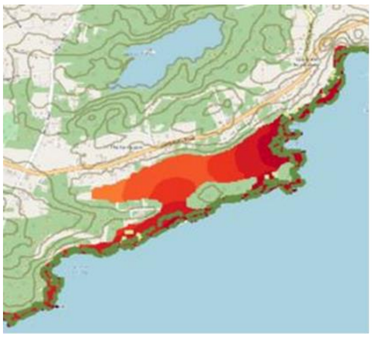
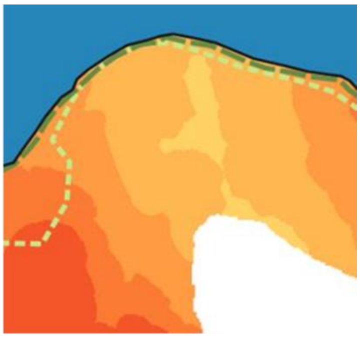
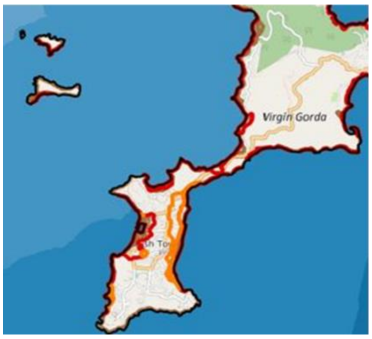
Assess and validate the vulnerability mapping of the UK's OTs of Anguilla and BVI to natural hazards, and the value of natural capital in mitigating impacts

Final report

C16-0208-1070 Phase 2







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Joint Nature Conservation Committee

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Summary

Following the extreme 2017 hurricane season and the devastating impact on the Caribbean Overseas Territories (OTs), this project used pre-and post-hurricane satellite imagery to:
1) Refine and develop the existing GIS based vulnerability model in Anguilla, post hurricane events;
2) run the refined model on Anguilla and British Virgin Islands (BVI);
3) use the vulnerability mapping to inform, build capacity and knowledge in the OTs and present opportunities.

The high-level purpose of the work is to provide data for governance and policy and natural capital assessment, showing how natural capital can and does protect the livelihoods and other infrastructure on the islands.

Areas investigated include; inland flooding which highlighted areas at risk, and looked at the role of channels, ghauts (with and without vegetation) and hollows; storm surge, based upon 6.2 metre surge as reported during Hurricane Irma.

Results show that most of the observed actual damage occurs within the storm surge areas modelled as at 'high risk' zones, with the majority of the areas of observed potential damage falling within areas modelled as 'low' to 'moderate' risk zones. Within the modelled extent, the inland flooding followed a similar trend, however observations were confounded by the delay in suitable data capture, leading to greater uncertainty.

Both models accounted for protection afforded to the island by its natural capital, and how it reduced the associated risk within a given area, therefore supports the evidence base that natural capital does contribute towards the protection of livelihoods and other infrastructure on the islands.

Recommendations include:
1) extend the application of the model to the other Caribbean Overseas Territories using radar data or, where available, LiDAR or other sources;
2) using the updated shallow water map, underway for the Darwin Plus Project Mapping Anguilla's blue belt, to improve the accuracy of the Anguilla storm surge model;
3) extend the economic assessment (from Phase 1) to include the updated Phase 2 risk model.

Two workshops were run on the islands to show the results of the modelling and the validation work and to confirm the findings against local knowledge. The models were deemed to be sufficiently accurate to be helpful.

The immediate impact of this study is that the islands now have the ability to make more informed decisions when siting emergency response stations and vehicles prior to an event. Furthermore, disaster management now has the ability to better target resources pre- and post-event. In the medium term, the islands now have the ability to raise awareness for the value of natural capital. For the long term, this study gives the islands an improved ability to take into account natural capital during the planning decision process to maximise the protection that nature can give.

Contents

Introduction

Following the extreme 2017 hurricane season and the devastating impact on the UK's Overseas Territories (OTs) in the Caribbean. This project used pre-and post-hurricane satellite imagery to:

1) refine and develop the existing GIS based model in Anguilla post hurricane events;
2) run the refined model on Anguilla and British Virgin Islands (BVI);
3) use the vulnerability mapping to inform, build capacity and knowledge in the OTs and present opportunities.

This work has been undertaken in two phases, Phase One validated the model on Anguilla and Phase Two applied the model for BVI.

This work is to follow on from the 2016 project produced by Environment Systems which developed the GIS based model to assess the vulnerability of 5 UK Caribbean Overseas Territories (Anguilla, British Virgin Islands, Tristan de Cuna, Montserrat, and Turks and Caicos Islands (TCI)) to storm surge and flooding events and their impacts on infrastructure and human life. This work also supports JNCCs suite of projects which aim to demonstrate the value of Natural Capital and build capacity on the islands in the integration of satellite data, Geographic Information Systems (GIS) and economic assessments of environmental goods and services (derived from natural capital) into their evidence for policy decisions to protect the livelihoods and other infrastructure on the islands.

The high-level purpose of the work is to generate data for governance and policy and natural capital assessment, showing how natural capital can and does reduce the potential risk of damage from storm surge events.

Objective

The objective of the project was to validate the existing vulnerability models created during Phase 1 of this work by identifying the features damaged in Hurricanes Irma and Maria, using VHR data, photographic images and knowledge from social media to obtain a validation of the model.

Stage 1: Purchase and correction of satellite data (optical and radar) – Anguilla and BVI

The post hurricane imagery was obtained by JNCC for Anguilla and BVI. Multiple images and data were needed to capture the islands with cloud free conditions. The images were fully corrected and made ready for use. For some of the images this required additional manual processing as conditions meant that georectification (ensuring the imagery was in exactly the correct space) was not straight-forward, this particularly related to some of the scenes acquired for BVI. In addition, Environment Systems acquired Sentinel 2 Imagery for all cloud free useful scenes post Irma and then post Maria hurricanes to use as additional evidence of damage zones.

All the imagery, including the Sentinel 2 data, was transferred to the islands during the capacity building visits in March 2018. These are now available within the archive of imagery for the islands so they can be re-used for different types of analysis.

Sentinel 1 imagery (RADAR) data over the islands was also acquired for two passes after Hurricane Irma. This was evaluated for usefulness to look at damage and change. Unfortunately, the scale of the imagery (30m pixel size) meant that individual objects such as houses and small flooded hollows could not be identified from background 'noise'. These images were therefore not further used in the analysis or given to the islands as part of the archives.

Stage 2: Validation, development and vulnerability assessment – Anguilla

Method
The vulnerability model was re-run using the actual track of the hurricane on Anguilla using the methodology described in (Williams, *et al*. 2017). The detail of the methodology is available in Appendix 1. This describes:

- The creation of the modelled damage line. Both the extent of the storm surge and flooding on inland areas was carried out by digitisation of experienced Satellite Image Interpreters.
    - The storm surge was reported by islanders to be approximately 6.2 metres.
    - Actual damage was defined as water or storm surge damage clearly visible in the imagery (seen from above).
    - Potential damage was defined where water or storm surge damage was likely but was not clearly visible in the imagery as it was obscured by vegetation, etc.
- The validation data and ground truthing.
- The storm surge risk model and how it was scored.

In addition to the creation of damage lines, in Anguilla sedimentation patterns around the coast were also assessed. These were compared to the presence of visible erosion channels.

A simple opportunity map was created showing areas where, due to the slope and proximity to water, it might be possible to plant mangrove. The models were re-run, assuming all these areas were planted, and showed how this natural capital would then protect a range of assets (infrastructure/buildings etc.), moving them from high risk to lower risk categories.

Stage 3: Produce Refined Anguilla Model

Damage assessment

When comparing the pre- and post-event satellite data, the extent of the storm surge is clearly evident. Figure 1 shows the extent of the confirmed damage line, overlaying the pre-event imagery. Figure 2 shows the same example area post-event, with extensive loss of vegetation within the area inundated by the storm surge.

