of the cloud base, which marks a difference in the forest species present, is a significant factor.

3. Detailed terrain mapping of all five Territories

The creation of the DTM enables the production of intermediate data layers, including digital contour maps, slope, and aspect layers as well as additional map layers relevant to modelling water flow in coastal and inland environments. In the case of Anguilla and the Turks and Caicos Islands, the terrestrial map has been merged with available bathymetry data to provide the basis for subsequent marine storm surge modelling. The method and an example for each layer is documented below.

3.1. Contour map production

Contour maps at 5 m and 20 m for each of the five listed OTs were produced using the DTM. These contour intervals were created through Geospatial Data Abstraction Library[4] (GDAL). Within contour, the elevation input is specified (preferably a DTM rather than its surface counterpart) together with the elevation interval between the contours (i.e., 5 m and 20 m contours) (Figure 4). The output from this process is a polyline shapefile. An example of the 5 m and 20 m contours is shown in Figure 5 and Figure 6 respectively. Contour outputs for all 5 OTs have been made digitally available to the licensees for future use.

[4] GDAL is a translator library for raster and vector geospatial data formats that is released under an X/MIT style Open Source license by the Open Source Geospatial Foundation.

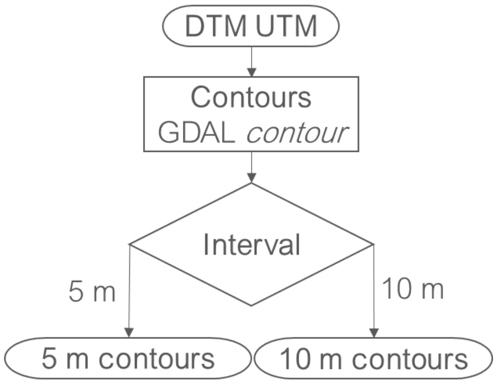


Figure 4 Work flow for producing 5 and 10 m contours from DTM.

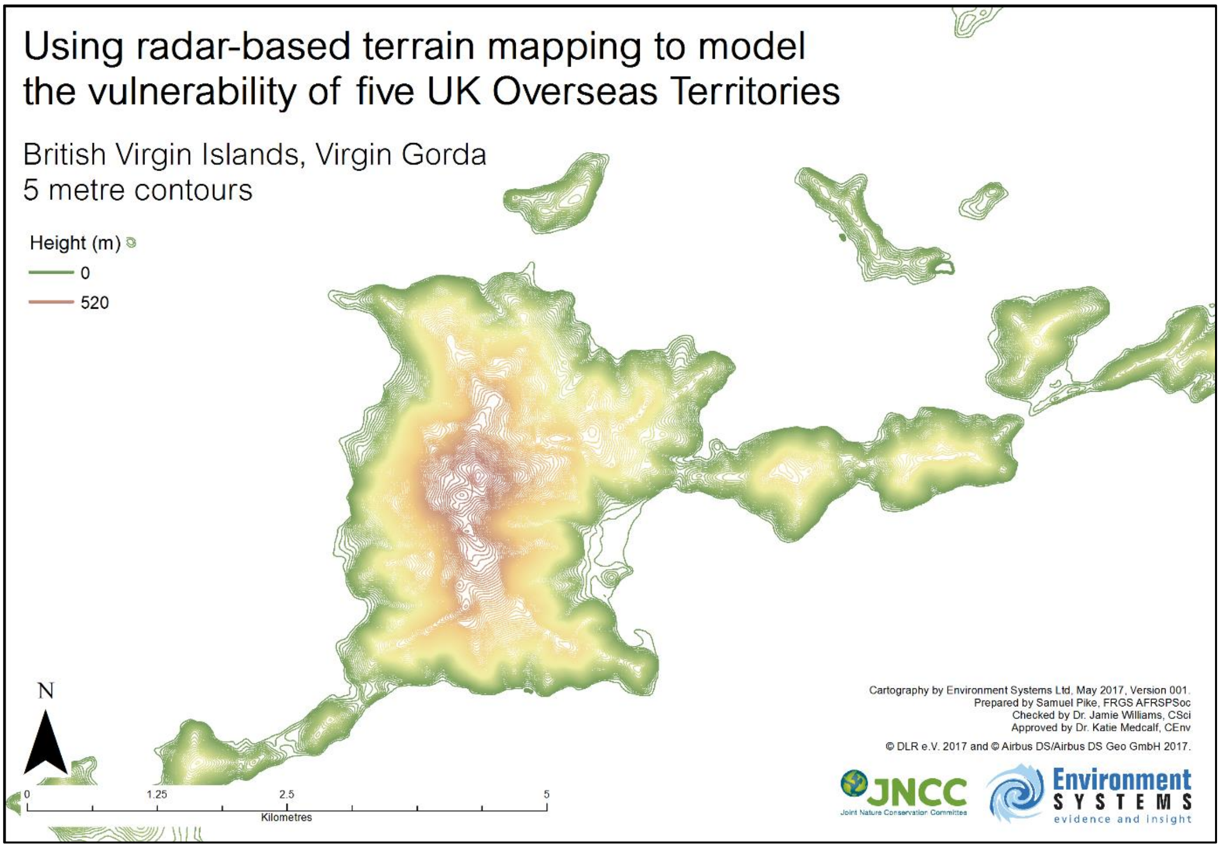


Figure 5 An example 5 m contour map, created from WorldDEM™ DTM 12 m grid.

The five meter contour map can be used by a range of policy makers, from those siting new roads and tracks through to those intending to quarrying or needing to work out fuel usage along major routes. In terms of natural capital the extent of the low-lying land near the sea is particularly significant for all the islands, as this is most at risk from inundation in a situation of future potential sea level rise due to climate change.

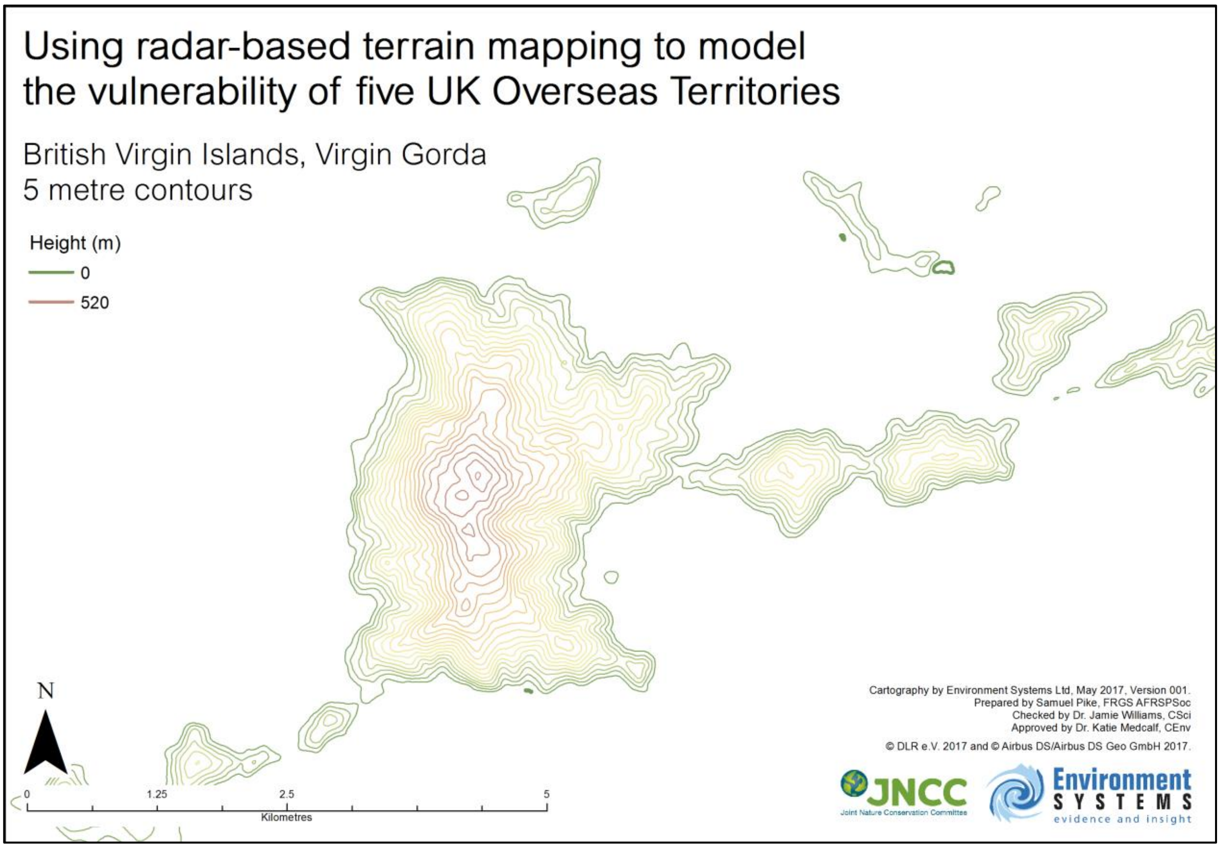


Figure 6 An example 20 m contour map, created from WorldDEM™ DTM 12 m grid.

The twenty meter contour maps will be of particular use for emergency planners looking for areas of flat high ground suitable to designate as shelter from tsunamis set off by volcanic activities.

3.2. Seamless land and sea model

A seamless land and sea model has been created using existing bathymetry data to enable the calculation of a storm surge model. This was produced from the WorldDEM DTM and SeaZone bathymetry data, using `rasterize` in the GDAL library (Figure 7). The seamless land and sea model for Anguilla is shown in Figure 8. A seamless land sea model for Anguilla has been made digitally available to the licensees for future use.

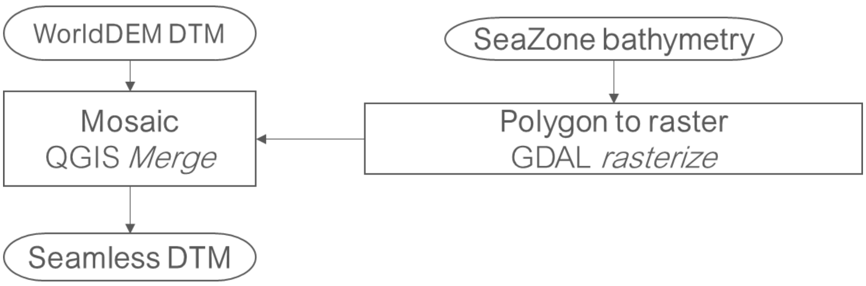


Figure 7 Work flow for producing the seamless land and sea model from DTM and SeaZone data.

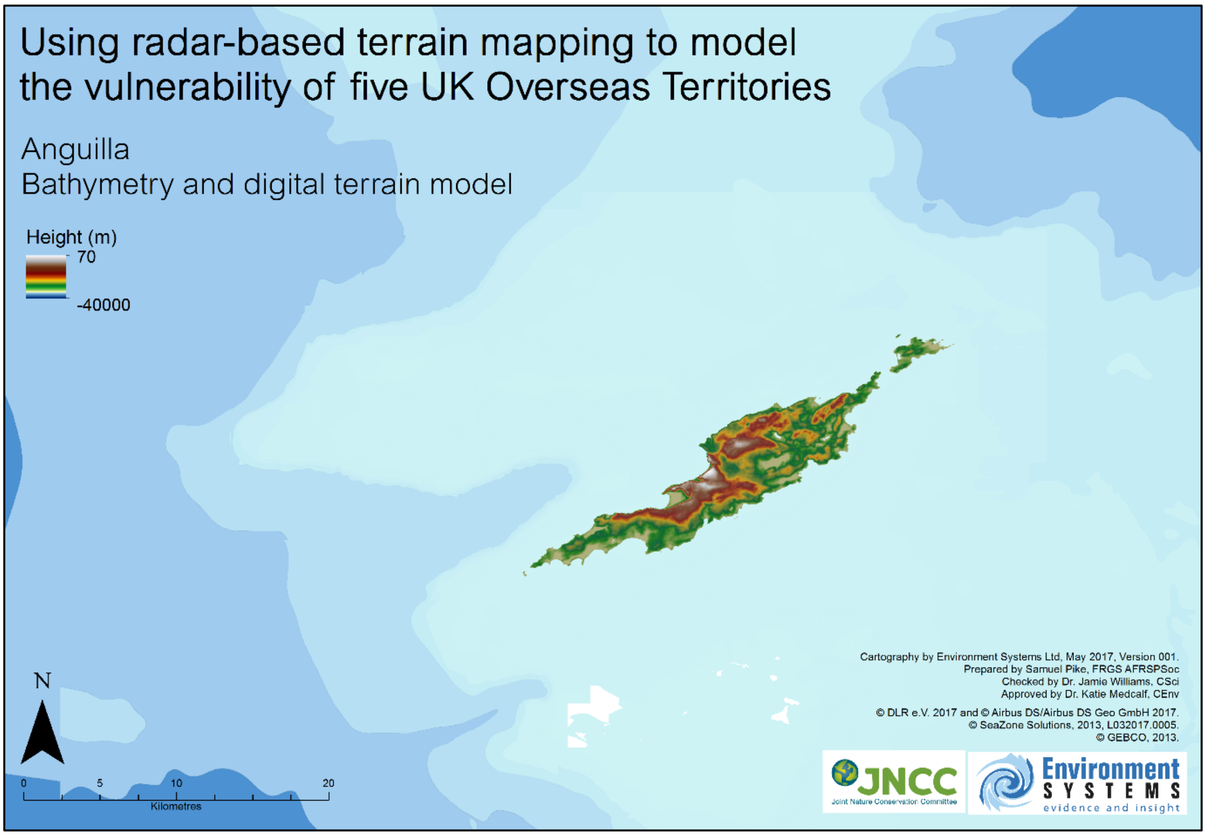


Figure 8 Seamless land and sea map for Anguilla, created from WorldDEM™ DTM 12 m grid and SeaZone data.

Basic bathymetric data can be fused into the terrain model to give a seamless land sea interface. This layer is particularly useful when considering storm surge, as with a shallow seabed the storm waves will have a higher energy than with a deeper steeply sloping sea bed. The higher the waves' energy, the higher their impact, potential to travel inland and, consequently, potential for damage to both natural and man-made capital.

3.3. Slope layer

A slope layer showing steep and shallow surfaces has been produced for the five OTs. Slope is the angle of steepness or flatness of the terrain, with higher values (up to 90º) indicating steeper slopes to the horizontal plane, and values of 0 indicating flat surfaces. Slope has been calculated within Geographic Resources Analysis Support System[5] (GRASS) GIS using the `r.slope.aspect` module to create the layer (Figure 9 & Figure 10). Slope outputs for all 5 OTs have been made digitally available to the licensees for future use.

[5] GRASS is a free and open source Geographic Information System (GIS) software suite used for geospatial data management and analysis, image processing, graphics and maps production, spatial modelling, and visualisation.

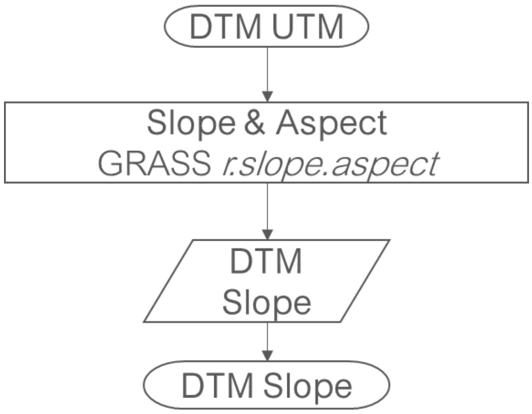


Figure 9 Work flow for producing slope maps using GRASS.

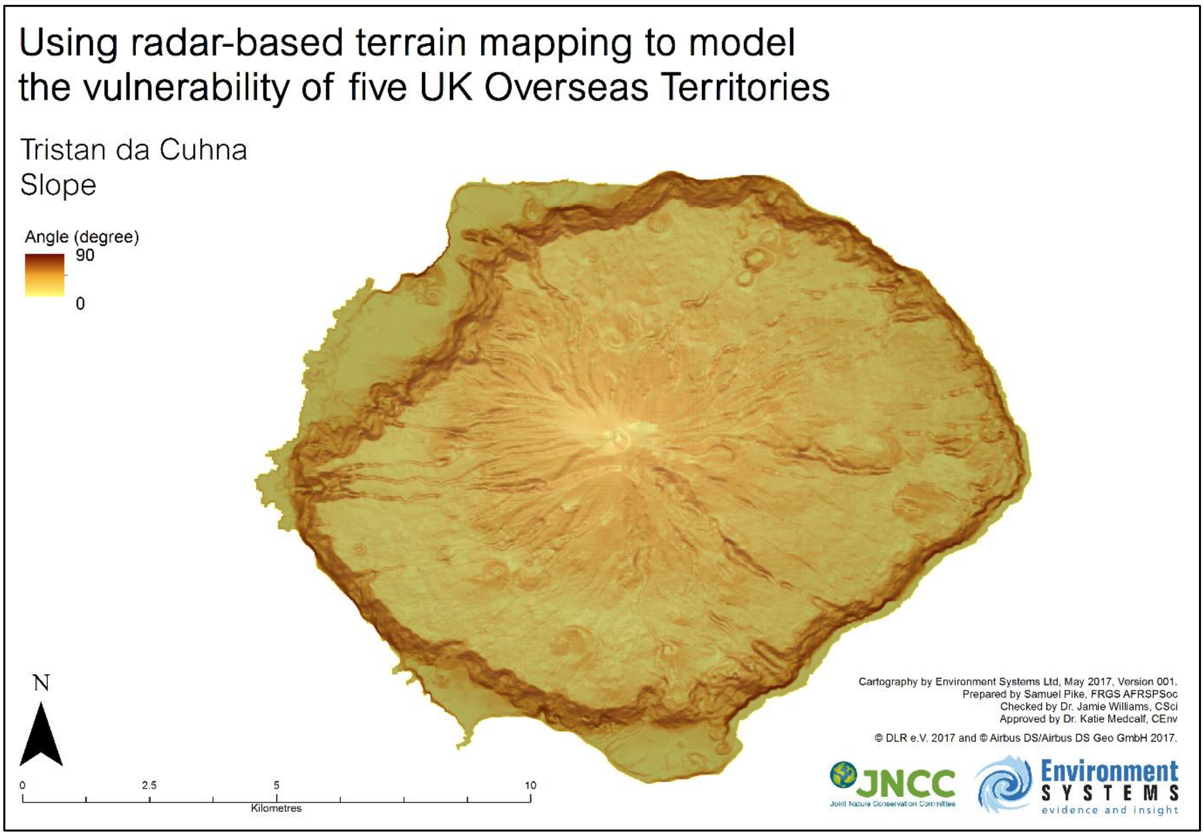


Figure 10 Slope map of Tristan de Cuhna, created from WorldDEM™ DTM 12 m grid

Slope is an important factor when considering erosion risk, with steep, unvegetated slopes with unconsolidated material having a high risk. Slope is also significant for considering other issues, such as building stability and road routes. On steeper slopes the deep rooting systems of native vegetation can stabilise the hillside and, therefore, play a very important and valuable role in terms of natural capital. The economic value of this vegetation is likely to be significant, as hard engineering solutions would be needed to replace it (Figure 11).

Figure 11 Road cutting on Montserrat showing depth and importance of roots to consolidate the steep slope surfaces.

3.4. Creation of an aspect layer.

Aspect refers to the direction that a slope is facing, with values of 0, 90, 180 and 270 indicating north, east, south and west respectively. Aspect was calculated within GRASS GIS `r.slope.aspect` module (Figure 12). An example of an aspect layer is shown in Figure 13. Aspect outputs for all 5 OTs have been made digitally available to the licensees for future use.

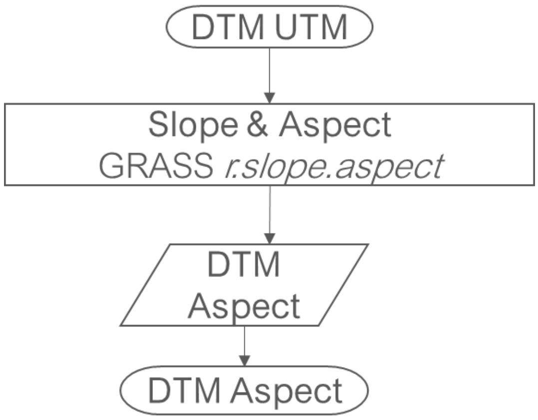


Figure 12 Work flow for producing aspect maps within GRASS.

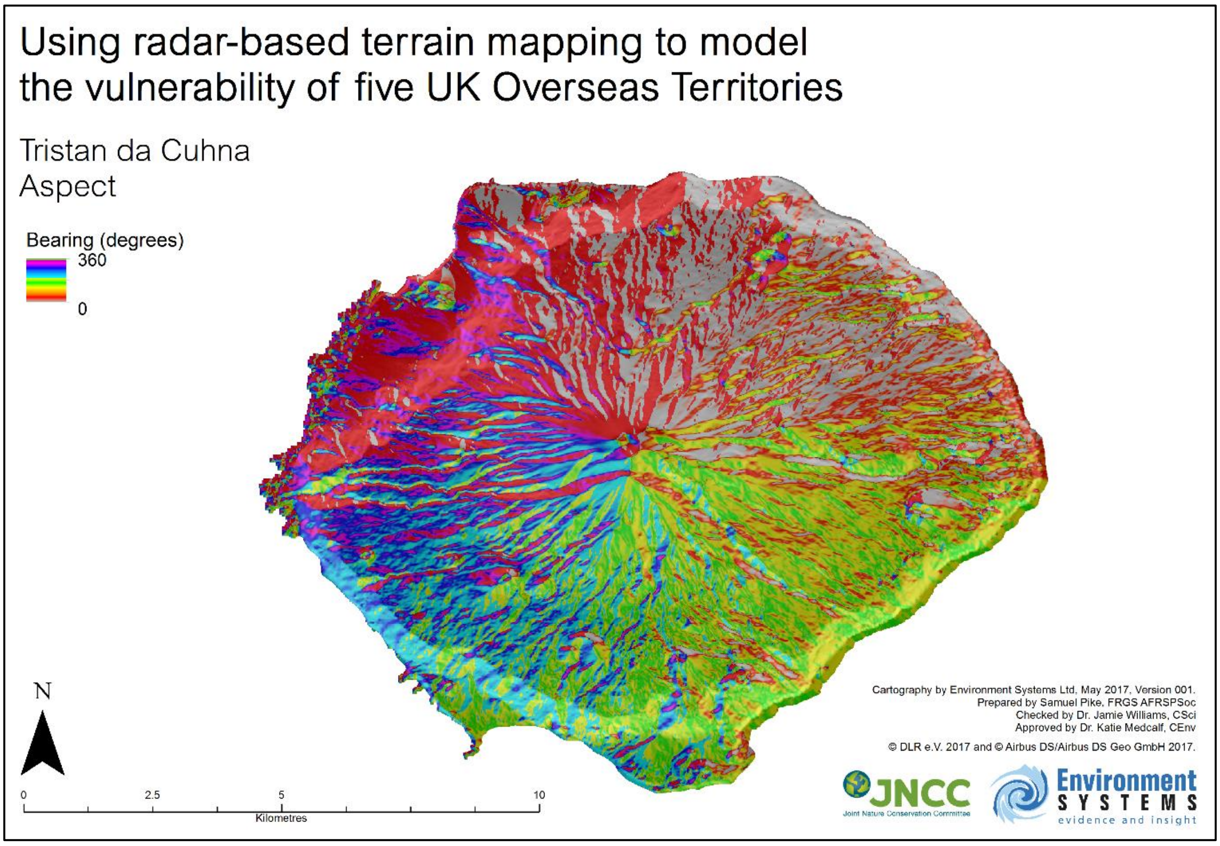


Figure 13 Aspect map of Tristan da Cuhna, created from WorldDEM™ DTM 12 m grid, with values of 0, 90, 180 and 270 indicating north, east, south and west respectively.

The aspect map will be most useful when considering the effect on vegetation and water resources. Those areas in the northern hemisphere on south facing slopes are more prone to droughts than those on north facing slopes. The degree of solar radiation and shade given is also closely related to some of the endemic species on the islands. The aspect maps can also help to efficiently site renewable power resources, such as wind and solar hardware, in locations with optimal conditions.

3.5. Creation of a concavity model showing where water might accumulate in storm events for each territory.

A well-defined index for water accumulation is the topographic wetness index (TWI). TWI is equal to $\ln(a/\tan\beta)$, where a is the local upslope area draining through a certain point per unit contour length and $\tan\beta$ is the local slope (Sörensen R. *et. al.*, 2006). This can represent and quantify the topological control on hydrological process, such as overland flow and run-off. In its most basic form, topographic information, such as slope and elevation, is combined with flow distribution parameters and the upstream contribution area. Before the TWI can be calculated, the DTM must be cleaned by removing any sinks or pits that may be present in the data. The catchment area can then be calculated to identify the local upslope area that drains through a certain point per unit contour length, with slope providing local tangent. The TWI was calculated using the SAGA-GIS[6] `Topographic Wetness Index` module (Figure 14). An example of a TWI layer is shown in Figure 16. TWI outputs for all 5 OTs have been made digitally available to the licensees for future use.

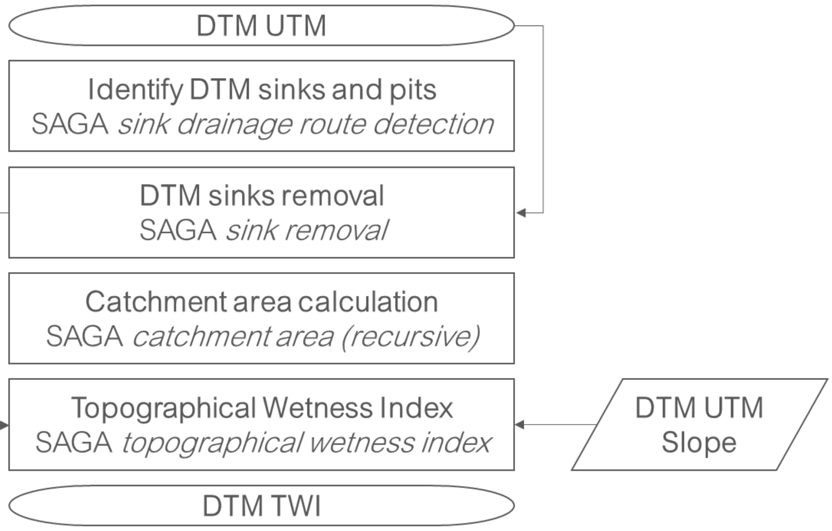


Figure 14 Workflow for producing Topographic Wetness index, using SAGA-GIS.

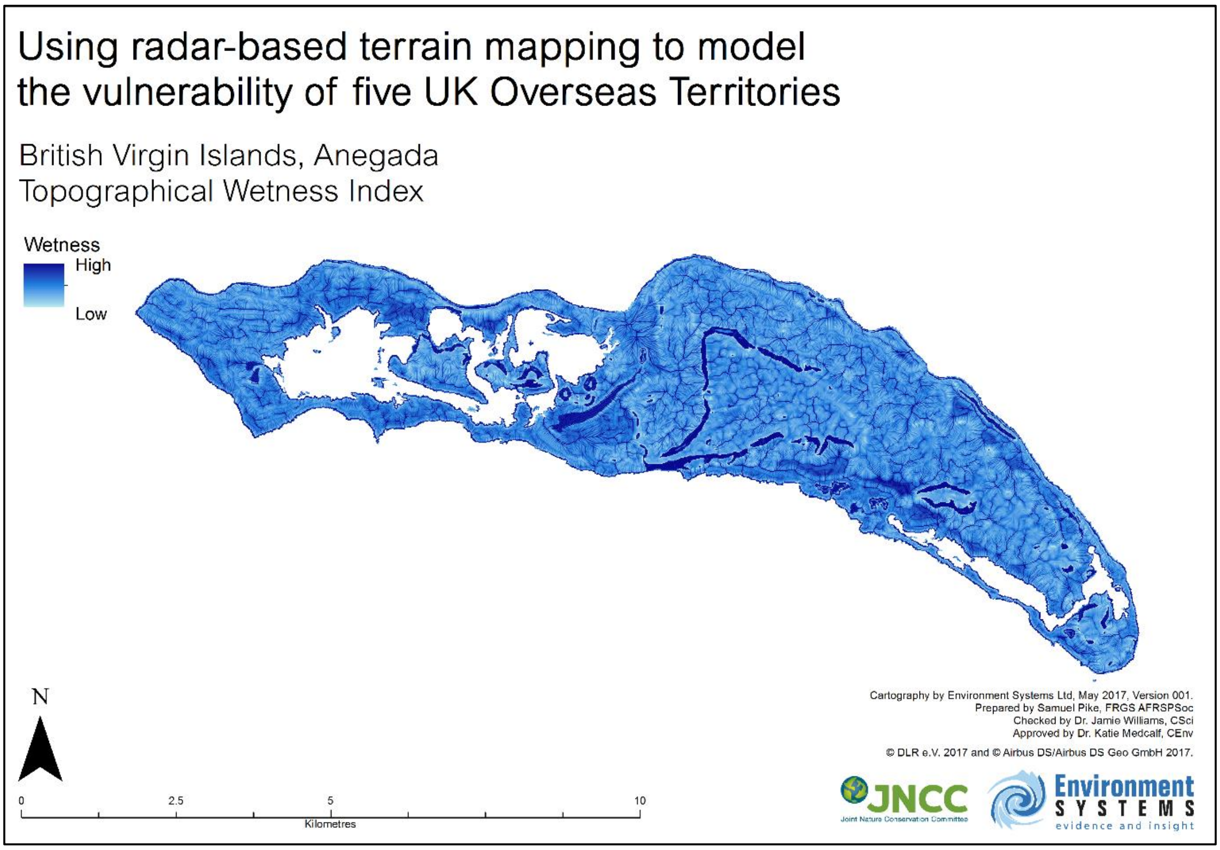


Figure 15 Topographic Wetness Index map of British Virgin Islands Anegada, created from WorldDEM™ DTM 12 m grid using SAGA-GIS. Higher values of the index indicate where water from overland flow and run-off is most likely to drain into and/or collect.

[6] System for Automated Geoscientific Analyses (SAGA GIS) is a free and open-source GIS software, used to edit spatial data. It is intended to give scientists an effective but easily learnable platform for implementing geoscientific methods.

Topographic wetness indicators have been most used to describe areas where surface water is present and overland flow is present together with ground water flow. The use of this model will need to be disused with each island and an evaluation made on the validity of the models for limestone dominated geology with no running water and infrequent rainfall events. They are most likely to be of assistance in showing areas likely to be affected by moving overland flows in extreme rainfall events. They may also have some relevance to vegetation type and cover, but further work would need to be carried out in order to confirm this.