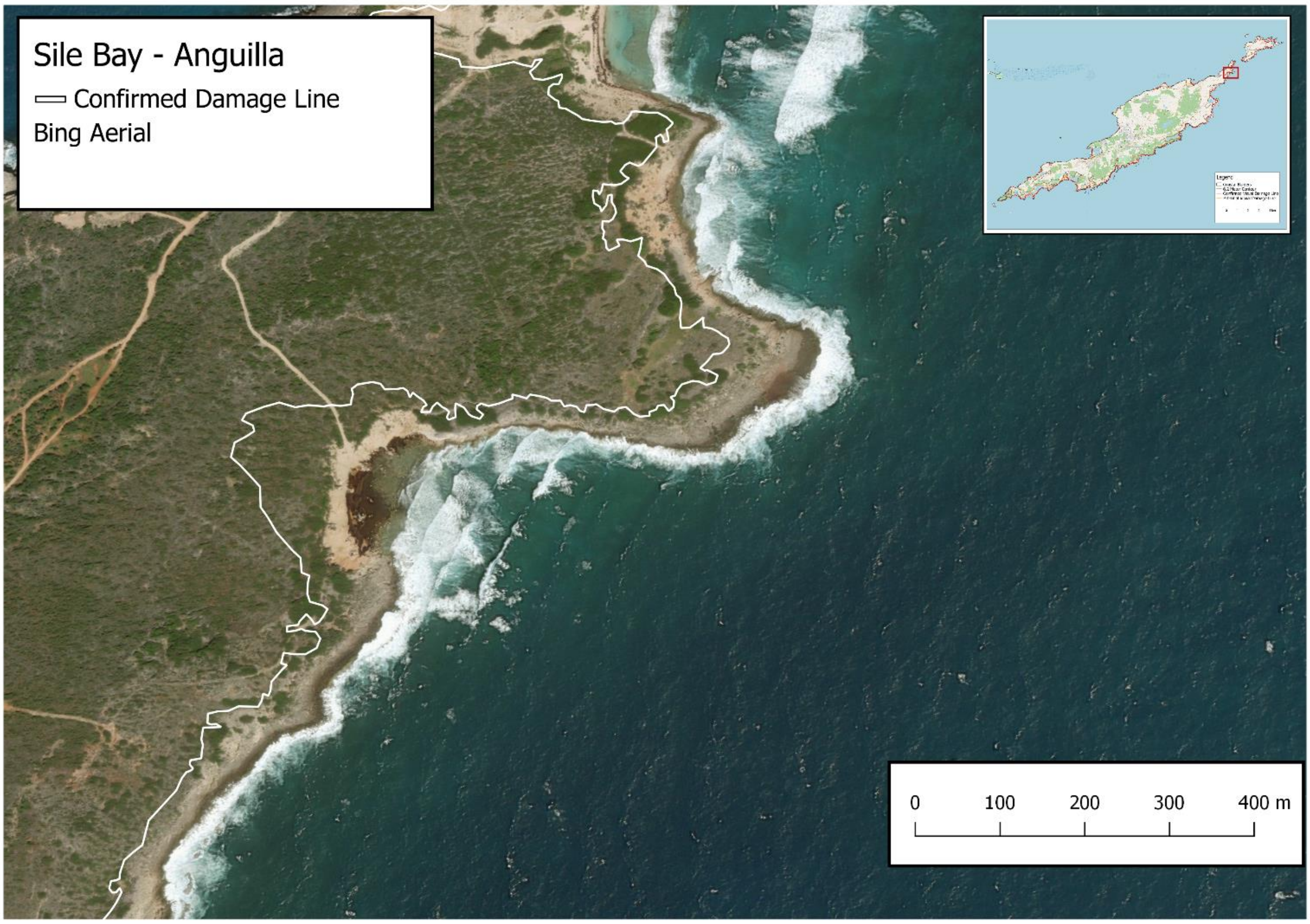

Figure 1. Image shows the baseline land cover (pre-event), with the post-event damage line.

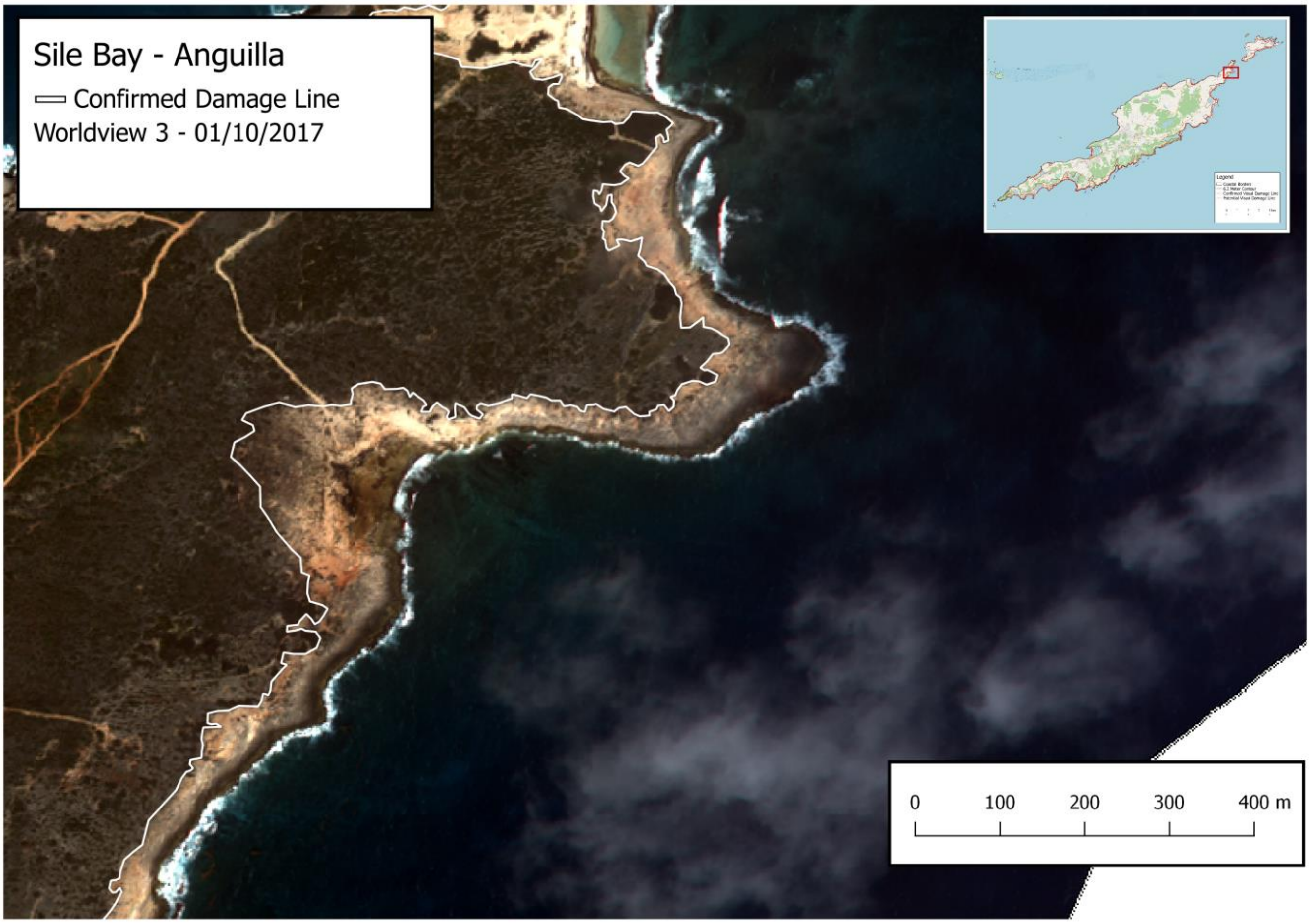

Figure 2. Image shows the land cover (post-event), with the post-event damage line.

In some cases, it was not possible to confirm that the damage was caused by the storm surge, therefore a second damage line was created to show the potential damage extent. Figure 3 shows an example area of confirmed damage, as interpreted from satellite imagery, along with the potential damage further inland. This classification of 'potential damage' reflects areas where the surge is highly likely to have occurred, but the land cover masks its impact (e.g. area under dense vegetation cover). In some cases, damage can also be seen inland with bare ground visible where it was not in pre-event imagery. In this case, the potential damage line is expanded to show that these areas have been considered.

The map showing all of the confirmed and potential damage lines across the island can be seen in Figure 4. It is evident from Figure 4, that the southern side, along with some low-lying areas along the northern coast, is where the majority of the confirmed and potential damage lines are located.

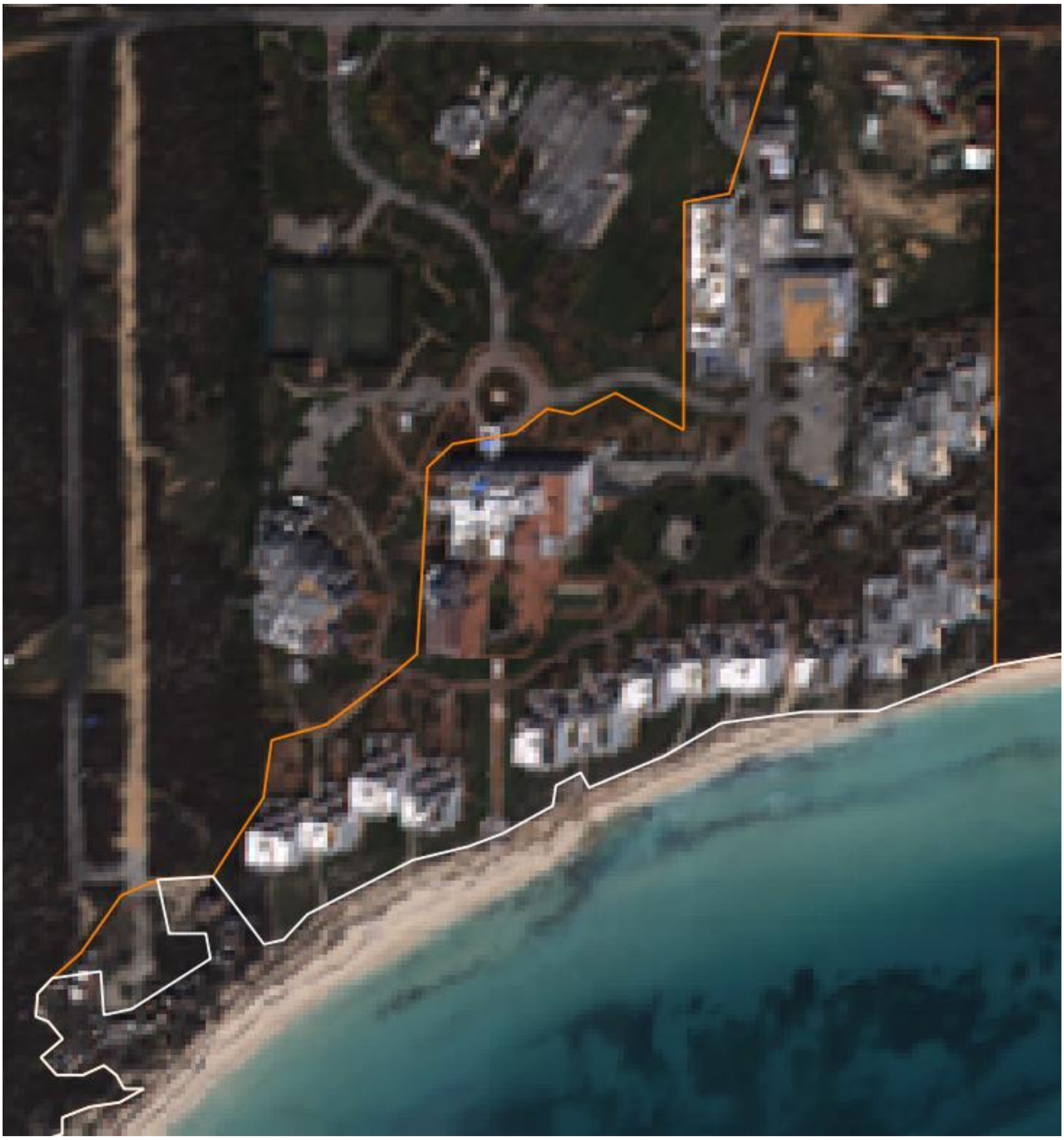

Figure 3. Confirmed damage line in white; the potential damage line in orange.

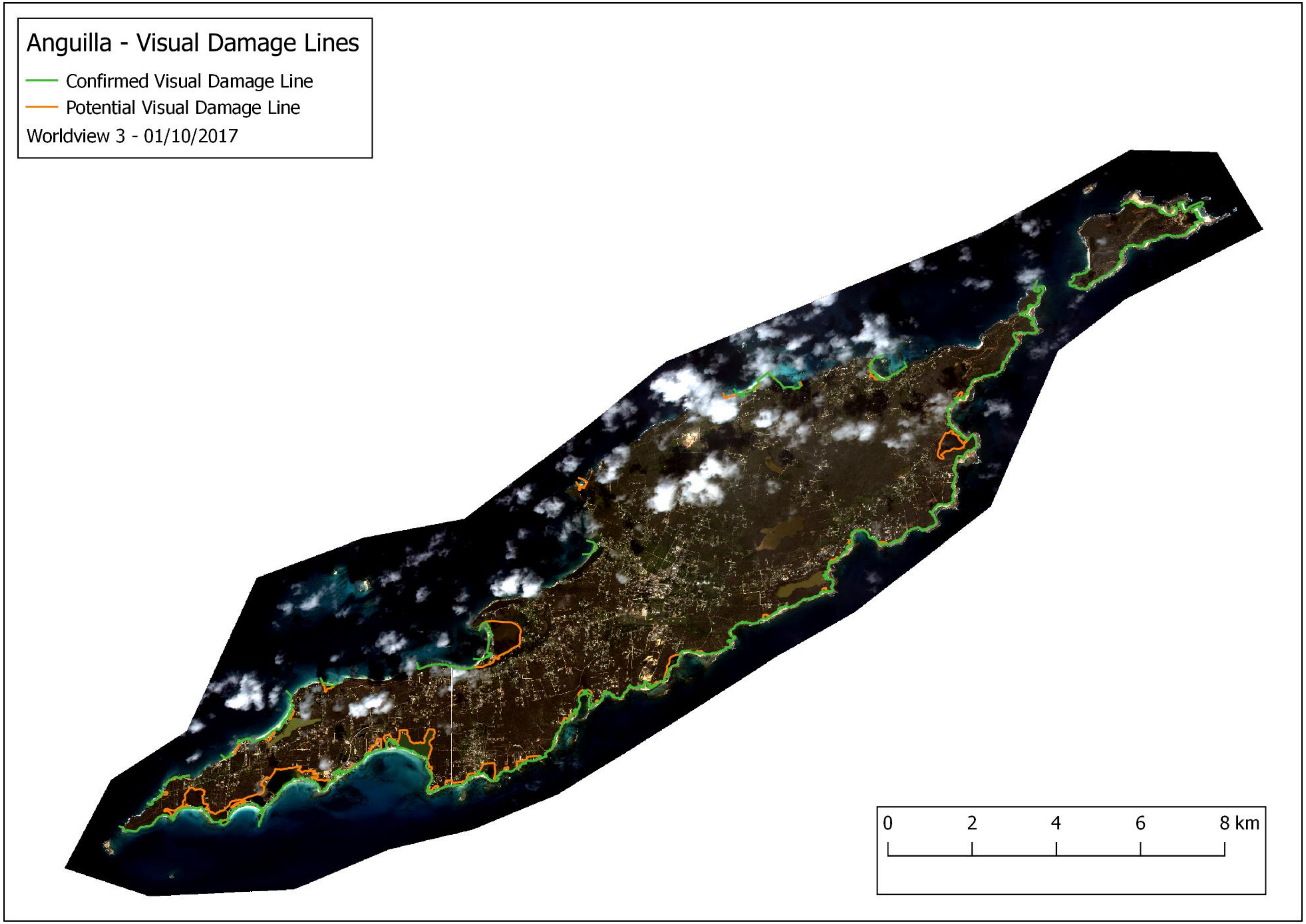

Figure 4. The final confirmed and potential damage line over Anguilla.