4. OTs vulnerability assessment procedure

A vulnerability assessment procedure has been developed based upon the terrain mapping and subsequent integration of available key datasets. Anguilla was chosen as the pilot study, because a wide range of data is available for comparative purposes. The combination of terrain mapping (including bathymetry) with all existing, available and relevant data on soils, vegetation, infrastructure, settlement patterns, rainfall, etc. was used to demonstrate the assessment procedure and its actual or potential outputs in the context of risks specific to this island, including an assessment of the value of natural capital in disaster mitigation. This process was then replicated in the Turks and Caicos Islands, with the objective of highlighting what could be achieved where only RS data and freely available data was present.

4.1. Channels that run during a serve storm event, and erosion risk maps.

A method for both delineation of channels that run during a severe storm event and ascertaining erosion risk is found within SCIMAP[7]. SCIMAP was originally designed to model erosion and water movement in temperate environments. However, its use was trialed during the Anguilla National Ecosystem Assessment and it provided maps that the stakeholders associated with actual conditions on the ground. It was, therefore, applied in this study using the satellite derived data. SCIMAP uses a digital elevation model, land-use or land-cover data, and rainfall data to give an indication of where the highest risk of sediment erosion occurs in the catchment. The model (Figure 16) only required the Anguilla DTM, mean rainfall, and habitat information to run. The habitat classes were associated with individual erodibility scores. Where soil information is also available, this too was scored appropriately.

As no direct rainfall measurements for Anguilla were available, the average annual rainfall (in mm) for Anguilla was used to create the precipitation layer for SCIMAP. This average value was modified to accommodate for an east-west gradient in rainfall quantities identified by local experts (DoE). The habitat erodibility, soil erodibility and rainfall data were converted into raster data formats. Where both habitat and soil information is present, these were combined into a single raster dataset by adding the erodibility scores (ensuring that the final values range from 0 to 1).

All these data were then input into the SCIMAP fine sediment risk module. The erosion risk is exported as a raster with values ranging from 0 to 1, with higher values indicating higher risk of erosion. The channels output was a polyline shapefile indicating the location of the main channels that would run during storm events. The channels that could potentially run during a serve storm event and the erosion risk outputs are shown in Figure 17 and Figure 19 respectively.

[7] SCIMAP is available for non-commercial use under a Creative Commons license.

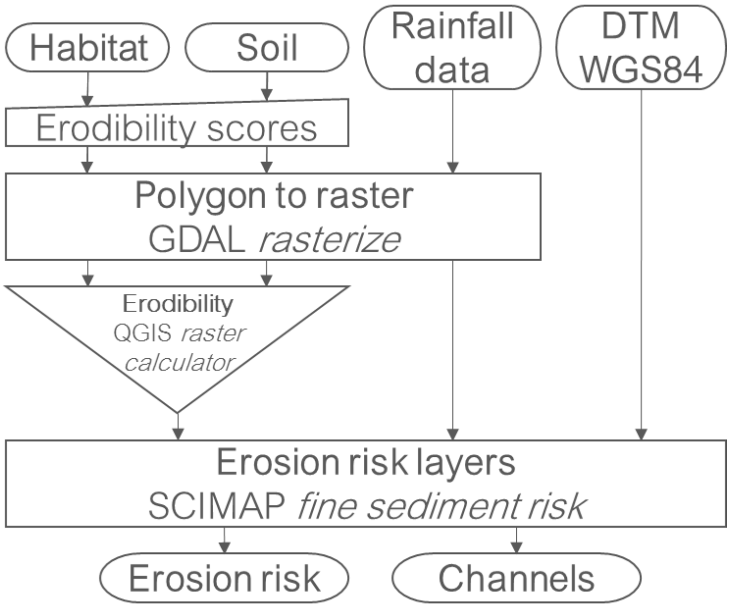


Figure 16 Work flow for producing both erosion risk and channels that run during a serve storm event, using SCIMAP.

A map showing drainage channels on Anguilla (Figure 17) was presented to stakeholders as part of the Anguilla National Ecosystem Assessment. Stakeholders saw the value of such data as, although they did not form streams such as might be seen in temperate areas, these channels are areas at more risk of both overland flow and of increased erosion. They could also be a primary mechanism for carrying pollutants and sediments from the land into the marine environment. Where excess nutrients and sediments are deposited on sensitive features such as coral reefs, die back in coral forming species can occur, leaving the reef more vulnerable to action of storms. If coral reefs are destroyed in storms they leave the shore at more risk of damage and erosion.

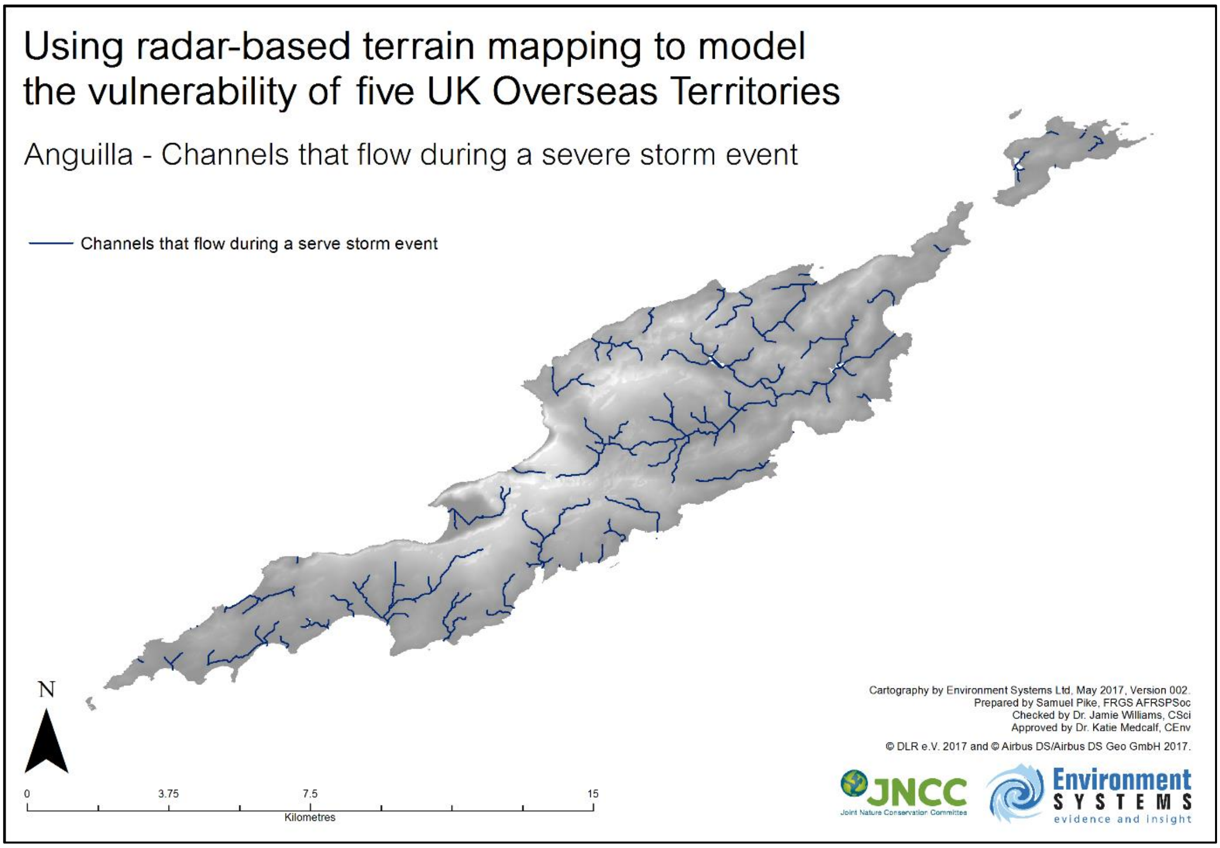


Figure 17 Map showing channels that run during a severe storm event for Anguilla, as produced by SCIMAP.

Figure 18 is taken from the work on the Anguillan National Ecosystem Assessment and shows the suspended sediment load in the water surrounding Anguilla two days post hurricane Gonzalo together with channels that run during storm events. A high visual correlation is present between the channel outflows and the surrounding marine environment.

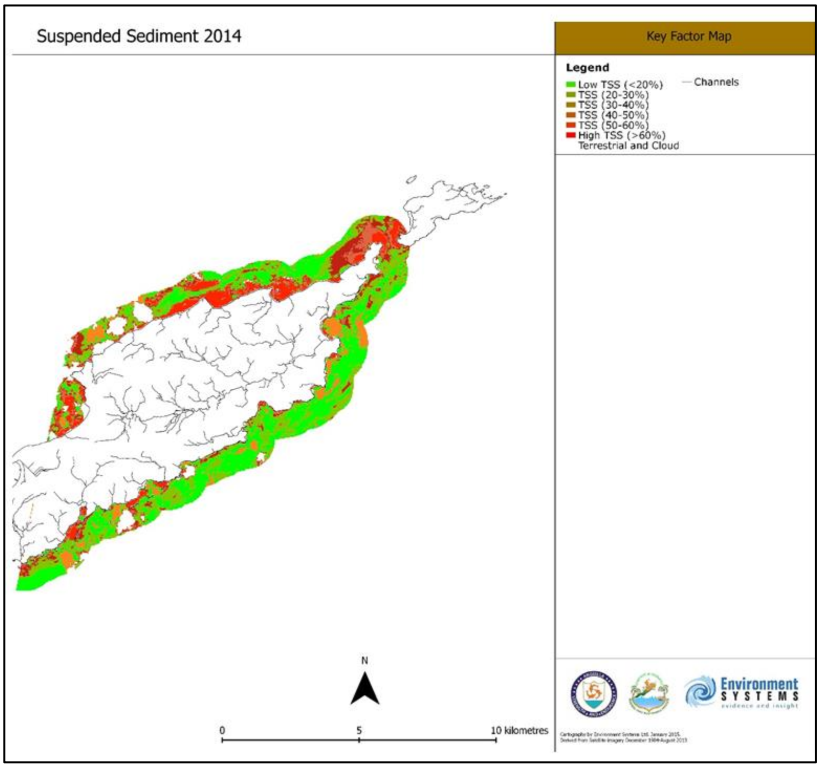


Figure 18: Suspended sediment burden post hurricane Gonzalo presented as part of the Anguillan National Ecosystem Assessment

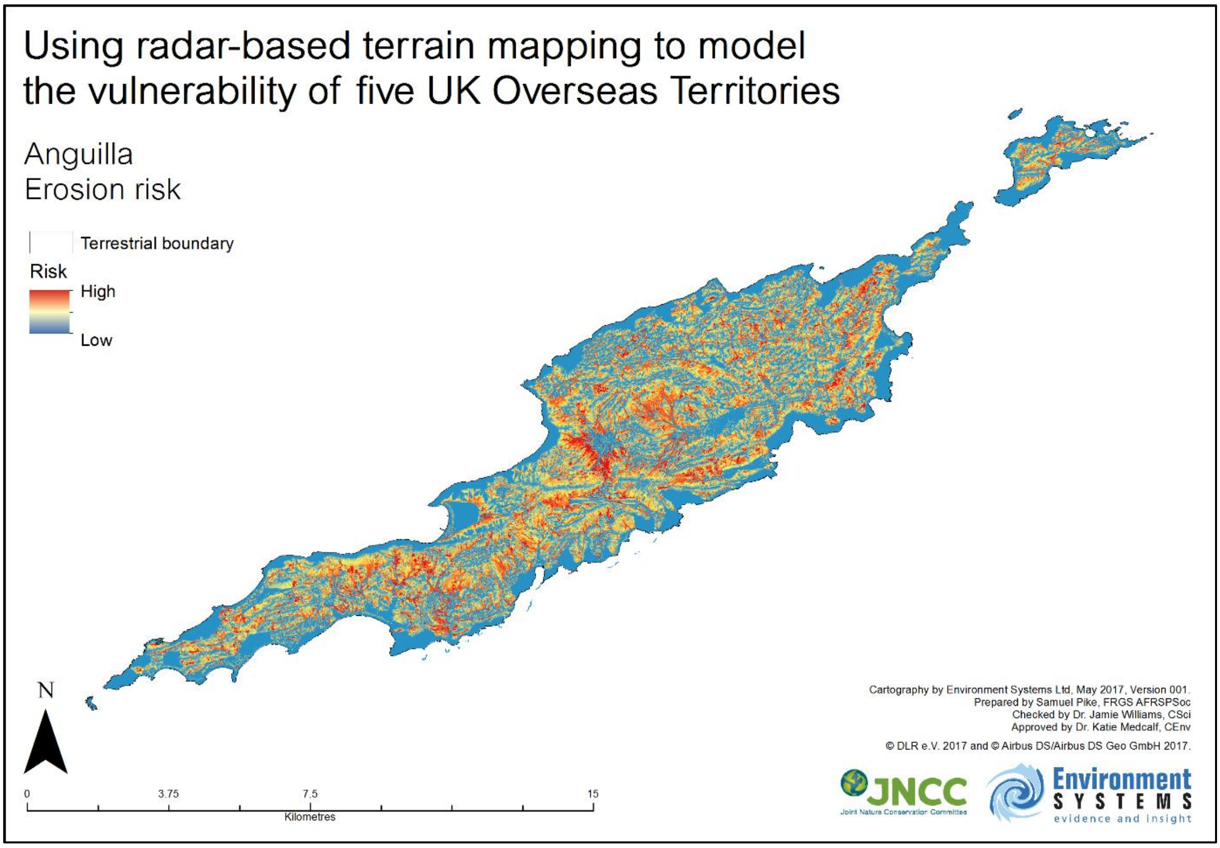


Figure 19 The map shows areas at high and low risk of erosion over Anguilla. The map was created using SCIMAP.

The soil erosion risk maps are useful to land planners and managers who are involved in siting man-made features, such as roads and houses, as they show areas vulnerable to erosion and also highlight places where erosion could be made worse by clearing off native vegetation. Figure 20 shows the results of mapping the erosion channels that might run in extreme events in TCI; in some cases these follow the courses of roads and tracks, which are indeed likely to be a prime area of overland flow in extreme rainfall events.

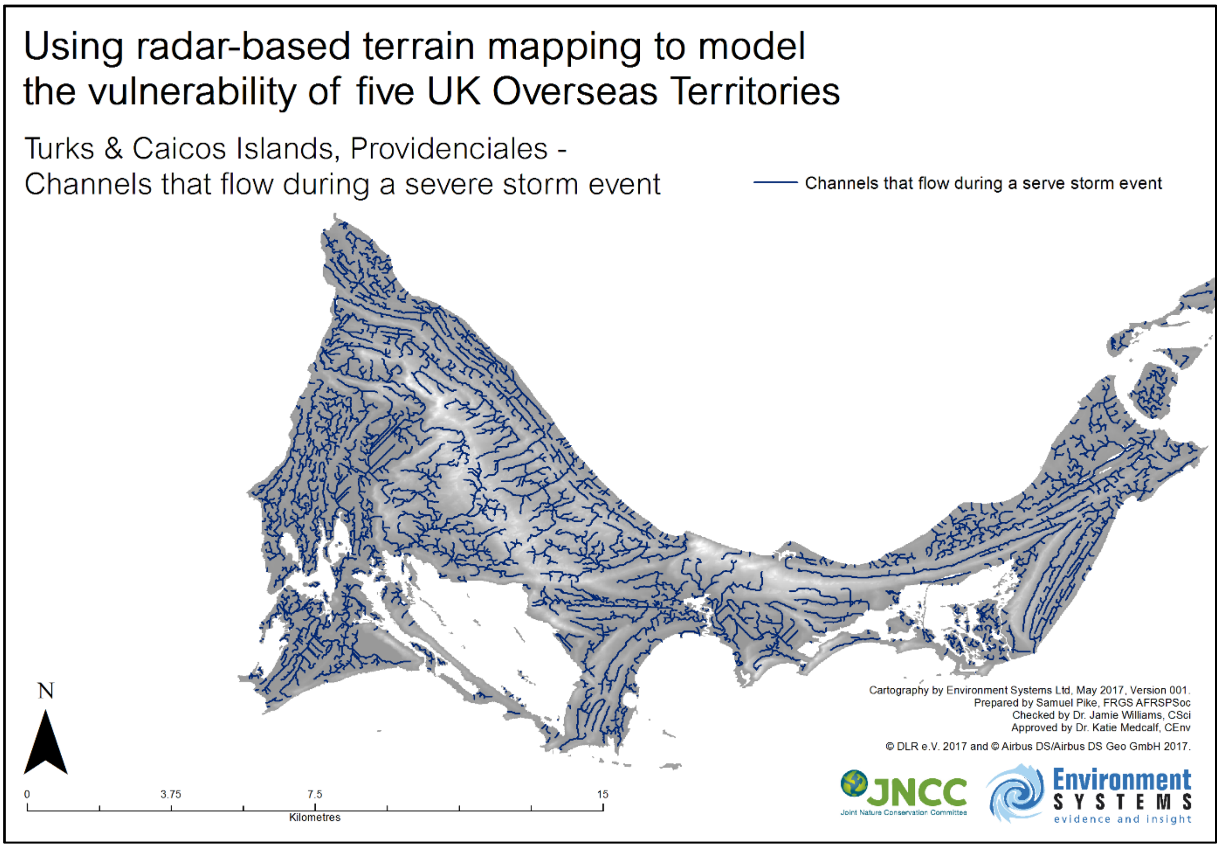


Figure 20 Map showing channels that run during a severe storm event for TCI, as produced by SCIMAP.

The map in Figure 21 shows areas most at risk of Erosion in TCI based on the DTM and a very simple habitat map. This map has not been validated by local knowledge and it might be that other data sets, such as a more detailed habitat map, soil and geology information, might be needed to refine the model. However, the model clearly shows steeper slopes, which could be a greater erosion risk; many of these areas are near the coast and movement of sediment into the marine environment could be a cause for concern.

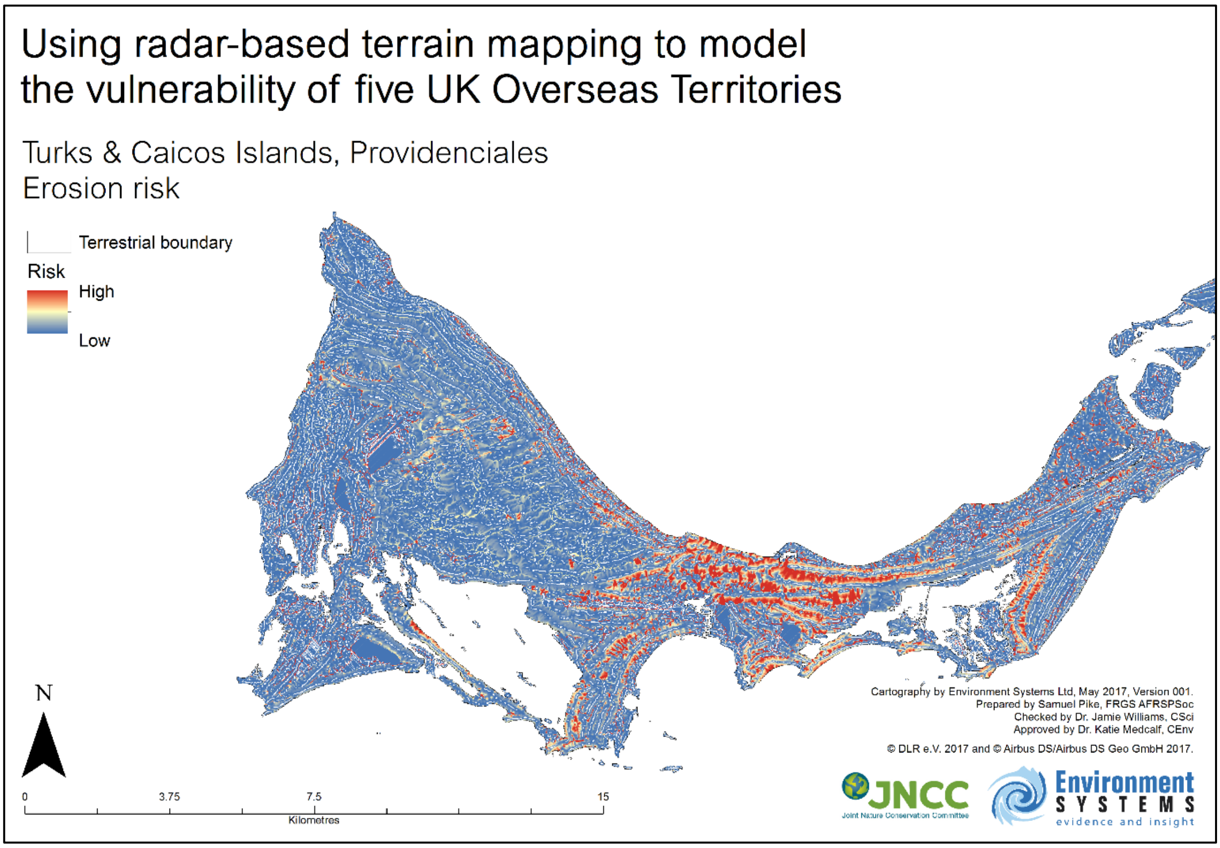


Figure 21 The map shows areas at high and low risk of erosion over TCI. The map was created using SCIMAP.

4.2. Creation of terrestrial flood risk zones.

The inland flood risk model is created to show areas at risk. It focuses on the path of least resistance of inland waters, that is, areas where overland flow of water might cause an issue, together with areas where water might pond. It does not attempt to replicate the metrological, temporal, and topographical pressures that cause a specific flood event. The model is, therefore, focussed on the conditions and parameters of the ground surface. Indicators that are included in the model include the DTM, the type of land cover, and information on soil and geology, as well as the slope and channels that might run in a rainfall event.

The model was created by first finding all those places in the landscape where water has the possibility to pool, that is, hollows. Following this the areas of the channels were intersected with these hollows to show areas with running water and where water might stand.

Hollows, or concavities, are terrestrial areas where water will pool after heavy rainfall, as there is no direct outflow. These areas can be detected using a fill function (Figure 22). This function is usually used to prepare a DTM layer for further hydrographical analysis; as many hydrographical models will fail when confronted with an area lacking direct access to an outflow, the fill function will fill the hollows. This is the equivalent to, in reality, finding a hole in the ground and filling it up with soil until the area is level with the adjacent ground. The filled DTM shows the area of interest as if someone had done this with every single hole. Settings allow the user to specify a maximum depth up to which holes will be filled, rather than retained as features.

Once the DTM has been filled, identifying hollows can easily be done through raster maths – the hollows are all the areas where the original DTM differs from the filled DTM. Subtracting the Filled DTM from the original DTM results in a raster layer with values ranging from 0 to your specified maximum depth (or to the depth of the deepest 'hole' found in the area). A value of -11, for example, would indicate that the 'hole' at this particular point is 11m deep.

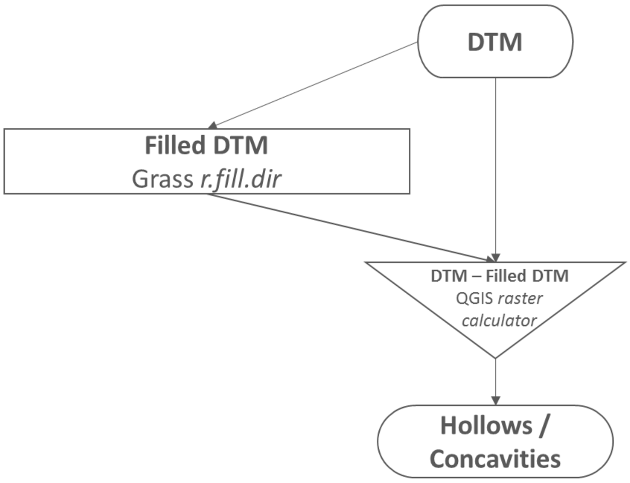


Figure 22 Work flow for identifying concavities.

The model was run for Anguilla in its current state of urban development (Figure 23); areas likely to be subject to excessive running water are shown in blue. These areas might be prone to flooding of buildings, but as the flooding is unlikely to amount to more than tens of centimeters would only damage a small portion of any building in these areas. On the other hand, in areas shown in red standing water could reach several meters in depth if conditions are severe enough. Here, damage to property could be much more substantial.

Flood risk is significantly influenced by vegetation type and amount. During the Anguilla National Ecosystem Assessment several scenarios were designed by the stakeholder groups. One of these was designated 'Nature at work'; under this scenario national planning put maximizing the value of natural capital at the forefront of planning policies. A number of maps were created in the Anguilla National Ecosystem Assessment work which showed the habitats under such a scenario. This habitat map was used to re-run the flooding work showing the difference made by working with nature. This is shown in Figure 24. Conversely the scenario developed called 'Open for Business' assumed the environment would have little consideration and development would be extensive. The habitat map created for this was used in Figure 25 to show a degraded natural capital scenario. Here, the movement of surface water is considerably greater and some of the hollows are more prone to flood. Scenario maps like this are very useful to show the value of nature in preventing or mitigating extreme events.

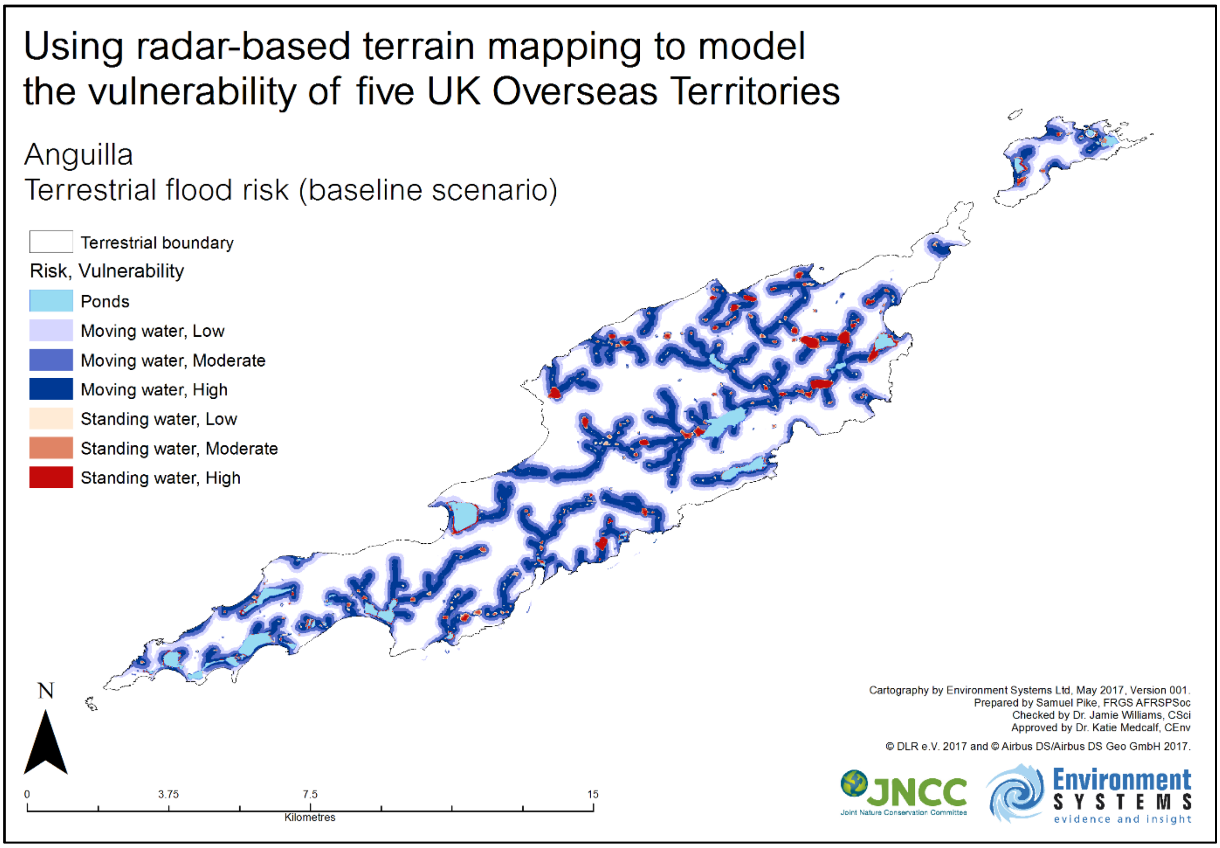


Figure 23 Map showing Anguilla terrestrial flood risk, under a baseline scenario.

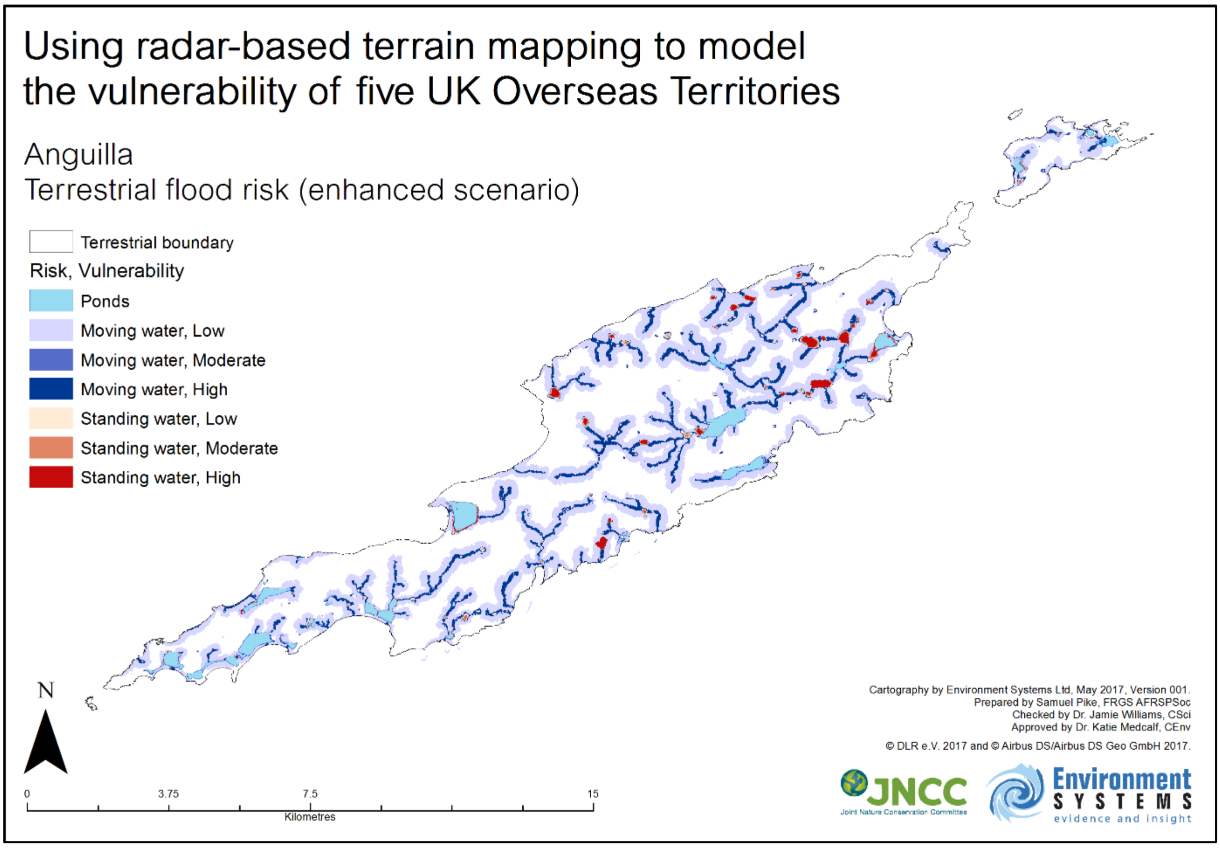


Figure 24 Map showing Anguilla terrestrial flood risk, under an enhanced scenario.