Storm surge

The storm surge risk was modelled for the Anguilla pilot study. Figure 5 shows the results of this modelling for a storm coming from the south east, which is the most common direction from which storm surges originate for Anguilla. 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 costal salt ponds are at risk. As these areas contain built infrastructure, storm events are likely to have an economic impact on Anguilla.

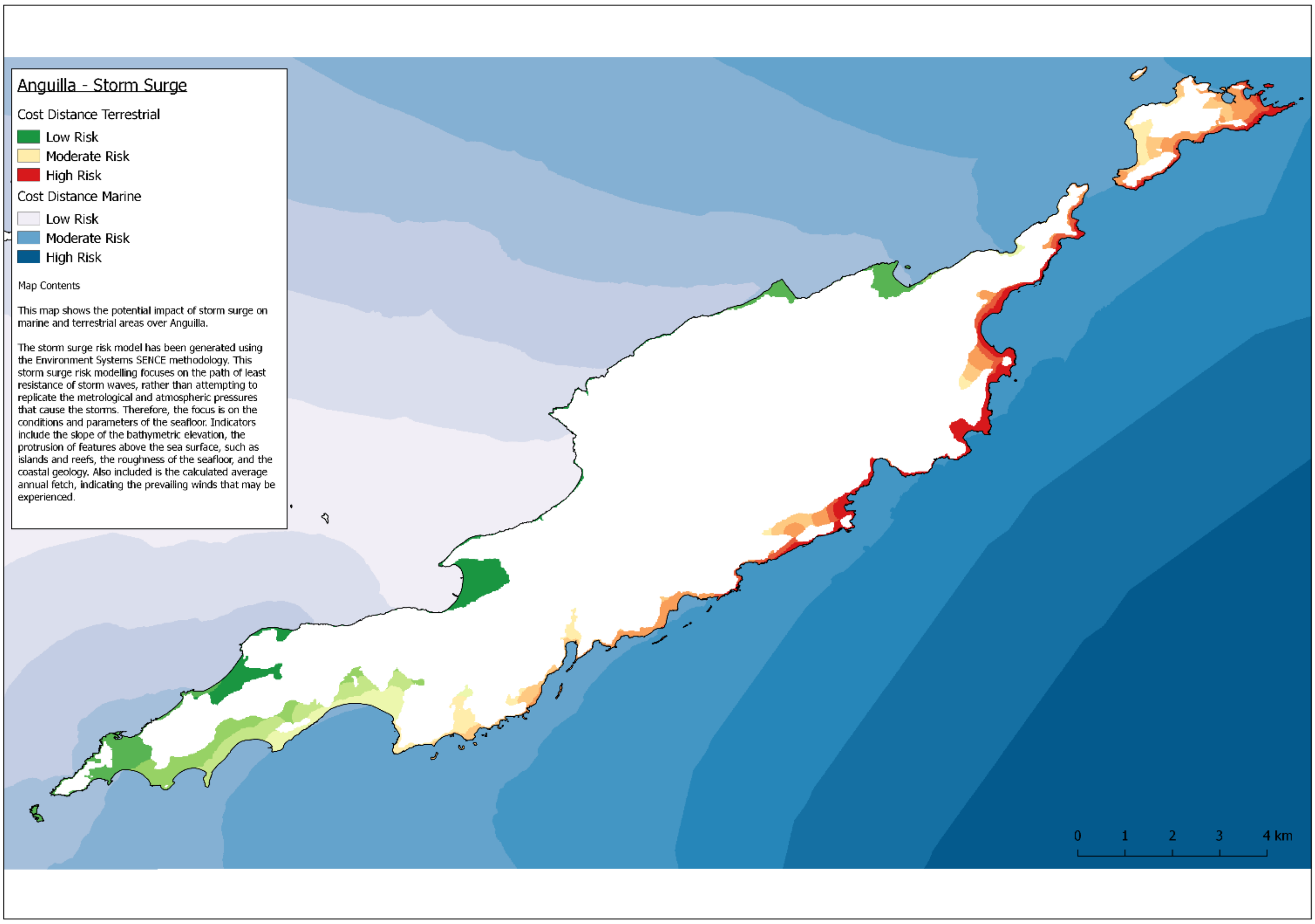

Figure 5. Map showing the damage risk from storm surge on the terrestrial areas over Anguilla. The storm surge risk model has been generated using the Environment Systems SENCE methodology.

Storm surge quality assessment

For Anguilla, a comparison was made of the visual extents of confirmed and potential flooding caused by the storm surge, and the risk zones from the storm surge model. This was achieved by calculating the percentage area for of the visual assessments, for each of the risk categories (low through to high). The results show that most of the visible damage occurs in the areas of high risk, with the majority of the areas of potential damage falling with the low to moderate risk zones Figure 6). This confirms that the model is identifying high risk areas which are most likely to have significant visual damage.

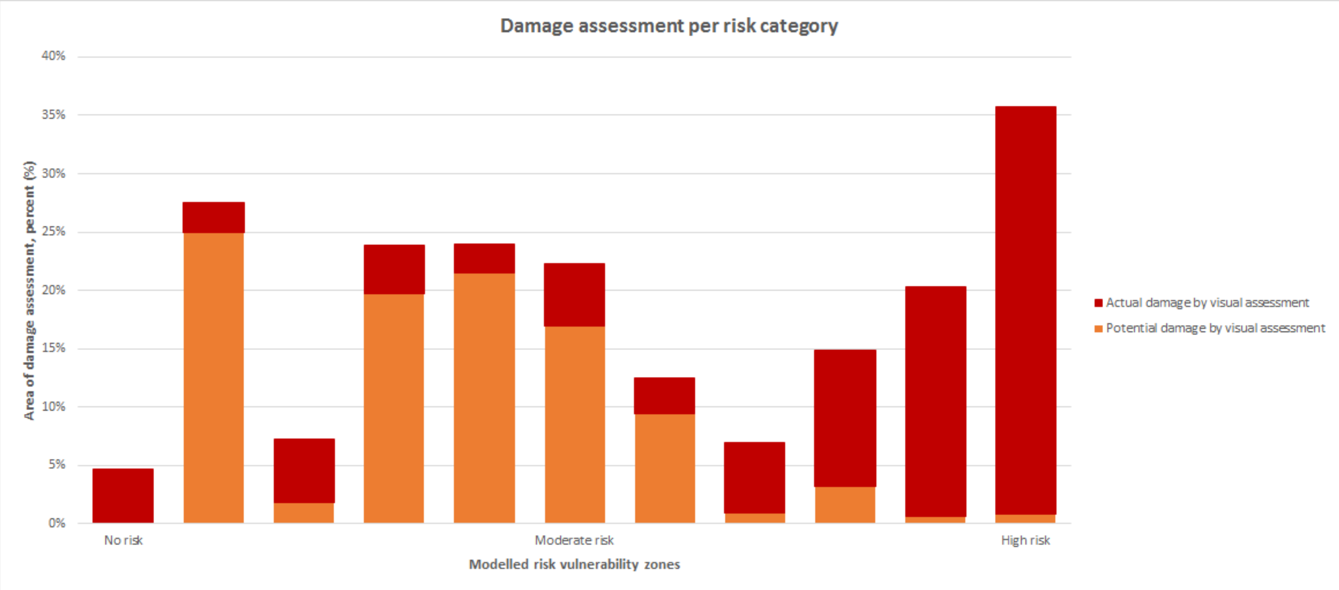

Figure 6. Stacked bar chart showing the percentage area for of the visual assessments, for each of the storm surge risk categories (Low through to High), for Anguilla.