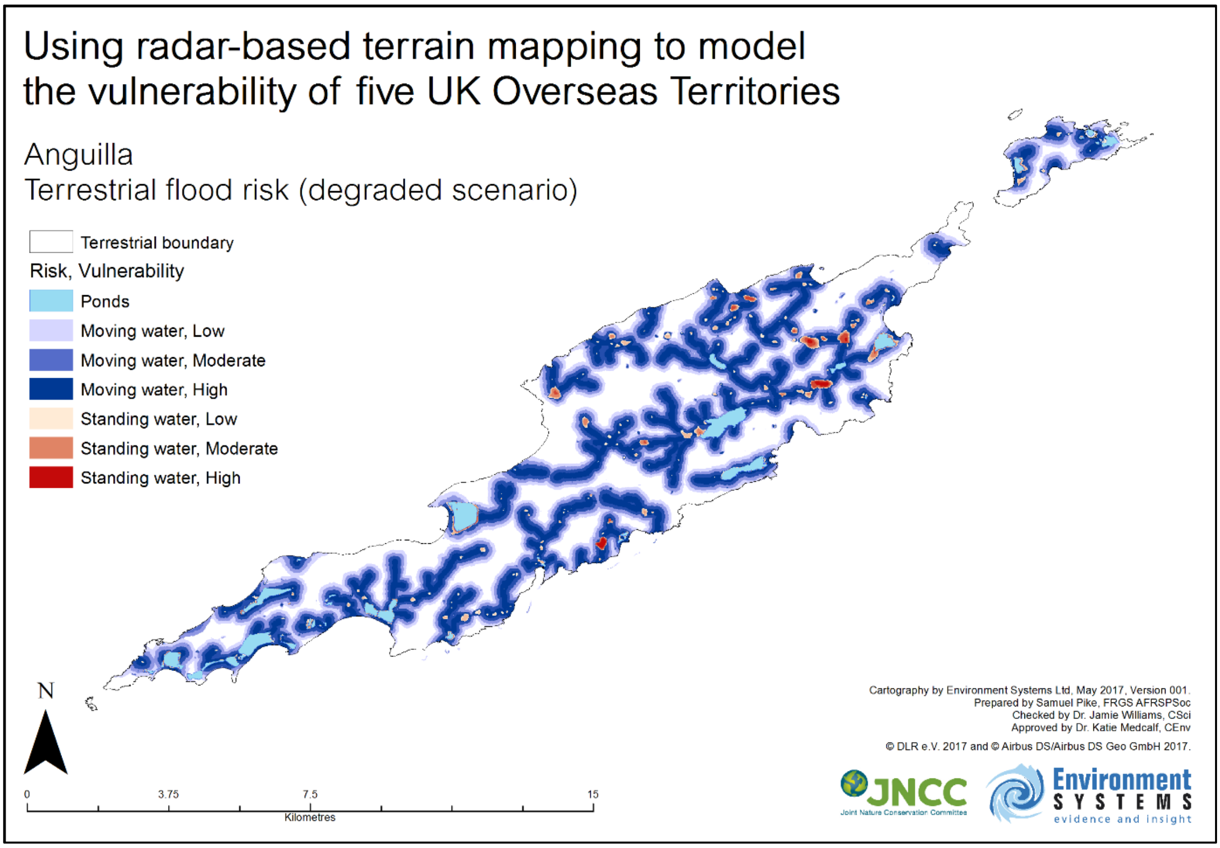


Figure 25 Map showing Anguilla terrestrial flood risk, under a degraded scenario.

4.3. Coastal Flooding

Two types of coastal flooding were assessed as part of this project:

- The first was the risk of coastal flooding which could occur with sea level rise due to global climate change.
- The second was the risk of coastal flooding due to storm surges from severe weather events. As well as considering the landform around the coast, this scenario considers the seabed and marine environment and how this will mitigate or enhance a potential flood event.

4.3.1. Coastal flooding by increased sea level.

To assess the risk to coastal flooding, the areas that are at or below 5 m above sea level were identified. These were then sub–divided in 1 m elevation intervals (Figure 26). These areas show the locations which could be subject to sea level rise at the different intervals, if no intervention was carried out to mitigate this rise.

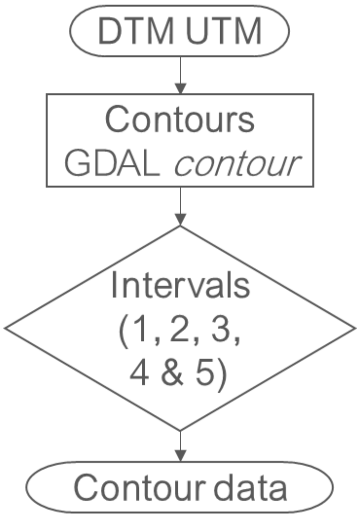


Figure 26 Workflow for delineation of coastal flooding areas.

Figure 27 shows the potential areas that might be impacted by sea level rise on Anguilla. Many of these areas are key locations for hotels and tourism related businesses; sea leave rise could, therefore, have a significant effect on Anguilla and the risks could be usefully considered in terms of the economy of the island. Figure 28 shows more detail around Rendezvous bay on Anguilla and highlights that areas close to salt water ponds, or which were sites of salt water ponds in the past, are particularly vulnerable.

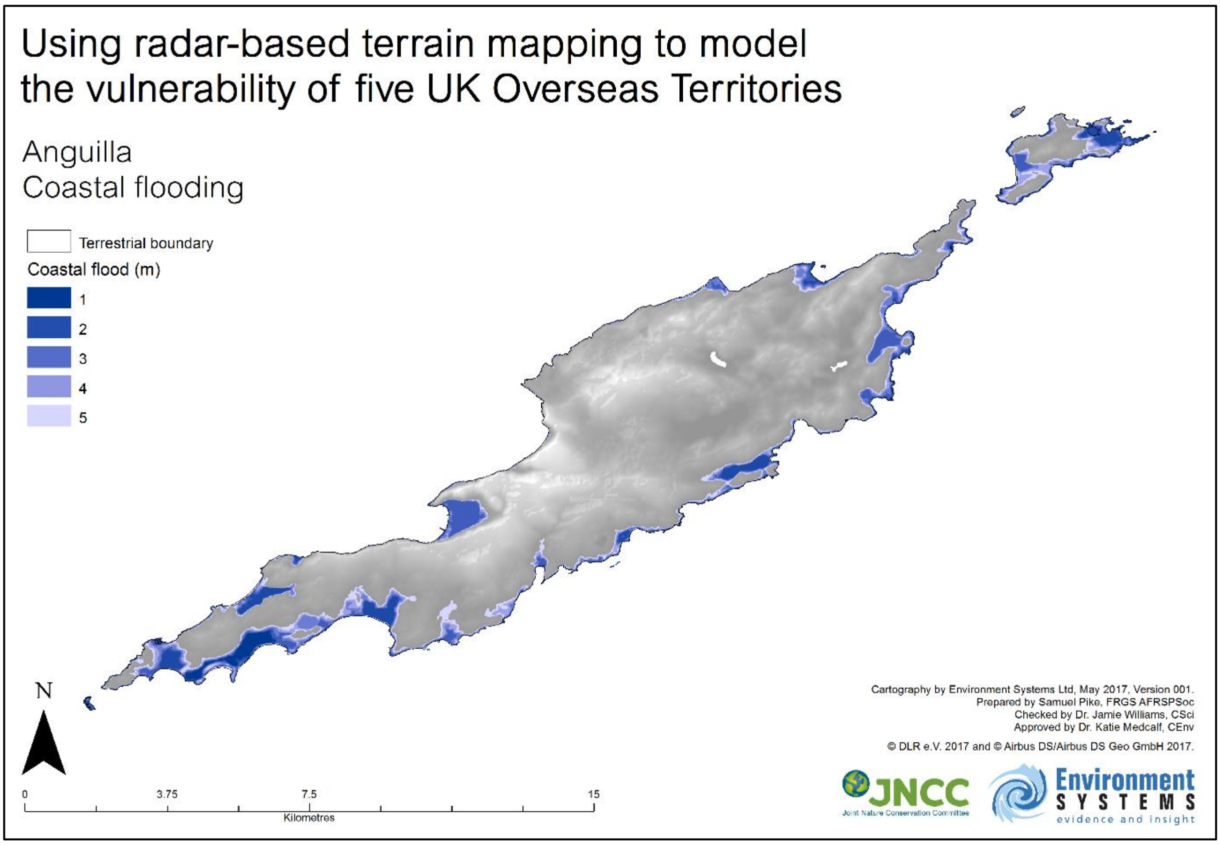


Figure 27 Map showing coastal flooding areas in Anguilla.

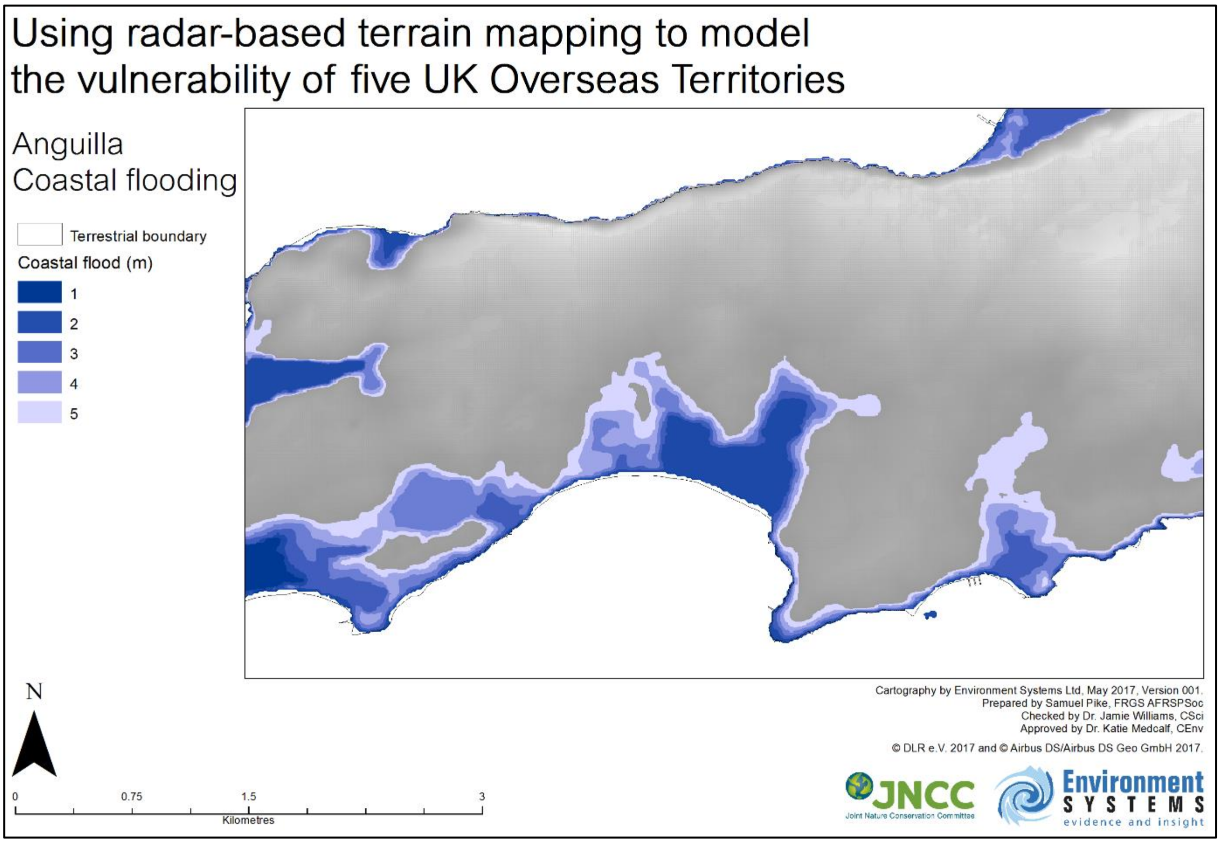


Figure 28 Close up showing areas that might be affected by sea level rise around Rendezvous bay.

This model is very sensitive to sub meter variation in the DTM. It is the most likely to give an approximate area for the 1-3 meter, and 4-5 meter flood extent, this being well within the accuracy of the model. These maps, therefore, are useful for highlighting areas which need ground survey to confirm their vulnerability and to put in place adequate sea defenses to protect built assets.

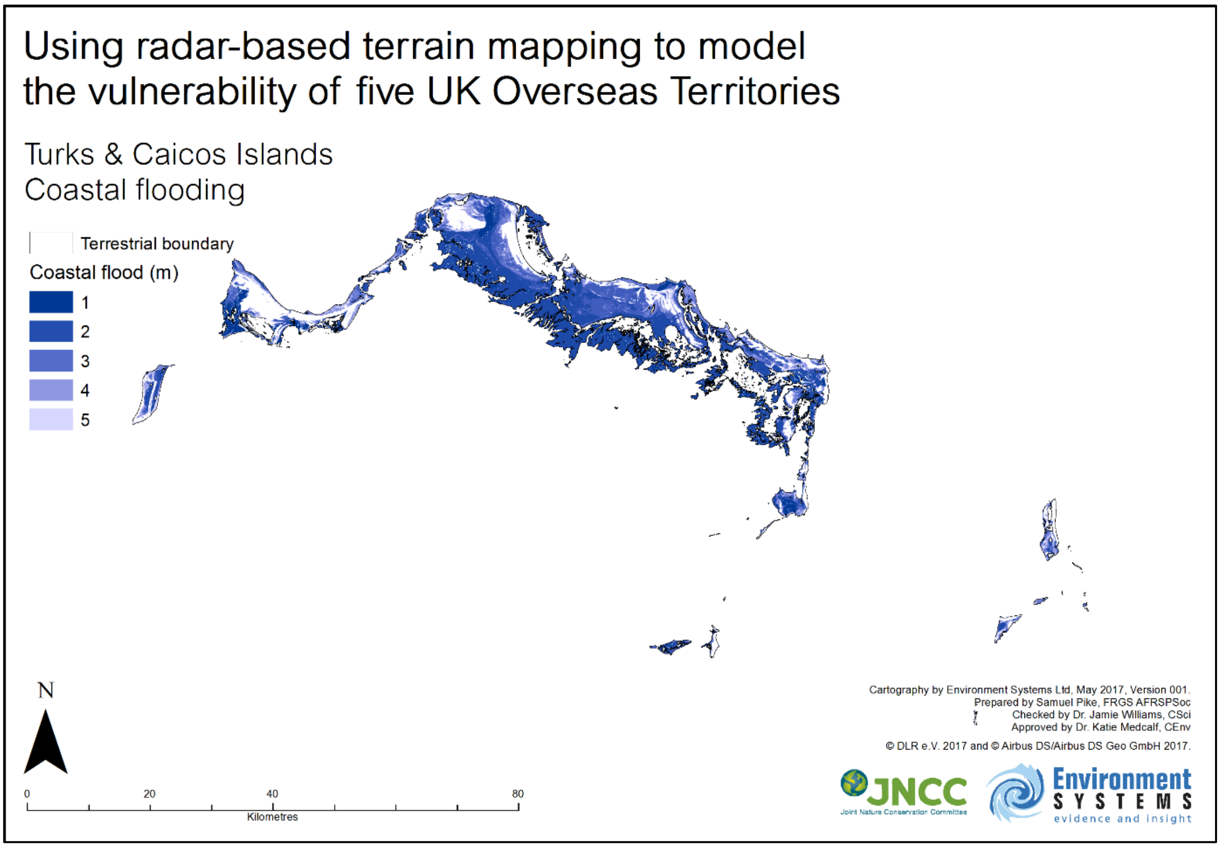


Figure 29 Map showing coastal flooding areas in the Turks and Caicos Islands

A similar model was run using the DTM data for TCI and is shown for the whole island chain in Figure 29. The model highlights the low lying land. North and Middle Caicos contain a large extent of coastal wetlands and salt ponds on their southern borders; although these areas are at risk from sea level rise they contain very few areas of built infrastructure. Of more concern is the risk to the high value beach resorts on Providenciales, as sea level rise is a real threat to some of these businesses.

4.3.2. Storm surge risk maps

Storm surge modelling is normally predicated on understanding the complex meteorological processes involved in an individual storm, which include consideration of a wide range of meteorological data specific to the event at hand. This project required a different approach to identify main areas at risk from storm events in general. This resulted in the development of a generalised model to give a good indication about where relative risk is greatest on the island.

The storm surge risk model has been generated using the Environment Systems SENCE[8] methodology. This storm surge risk modelling focuses on the path of least resistance of storm waves, rather than attempting to replicate the metrological and atmospheric pressures that cause the storms. Therefore, the focus is on the conditions and parameters of the seafloor. Indicators include the slope of the bathymetric elevation, the protrusion of features above the sea surface, such as islands and reefs, the roughness of the seafloor, and the coastal geology. Also included is the calculated average annual fetch, indicating the prevailing winds that may be experienced.

Fetch[9] was modelled to provide an indication of sheltered and exposed water, using the USGS Wind Fetch Model and average wind directions for the study areas. This was based on reasoning that the longer the distance a wave has travelled, as a result of wind and uninterrupted waters, the larger the wave and the greater the exposure of the underlying near-surface sea bed cover.

All the input layers[10] are associated with a score of resistance to storm surge waves, and converted to raster format, if required. These scored rasters are given a weighting of importance and summed to create a single input unit cost layer for the `r.cost.raster` function Figure 30.

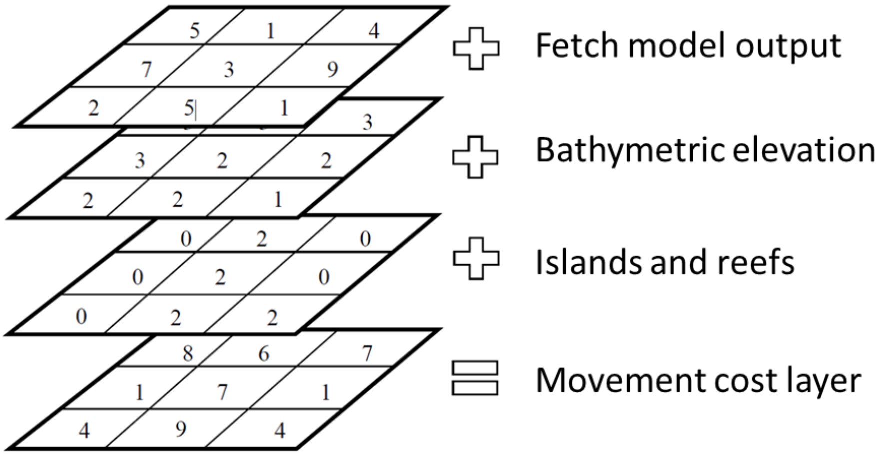


Figure 30 Conceptual diagram of additive raster model, creating the movement cost layer.

8 Spatial Evidence for Natural Capital Evaluation http://www.envsys.co.uk/sence/

9 Fetch, or fetch length, is the length of water that a body of wind has blown over. Its effects can be associated with sea state. The longer the fetch, the more wind energy the wave might have; this makes fetch one of the main factors in storm surge events (CIRIA, 1996) https://www.umesc.usgs.gov/management/dss/wind_fetch_wave_models_2012update.html

10 These fetch data were produced using an open source plugin, which relies on ArcMap GIS proprietary software. Therefore, to allow re-application 'on island', the Fetch data will be made available as a digital layer.

A storm is replicated in raster format, with linear input pixels representing the strength and path of the storm as it travels through the area of interest. The `r.cost.raster` function is run through QGIS, ensuring that "knight's move" is activated and that any null values (i.e. islands and land masses) are set to the maximum possible value.

The output dataset indicates those shorelines that have are likely more susceptible to storm surge events, with lower values indicating a higher risk of exposure. This analysis resulted in the indication of relative risk potential at the coastline.

A terrestrial movement cost for the coast (0 - 5 m in elevation) was then produced. A cost distance analysis was applied to the terrestrial movement cost layer, which accounted for the variation in relevant marine risk potential at the coastline, the topography and land cover. The result is the terrestrial relative risk potential map.

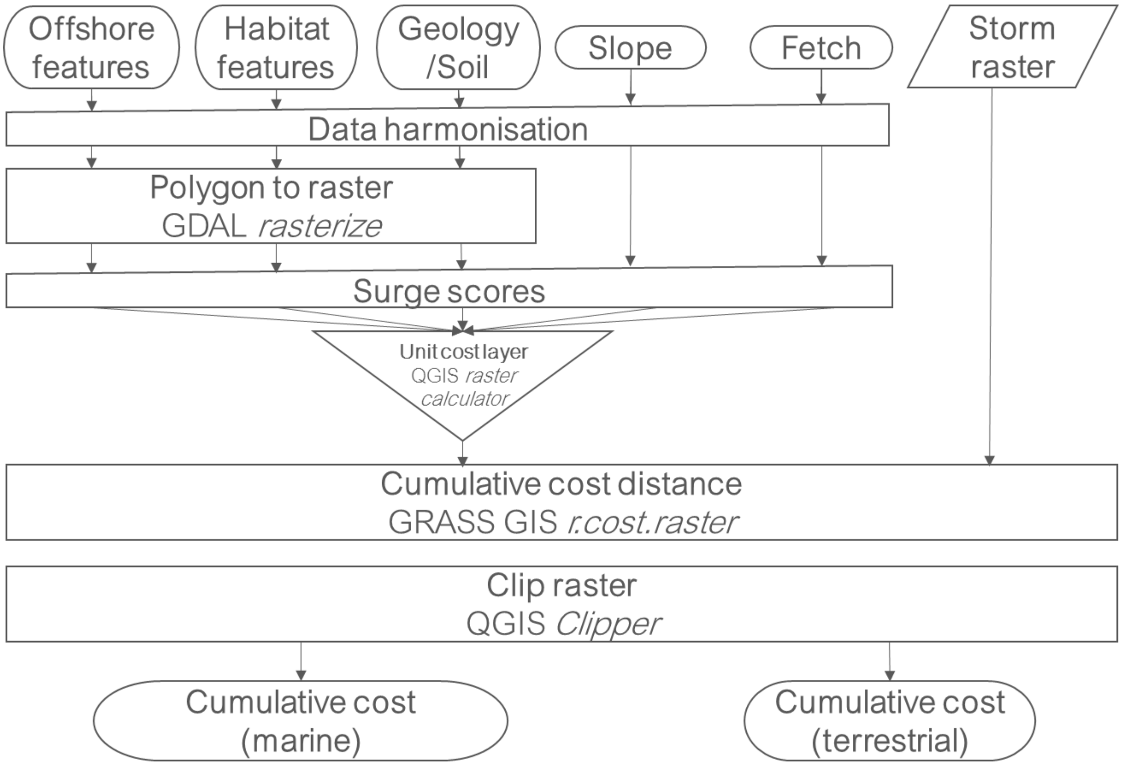


Figure 31 Work flow for producing storm surge risk map.

The Anguilla pilot study in Figure 32 shows the results of risk of storm surge from a storm coming from the south east. The blue colours show areas of strongest wave action, whilst the red show areas most at risk of the storm surge from this direction. Many of the bays and the area around the coastal salt ponds are at risk. As these areas contain built infrastructure, storm events are likely to have an economic impact on Anguilla.

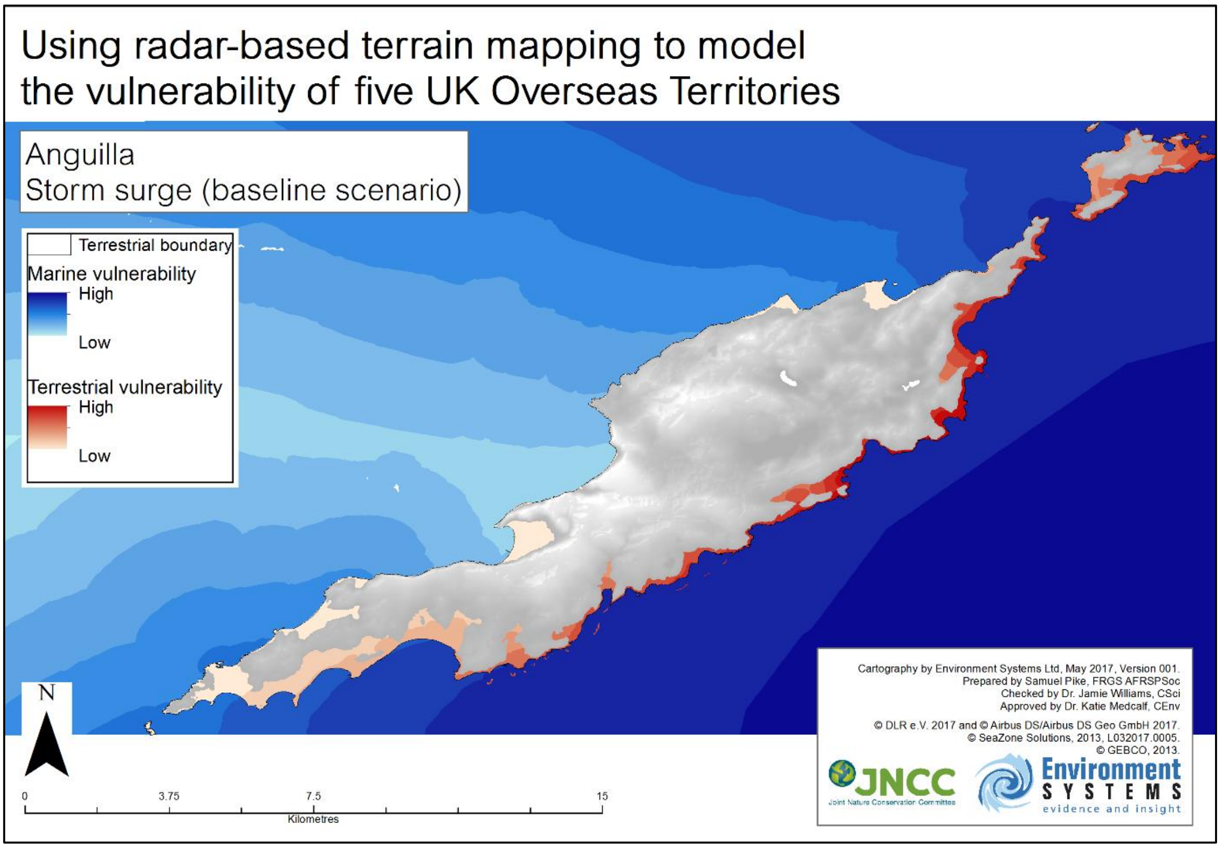


Figure 32 Map showing Anguilla storm surge risk, baseline scenario.

Storm surge can be mitigated by certain types of coastal vegetation, mangroves in particular break the energy of waves and help mitigate the severity of flooding. The protection given by coral reefs and by mangroves is described in Figure 33 and Figure 34.

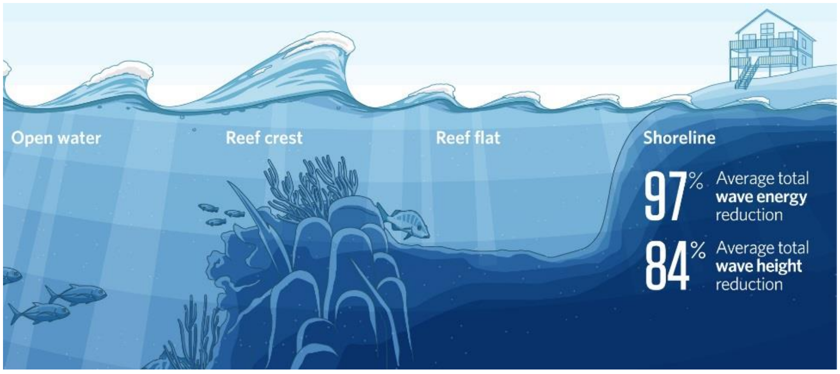


Figure 33 coastal protection by coral reefs (source: Ferrario et al 2014)

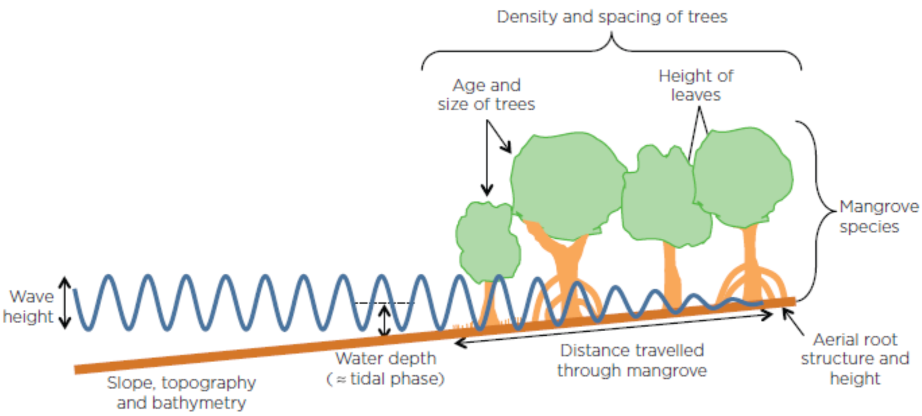


Figure 34 coastal protection by mangroves (source: World Bank. 2016).

The map in Figure 35 shows the same storm risk modelled in line with the Anguillan National Ecosystem Assessment, Nature at Work scenario with the most favourable distribution of habitats and infrastructure placed in ideal locations. The risk to infrastructure is reduced in this scenario and each storm from this direction (the most frequent direction of hit) would have significantly less impact on the built environment of the island.