Inland flooding

The inland flooding model was run for Anguilla (Figure 7); 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. However, it is worth noting that the depth of flooding could increase in the future (Kossin, J. 2018). Conversely, in areas shown in green, standing water could reach several metres in depth if conditions are severe enough. Here, damage to property could be much more substantial.

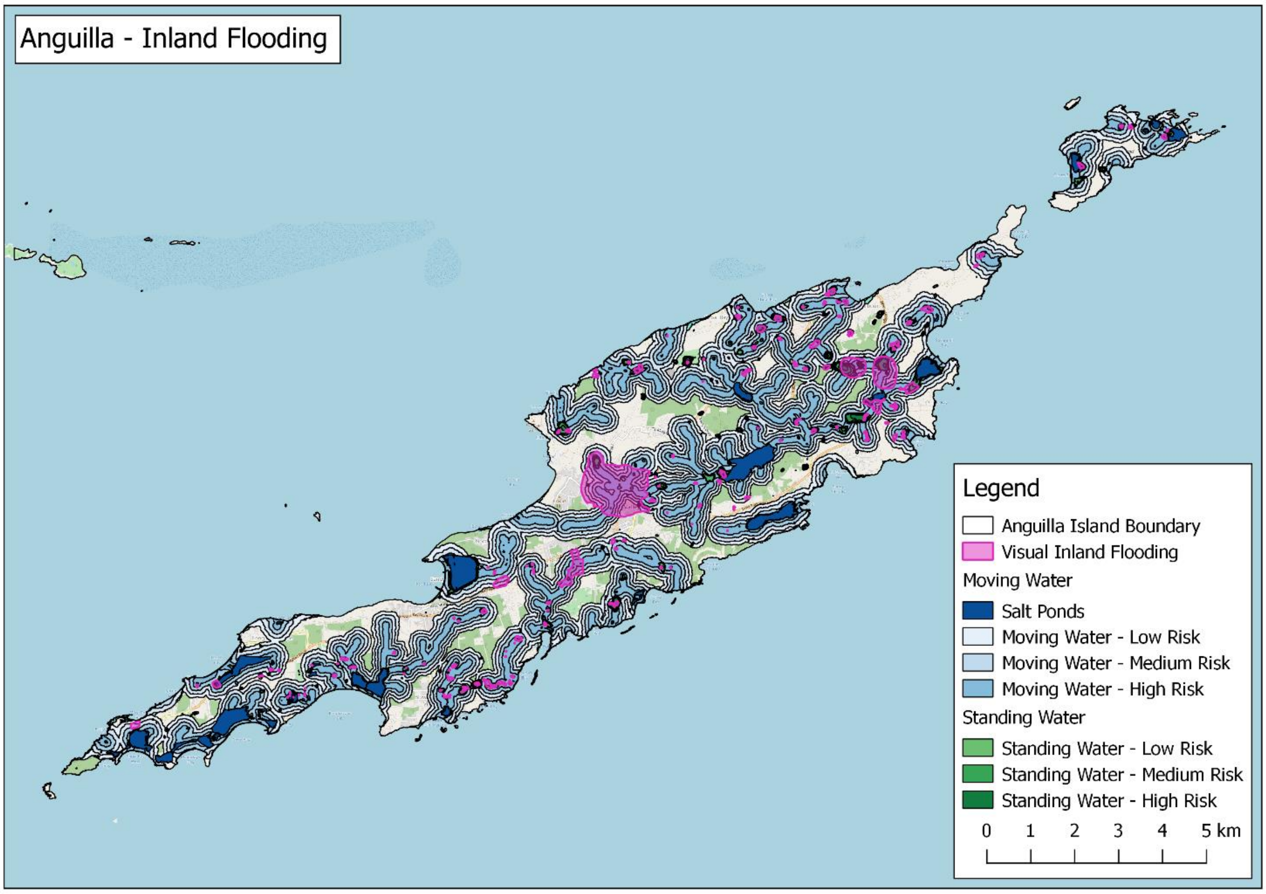

Figure 7. Comparison of modelled inland flood risk and visual damage assessment.

Inland flooding quality assessment

For Anguilla, a comparison was made of the visual extents of actual and potential inland flooding caused by the hurricane, and the risk zones from the inland flooding model. This was achieved by calculating the percentage area for of the visual assessments for each of the risk categories (Low through to High). The results show that most of the visible damage occurs in the areas of high risk, with the majority of the areas of potential damage falling within the low to moderate risk zones (Figure 8). The 78% of damage observed ('No risk' in Figure 8) that was not reflected in the model, is the result of the visual interpreters being unable to sufficiently differentiate flood damaged areas from those damaged by wind.

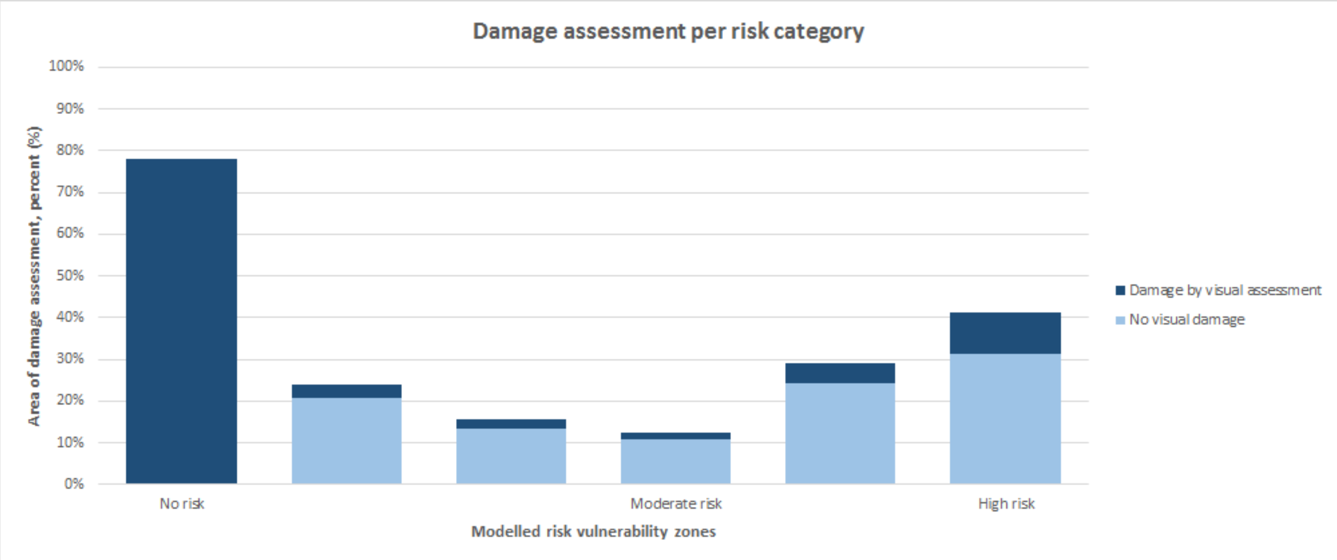

Figure 8. Stacked bar chart showing the percentage area for of the visual assessments, for each of the inland flooding risk categories (low through to high), for Anguilla.