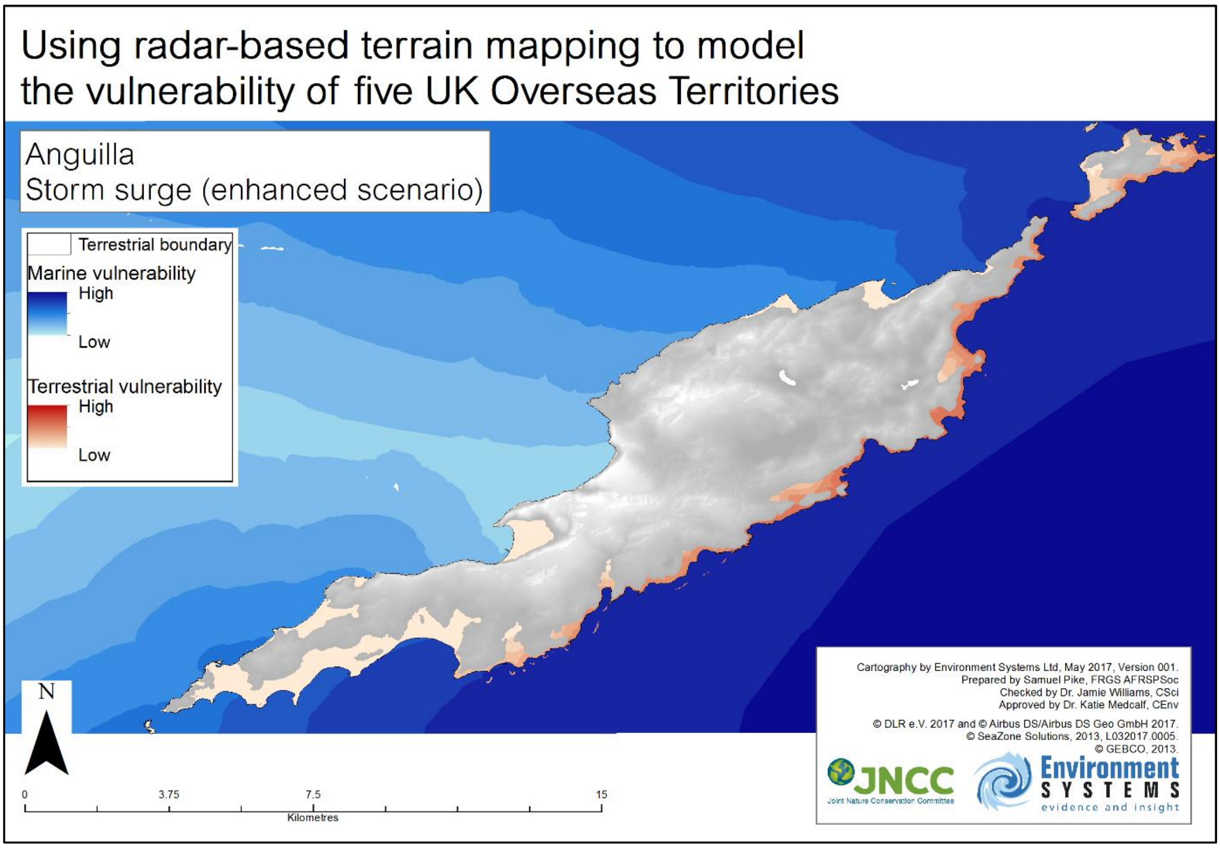


Figure 35 Map showing Anguilla storm surge risk, enhanced scenario.

Figure 36 shows the situation under the same types of storm events if the natural environment is not considered and development in sub-optimal location goes ahead. In this scenario each storm from this direction will have a significantly greater effect on the island's infrastructure and economy.

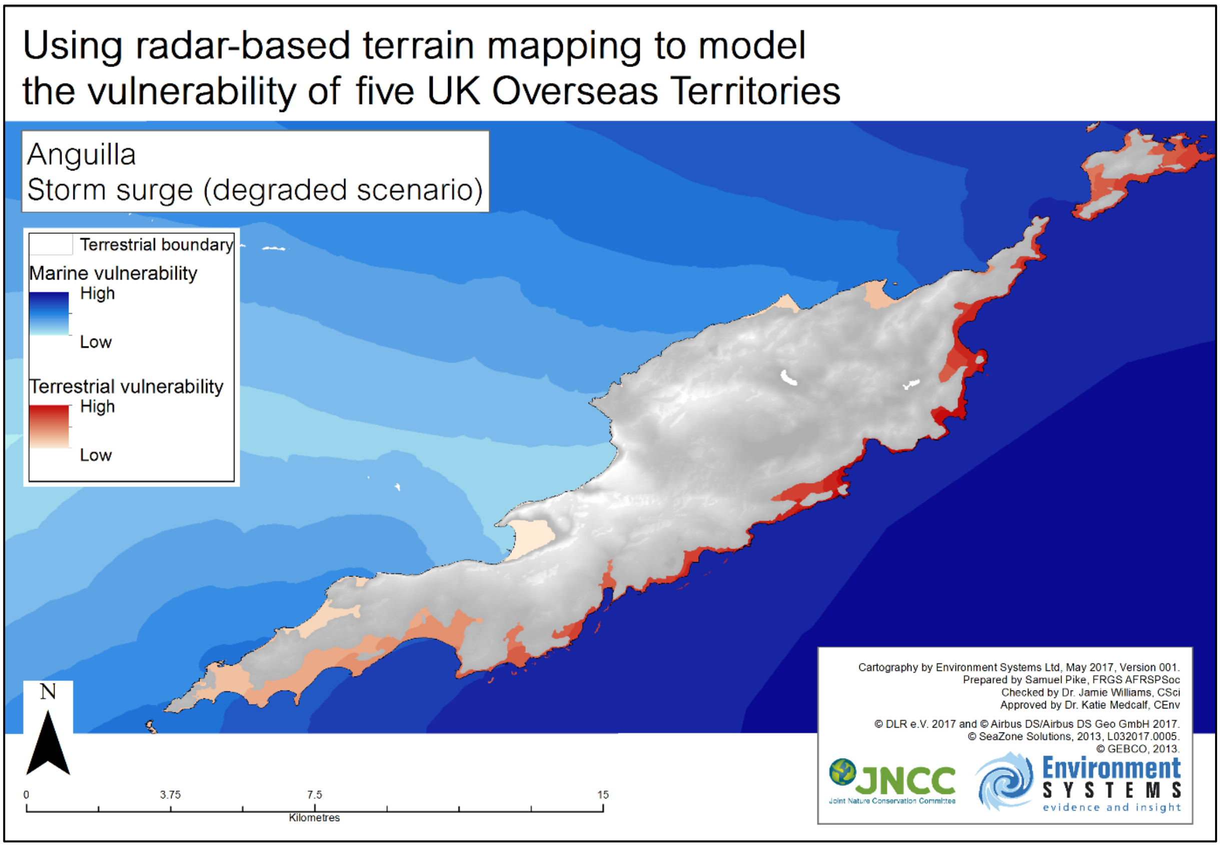


Figure 36 Map showing Anguilla storm surge risk, degraded scenario.

5. A procedure to assess the economic value of natural capital for flood protection

Following the mapping and modelling carried out using the RS datasets further work was undertaken to describe the economic impact of the risk considered. This section describes a generic procedure to assess the value of ecosystems for the protection of man-made capital (Figure 37) during coastal and inland flooding events. Flood risk is defined as a function of the hazard, exposed areas and the vulnerability of assets in exposed areas.

$$\text{Flood risk} = f(\text{hazard} \times \text{exposure} \times \text{vulnerability})$$

Hazard and the role of ecosystems: The natural hazard assessment based on the digital elevation model indicates which areas are affected by coastal and inland floods, what the inundation depth is at these locations (‘flood zones’ in Figure 37) and how high wave energy and flood velocity zones are distributed across the island.

Ecosystems such as salt marshes, coral reefs, mangroves, and forests hold the potential to reduce flood risk. Mangroves, salt marshes, and coral reefs mitigate wave energy and run-up during coastal floods and thus mitigate the hazard and the extent to which assets are exposed. Forests and other vegetation can mitigate flood damage by braking waves and reducing runoff and erosion risk. Figure 37 shows that bathymetry, storm characteristics, and the extent of green infrastructure affect the wave exposure and velocity of the flood.

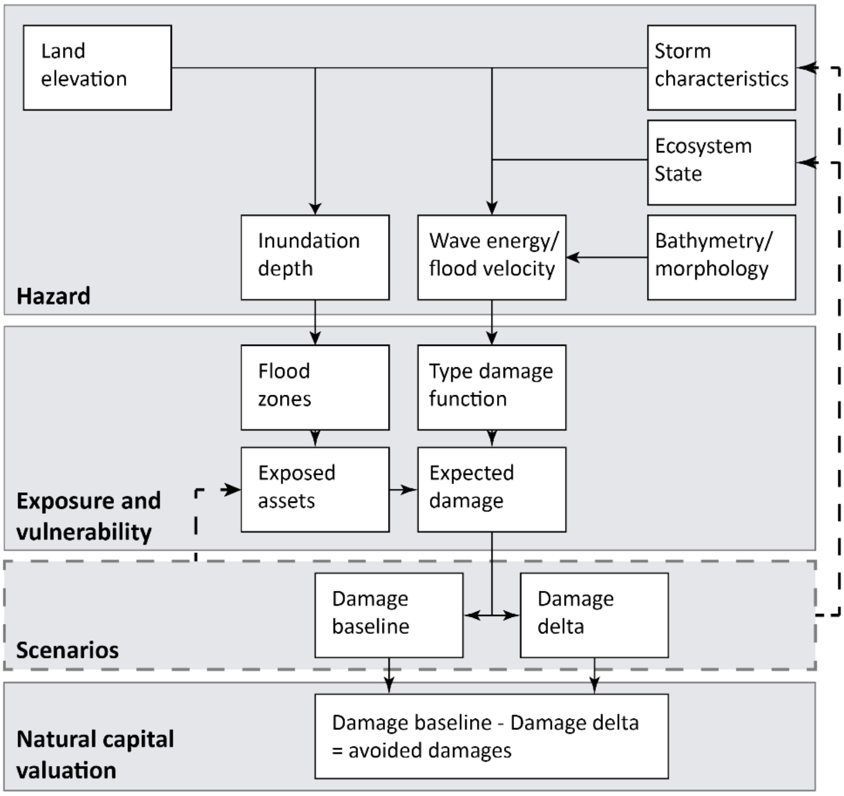


Figure 37 Framework to assess the value of natural capital for flood protection of man-made capital (adapted from Van Zanten, Van Beukering, and Wagtendonk 2014).

Exposure and vulnerability: When the flood zone maps are overlaid with real estate and infrastructure maps, it is possible to identify the economic assets that are directly physically exposed to the impacts of a particular flood. Expected damage to the economic assets that are exposed in flood zones is estimated using depth-damage functions ('damage curves' in Figure 37), as explained in detail in previously. These functions draw a relation between the depth of the flood and the relative damage to a property or stretch of road (or other infrastructure). As storm damage is, besides flood depth, also related to wave impacts, different damage curves apply for areas with a high wave exposure and storm water velocity. The relative damage is the percentage of the reconstruction costs (the cost of reconstructing the structure back to the pre-flood state) of a property that is lost or damaged as a result of the flood. Using this approach, the value of the expected damage during a flood can be estimated.

Scenario analysis and natural capital valuation: The reduced flood risk due to the presence of green infrastructure can be quantified using an avoided damage approach. This approach entails that expected damages of a baseline scenario are compared to a hypothetical scenario where the extent or quality of the ecosystem has decreased or increased ('damage delta' in Figure 37) or the exposed assets have changed. For example, the enhanced scenario maps Figure 35 and Figure 24 show that mangrove restoration can reduce the extent of flood zones and thereby expected damages to properties in comparison to the baseline scenario. The difference between the scenarios represents the value of natural capital during the specified natural hazard.

5.1. Step 1: Assessing the relation between the intensity and extent of the flood and the health and spatial extent of ecosystems

The first step in describing the economic analysis is the spatial modelling (see Figure 26 and Figure 31). A representation of how these pathways affect an area in detail is shown in Figure 38.

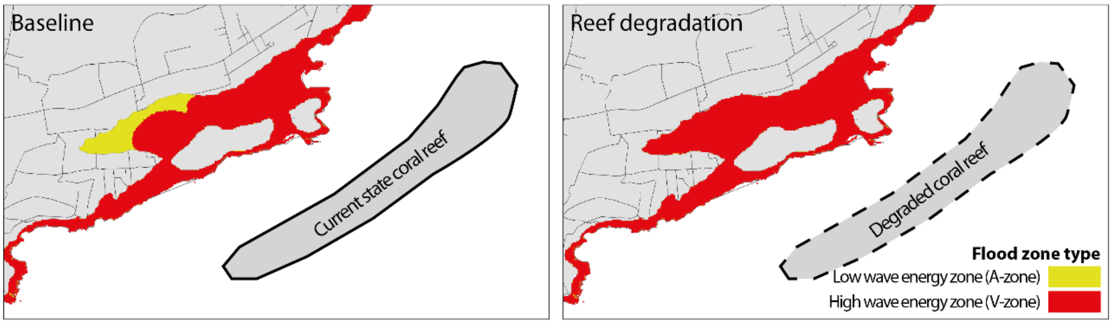


Figure 38: the relation between the potential impact of the flood and the presence and health of ecosystems.

5.2. Step 2: Assess exposure, the economic value contained in the flood zones

In order to determine to what extent flood risk is reduced by natural capital, the economic value exposed to floods needs to be assessed. This analysis relies on spatial socio-economic data that describes the economic value of assets contained in flood zones. In flood risk analysis, it is common practice to focus such an analysis on immovable properties, such as real estate and infrastructure. These properties are most likely to be exposed to the effects of floods. Moving assets like cars or yachts are often brought to a place that is not affected by the natural hazard and thus damaged to a lesser extent, whereas indirect effects such as business interruptions are more difficult to quantify. Hence, the presented method in this report provides a lower-bound estimate and most likely and underestimation of the total damages suffered.

Valuing natural capital using the avoided damages approach can be performed at different spatial scales. Exposed economic value can be estimated based on land use/land cover classes, but also at object level per individual house. Given the relatively small scale of the overseas territories, this procedure adopts an object level approach. This means that the procedure identifies individual objects (properties, infrastructure) that are exposed to natural hazards.

The following datasets provide information on exposed value:

- Cadastral dataset with the locations of properties, structural characteristics of properties (i.e. area, floors, number of rooms) and appraised value
- Openstreetmap data to describe the locations of properties and occupation class (i.e. residential, commercial or government)
- Real estate transaction dataset provided by real estate brokers
- High resolution habitat/land use/land cover data to assess the locations of properties
- Any other local or regional statistics on property values and construction costs
- Infrastructure map

In Anguilla, the exposure of economic assets in floods zones is described at object (building) level. From the datasets listed previously, that can be used to describe the value contained in flood zones, only a habitat map and Openstreetmap data were available. A layer with buildings was constructed by updating the buildings in the habitat map with buildings from Openstreetmap.

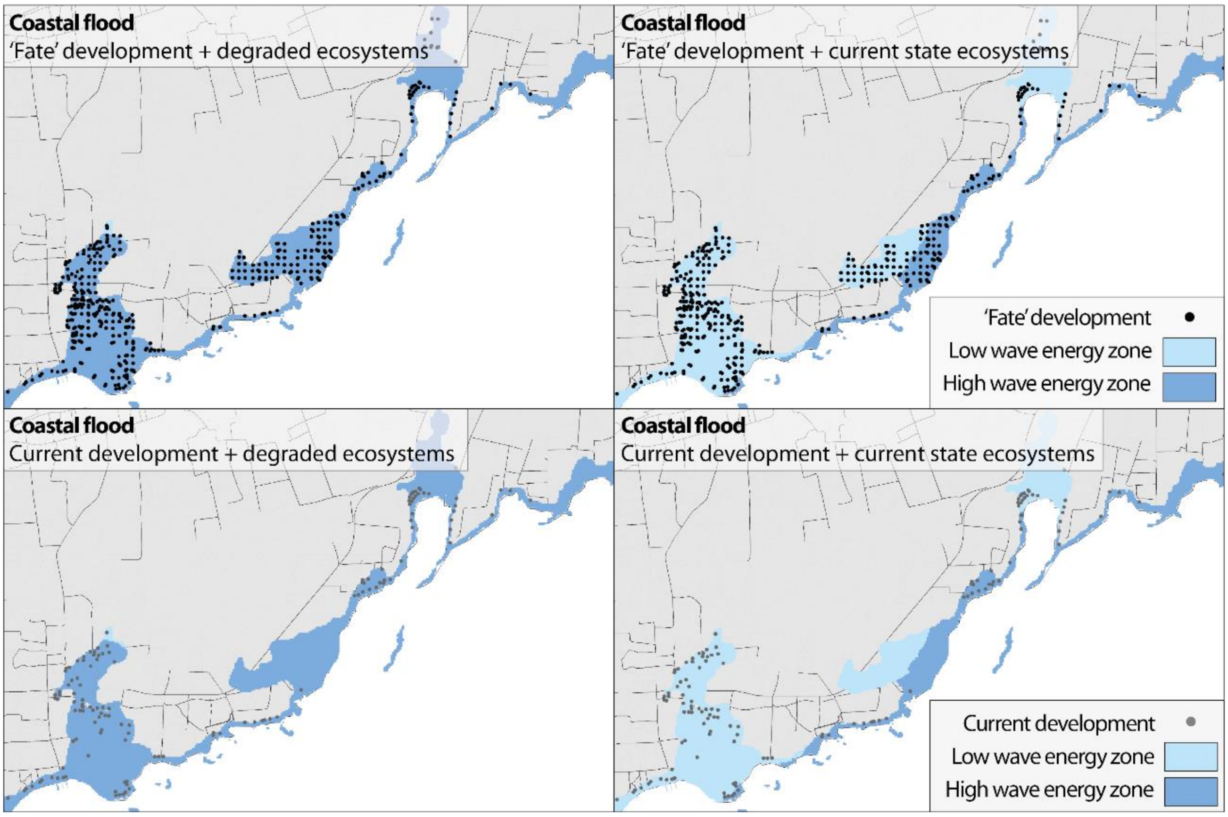


Figure 39: Low wave energy zones (A-zones) and high wave energy zones (V-zones) to illustrate four different coastal flood scenarios on the southeast coast of Anguilla: 'fate' development and degraded ecosystems (top left), 'fate' development and current state ecosystems (top right), current development and degraded ecosystems (bottom left) and current development and current state ecosystems (bottom right).

Spatial economic development scenarios are maps of future building development as developed by Environment Systems for the Anguilla National Ecosystem Assessment. Figure 39 shows the exposure and the extent of the different wave energy zones for four different scenarios describing current and degraded ecosystems and current development levels and increase coastal development under the 'fate' scenario.

Structural building characteristics were estimated by calculating the area covered by the building and by estimating the number of floors of a building using the difference between a digital elevation model and a digital surface model (threshold > 4 meters is more than one floor). A digital surface model is an elevation map that includes vegetation and buildings, whereas a DTM only includes land elevation. Assessing the difference between these layers in building polygons gives an indication of building height.

5.3. Step 3: Assess vulnerability and damages to exposed assets. How fragile are exposed assets to floods?

The vulnerability of exposed economic assets in flood zones is estimated using depth-damage functions. These functions draw a numerical relation between the inundation depth at location and the percentage damage of the total reconstruction costs of the object.

The functions shown in Figure 40 have been developed by the American Federal Emergency Management Agency (FEMA) and are based on historical flood insurance claims. These functions, a set of coastal and riverine depth-damage functions, are applied for this procedure with respect to coastal and inland floods.

Besides the differences between coastal and inland flooding, different depth-damage functions apply to one and two storey objects: single storey objects have a 'steeper' depth-damage curve, as they lose a higher share of their value during shallower floods than two storey objects (Figure 40). In addition, different depth-damage curves apply in high velocity coastal flood zones (V-zones) and low velocity coastal flood zones (A-zones). V-zones are areas exposed to waves of 3 feet or higher. In this analysis, V-zones curves apply to areas on land that are exposed to waves and high velocity flooding, resulting in higher damages to objects besides the effect of inundation. A-zone curves only account for damages caused by inundation.

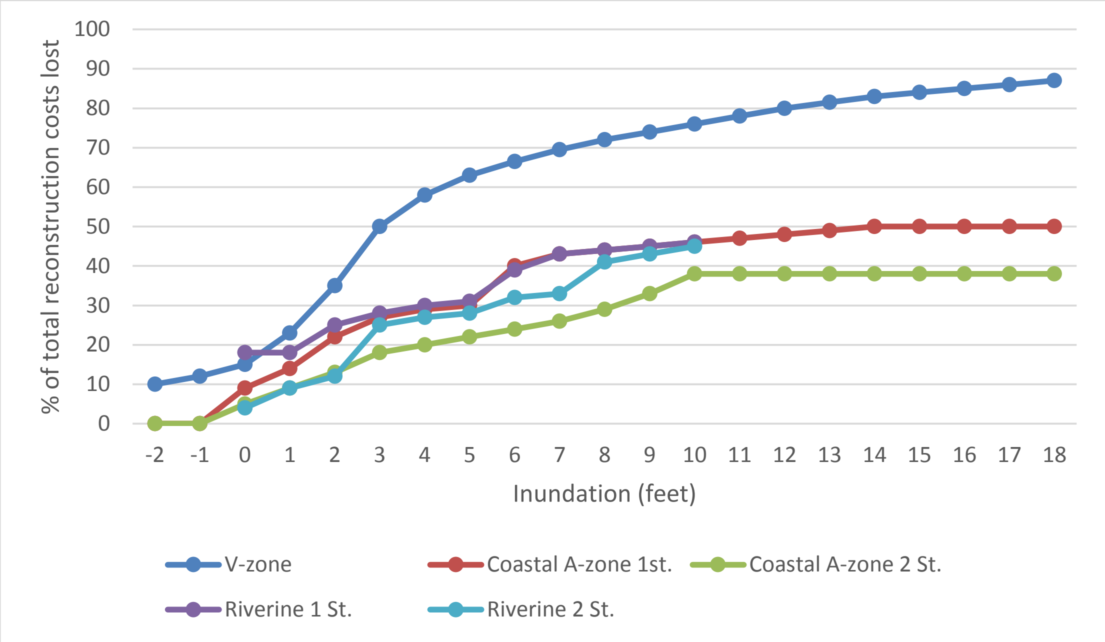


Figure 40 Coastal depth-damage functions for high velocity flood zones (V-zone) and low velocity flood zones (A-zones). In the A-zones, different functions apply to 1 storey and 2 storey objects (FEMA 2011).

Hence, to enable the application of the depth-damage functions (Figure 40) for each object, the type of flooding, the type of zone (A or V) as well as the number of floors need to be determined. Wave and high velocity flood zones (V-zones) can be determined using a wave risk model for coastal flooding. This analysis yields a map of coastal flood zones, indicating per cell a dimensionless value of expected wave energy. This value is established based on a cost-distance function that calculates wave energy dissipation as a result of coastal morphology, bathymetry and the presence of coastal ecosystems (green infrastructure) such as coral reefs and mangroves. V-zones depth damage curves are applied to areas with a high levels of expected wave energy (a risk score of > 5). A similar risk model can be applied to inland floods. This analysis will depict inland areas that are affected by either moving water or standing water as a function of rainfall, soil and the extent and quality of ecosystems. In areas with standing water, riverine depth-damage functions apply (Figure 40), whereas in areas with moving water the V-zone function is applied with an assumed flood depth of 0 feet.

The number of floors of objects can be determined using a cadastral dataset with structural characteristics, if such a dataset is available. Alternatively, if such a dataset is not available, the height of objects can be assessed using a high resolution digital surface model (DSM). Expected damages can be calculated by multiplying the relative damage with the total reconstruction costs of an object. The total reconstruction costs of an object are calculated by the average construction costs per square meter multiplied by the number of square meters of the property. In UK OTs, construction costs are estimated at $300 per ft^2 building surface area.

Depth-damage functions (see Figure 40 for the coastal depth-damage functions) developed by FEMA were used to estimate the relative damages to buildings in areas affected by floods.

Inland flood zones on Anguilla are either zones affected by moving water or standing water. The extent of areas affected by moving water depends on the quality and extent of ecosystems and vegetation. In areas affected by standing water, FEMA's riverine depth-damage functions apply for 1 and 2 storey buildings (Scawthorn et al. 2006), whereas for the areas with moving water the V-zone function (Figure 6) applies with an assumed inundation depth of 0 feet. For this function, 0 feet inundation equals 15% relative damage to the property (Figure 40).

For the exposed buildings in Anguilla, the expected damage was calculated by multiplying the relative damage to a building (i.e. the percentage of the total reconstruction costs of a building) with the estimated construction costs per square and the estimated surface area of a building using the equation below.

Expected damage = (m^2 building*no. floors building*construction costs m^2*relative damage)

5.4. Step 4: Scenario analysis. The value of ecosystems in current and future development scenarios

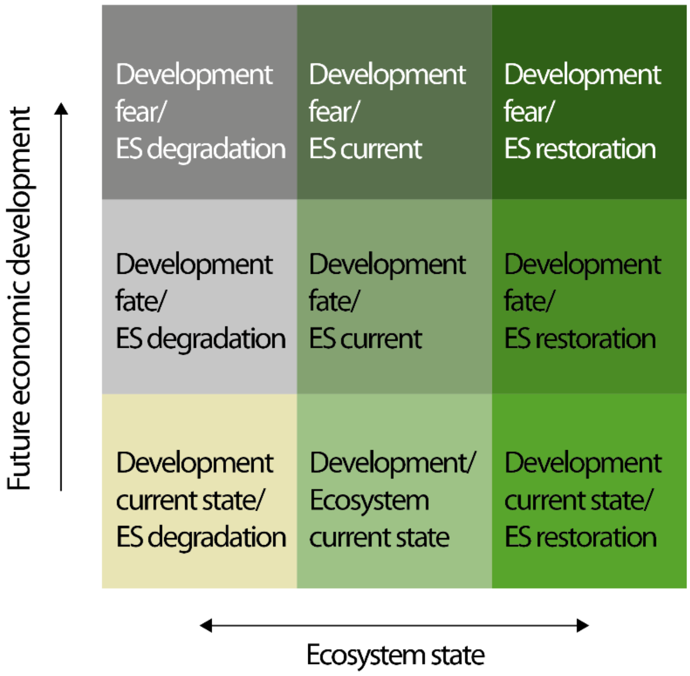


Figure 41 Scenarios to analyse the value of ecosystems in terms of avoided damages to properties during floods.

As shown in Figure 37, the value of ecosystems or natural capital for flood protection is studied using the avoided damages approach. This approach entails the quantification of flood risk by the comparison of different ecosystem states and development scenarios. It is important to also consider development scenarios in the analysis, as flood risk is highly dependent on the aggregated value of exposed assets. In this procedure, we estimate per development level the avoided damages by ecosystems in the current and enhanced ecosystem scenarios in relation to the expected damages under a degraded ecosystem scenario.

Figure 41 describes the nine scenarios that are used to study the value of ecosystems for flood protection. The scenarios represent combinations of varying levels of economic development (vertical axis) and the state of ecosystems and their capacity to reduce flood risk (horizontal axis).

Development scenario Expected damage		Avoided damage value current ecosystems (compared to degraded)	Avoided damage value enhanced ecosystems (compared to degraded)
Development 'fear' Expected damage		$110,781,000	$205,720,000
	$1,373,462,085	**$1,262,681,316**	**$1,167,741,921**
Development 'fate' Expected damage		$95,853,000	$155,864,000
	$1,223,027,731	**$1,127,174,774**	**$1,067,164,005**
Development baseline Expected damage		$19,586,000	$32,512,000
	$327,341,634	**$307,755,585**	**$294,829,399**
	Degraded ES	**Current state ES**	**Enhanced ES**

Table 1: Avoided damage estimates for the direct physical damages caused by coastal flooding. The numbers are based on expected damages to buildings and do not include other damages suffered such as loss of life and business interruptions. Please note that the values as displayed in the table do not reflect annual values, but that these values are associated with the low-probability event as specified in 4.3.2.

Table 1 and 2 show the sum of expected damages for all buildings affected and the sum of avoided damages by natural capital for the scenario matrix for coastal and inland floods for all buildings affected. The avoided damage value of ecosystems, displayed in the larger green font, represent the reduction of expected damage as compared across ecosystem state scenarios (the horizontal axis) with a degraded ecosystem as a reference.

Table 1 shows that during the coastal flooding event for the development baseline, expected damages range from $327million with degraded ecosystems to $294million with enhanced ecosystems, yielding avoided damages by enhanced ecosystems of $32.5million. In the ‘fate’ and ‘fear’ development scenarios, the south-east coast of Anguilla, which is often exposed to hurricanes, is increasingly developed. This results in strongly increasing expected damages, up to $1.37billion, and avoided damages by enhanced ecosystems of over $200million. The expected damage for the inland flooding event is for most scenarios higher than the damages from the defined coastal flooding event, ranging from $300million to a $1.47billion (Table 2). The analysis indicates that inland flooding in particular is mitigated by ecosystems, as the ratio avoided damage/expected damage is significantly higher for inland flooding than for coastal flooding under all scenarios. The avoided damage value represents an estimate of the required reconstruction costs as it is expected today.

Development scenario Expected damage		Avoided damage value current ecosystems (compared to degraded)	Avoided damage value enhanced ecosystems (compared to degraded)
Development 'fear' Expected damage	**$1,467,549,954**	$256,205,000 **$1,211,344,670**	$584,431,000 **$883,118,796**
Development 'fate' Expected damage	**$1,124,394,565**	$181,613,000 **$942,781,441**	$433,444,000 **$690,950,944**
Development baseline Expected damage	**$567,824,503**	$113,696,000 **$454,128,624**	$266,398,000 **$301,426,261**
	Degraded ES	**Current state ES**	**Enhanced ES**

Table 2: Avoided damage estimates for the direct physical damages caused by inland flooding. The numbers are based on expected damages to buildings and do not include other damages suffered such as loss of life and business interruptions. Please note that the values as displayed in the table do not reflect annual values, but that these values are associated with the low-probability event as specified in 4.3.2.

6. Conclusions

The WorldDEM data set allows for complete and detailed terrain analysis to be carried out and is available for all the OTs. Its vertical accuracy is such that the products producible from it, including contours, slope and aspect, will be a valuable addition to the data sets available to the island and could be used for tasks from siting new roadways and building plots through to ascertaining the best place for solar radiation.

The comparison with the LiDAR data from Anguilla showed that the dataset compares very well; issues have been found where features of less than a meter height are present, but these are generally possible to add in from other survey and data sets.

Modelling the risk of various activities; erosion, sea level risk and storm surge provided a set of maps that would be useful to land use planners and land managers on the islands. Using these risk maps it is possible to calculate the economic implications of the extreme events modelled. The techniques have been designed to be repeatable using Open Source software and basic GIS (Geographic Information System) knowledge so that capacity is built in the islands to undertake and re-run this type of analysis in the future.

Scenarios are a very useful tool in describing to policy makers and other stakeholders the possible outcomes of different types of policies and actions. Mapping these scenario shows that they are often spatially related with winners and losers in different parts of the island, depending on the choices made. Economic analyses of the scenarios show the extent to which the choices made benefit or disbenefit the island economies.

Using a scenario where natural capital is emphasised and features such as the presence of mangroves, coral reefs, and forests are maximised and strengthened showed that the protection such ecosystems offer to the island during storm events is likely to have a considerable economic impact. This way, the map models and economic analysis highlight the island’s natural capital as a significant resource to policy makers and interested stakeholders.

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