Contour line assessment

Storm surge quality assessment

For Anguilla, a comparison was made of the visual extents of actual and potential damage lines, and the 6.2 metre contour (Figure 9). This was achieved by calculating the percentage area of the visual assessments, for each within and outside of the 6.2 metre contour. The results show that all of the visible damage (actual and potential) occurs within the 6.2 metre contour (Figure 10). Only 30% of the area within the 6.2 metre contour had no visible damage. These areas may well be those most protected by Natural Capital, such as scrub and thicket vegetation where water ingress was not visible from above.

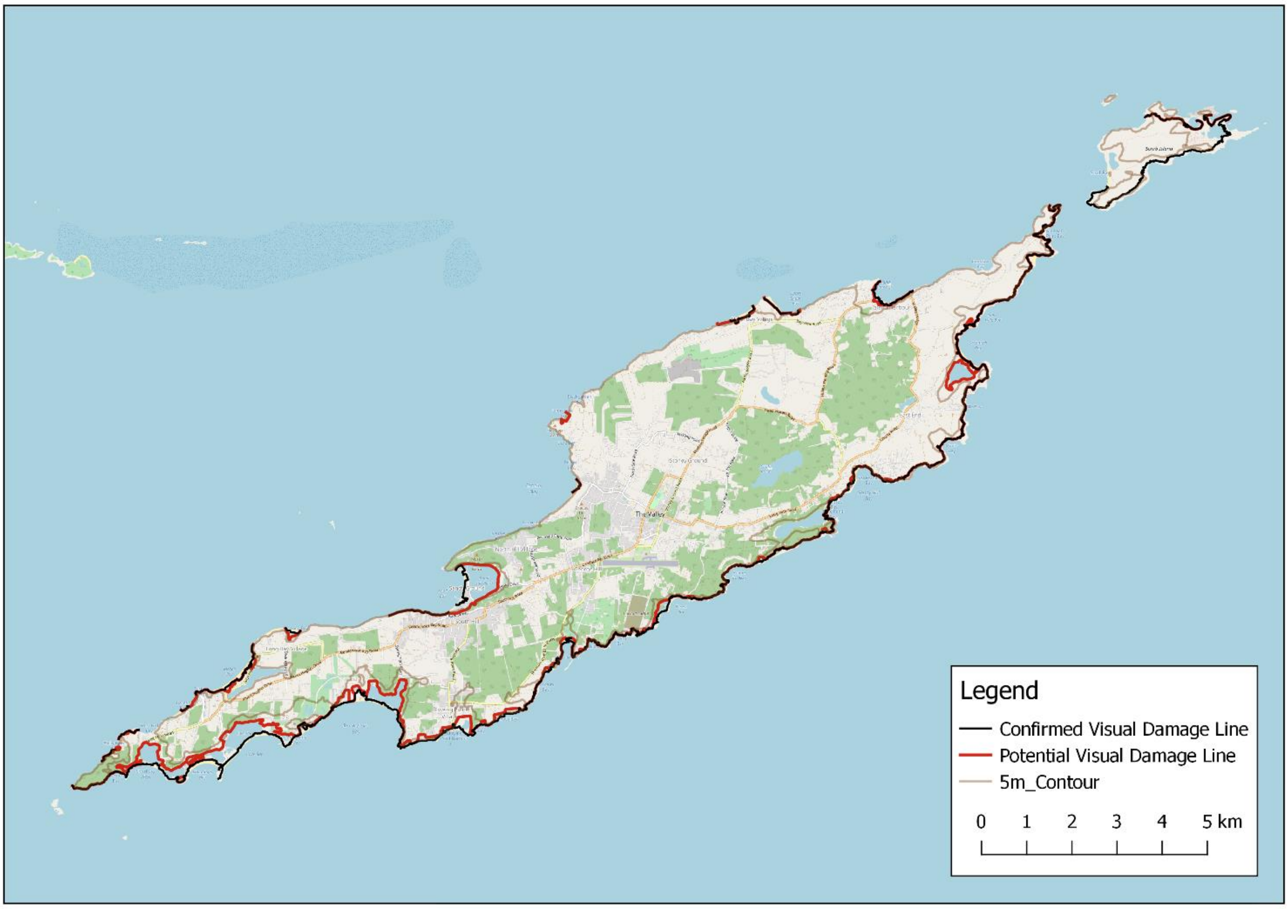

Figure 9. Anguilla Comparison to 6.2m contour. This map shows the visual damage lines of storm surge Irma and Maria, compared to a 6.2 metre elevation contour.

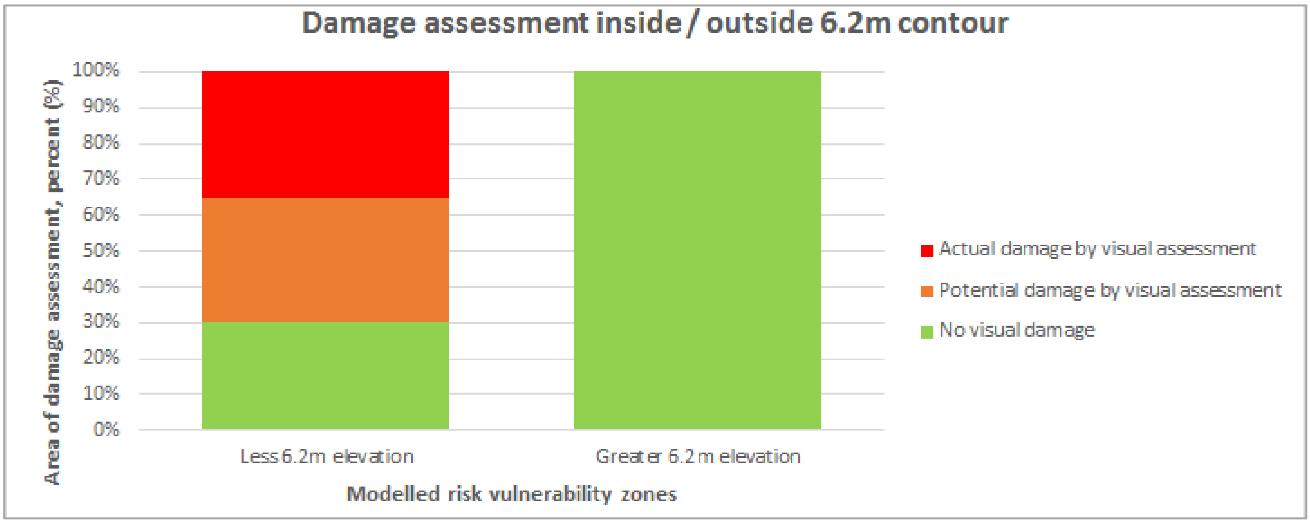

Figure 10. Stacked bar chart showing the percentage area for of the visual assessments (actual and potential) damage lines, and the 6.2 metre contour, for Anguilla.

Sedimentation

The ‘Total Suspended Solids Map’ (Figure 11) shows the soils lost from Anguilla during hurricane Irma and Maria. Very fine soil particles can remain in suspension in water for a considerable period of time without contact with the sea floor. This dataset shows the suspended solids in the ocean after the hurricanes storm surges damage to the islands soils. Unfortunately, due to the date of the imagery being after the hurricane events, some of the suspended soils had settled. The loss of soil as suspended soils can be seen over Tintamarre Island, Saint Martin, south of Anguilla. Here the tail of suspended soils coming off of the island can be easily seen. Due to cloud cover and time difference it was not possible to compare the sediment plumes with the channel and ghauts on the land.

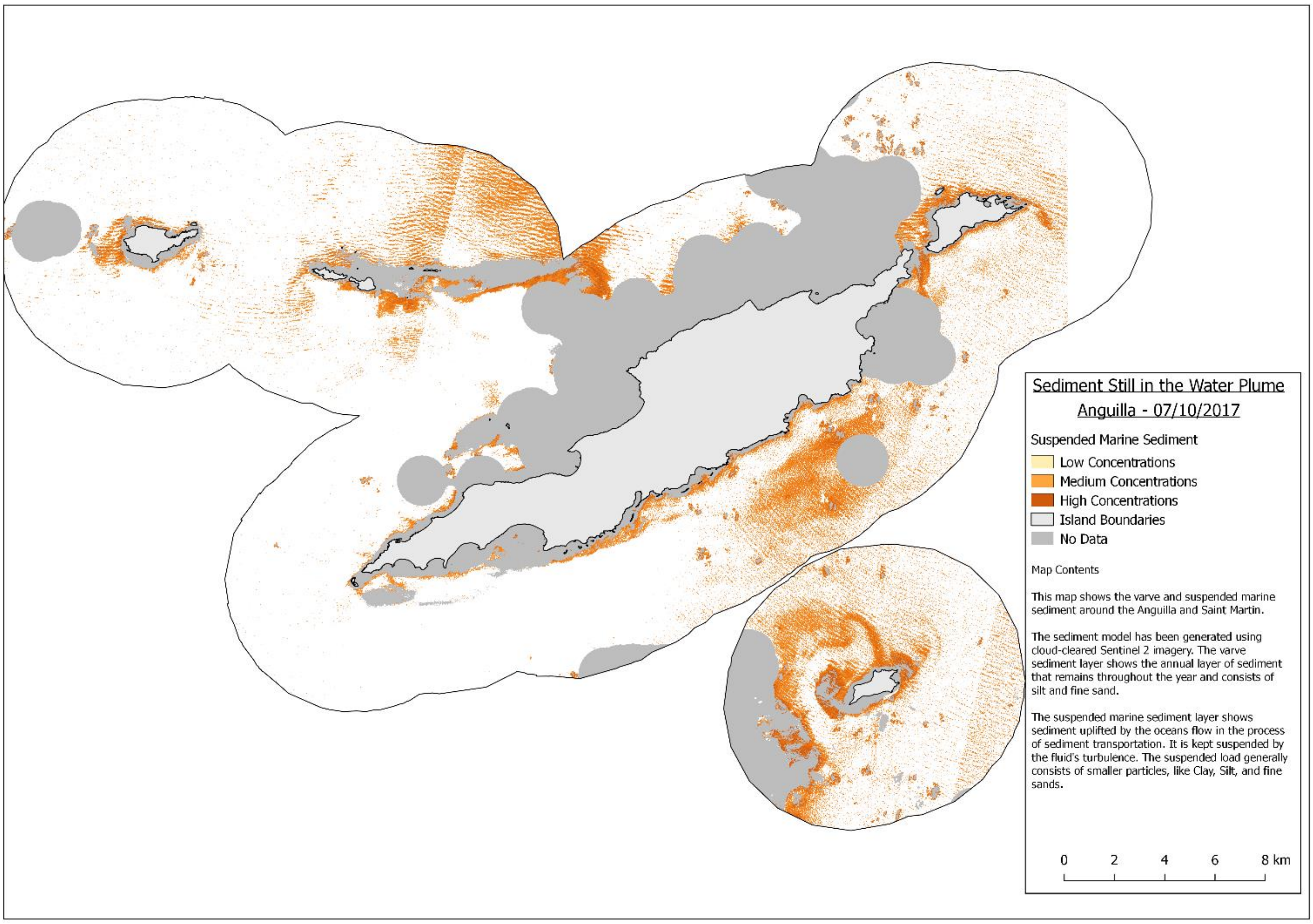

Figure 11. Total Suspended Solids. Map for Anguilla’s marine environment post-event.

Beach change

The satellite imagery (Worldview 2 and Worldview 3) was used to undertake a visual comparison of beach change. This was achieved by using expert staff to assess the change. A line shapefile was created using the same projection as the island, to identify areas of change along the coastline. Figures 12 & 13 show how the beach location and extent has changed due to the hurricanes. It shows that there was some small reduction in beach extent in Sandy Ground which had a 'low risk' form the hurricane, whilst there was a dramatic reduction in beach width on Rendezvous Bay where the risk and impact of the hurricane was 'high'.

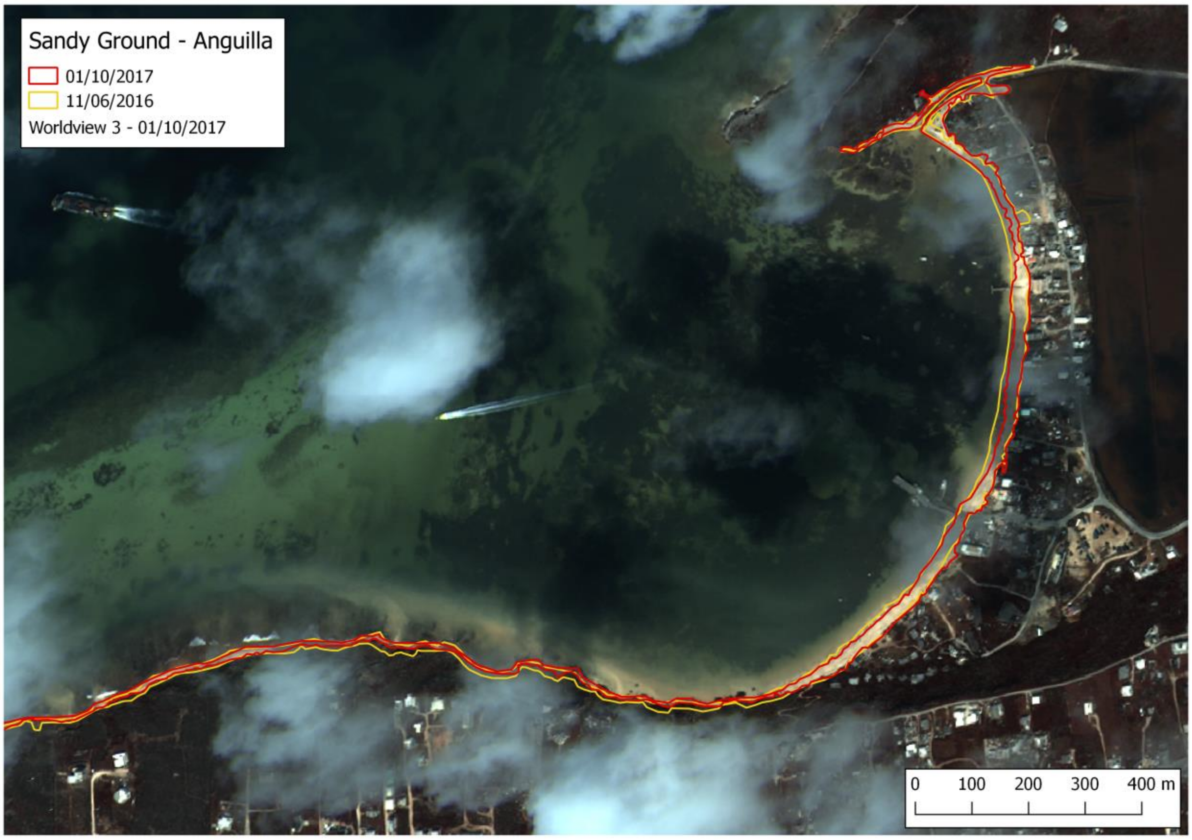

Figure 12. Beach change at Sandy Ground (Anguilla).

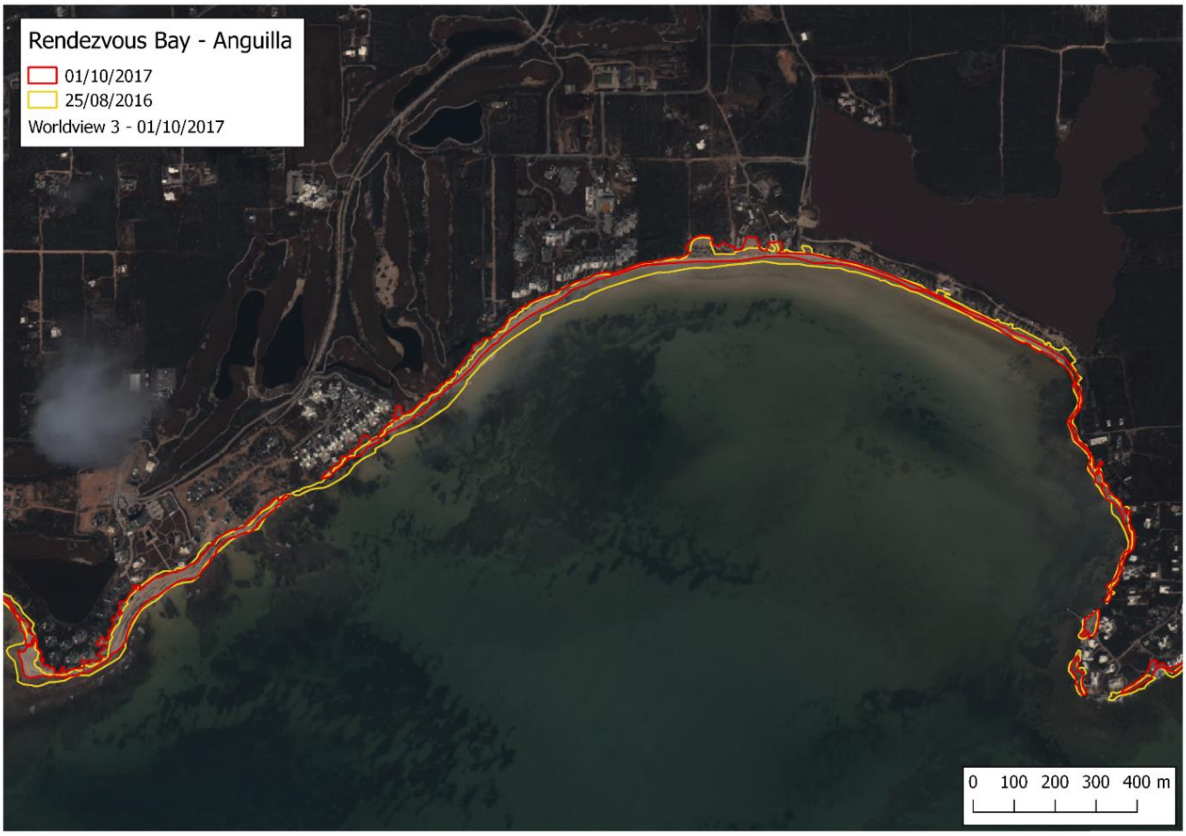

Figure 13. Beach change at Rendezvous Bay (Anguilla).

Discussion on the validation of the risk models

Storm surge

The extreme 2017 hurricane season and the devastating impact on the Caribbean Overseas Territories (OTs) presented an opportunity to validate the storm surge risk model, generated using the Environment Systems SENCE methodology, that was developed in Phase 1. The availability of pre and post event satellite imagery allowed actual observed damage (along with social media reports), to act as the validation mechanism.

When the modelled storm surge risk map for Anguilla is overlaid with the confirmed and potential damage lines, it is apparent that 95% of the actual confirmed damage fell within the storm surge risk extent (Figure 14). Furthermore, 35% of the actual (and 1 % of the potential) damage is located in areas deemed at high risk by the modelling. This is a good indication that the modelled storm surge risk map is a valid tool for assessing potential risk from a storm surge event.

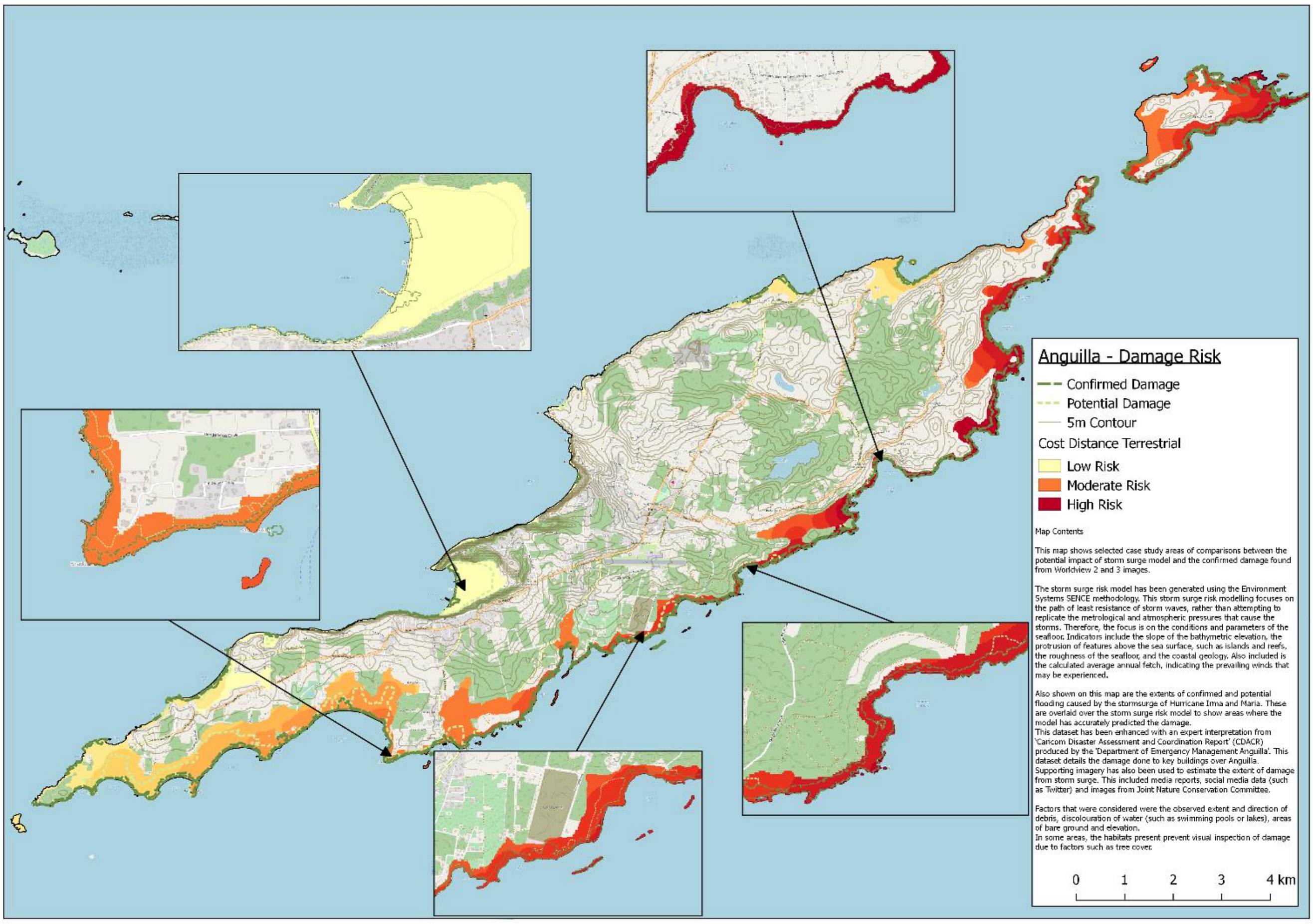

Figure 14. Damage Risk with case studies. Map -Selected case study areas were selected for comparisons between the potential impact of storm surge model and the confirmed damage found from Worldview 2 and 3 images.

Currently the Islands are using the 6.2 metres contour as a means of estimating storm surge risk. However, from the graphs and models it is apparent that this is not an accurate predictor of damage, with 30% of the land within the contour line not being damaged.

Inland flooding

The extreme 2017 hurricane also presented an opportunity to validate the inland flooding model created in Phase 1. As with the coastal storm surge, a damage assessment was undertaken using pre- and post-event satellite data. However, evidence of inland flooding within low value areas was not often apparent. This was most probably due to the flooding having passed by the time the satellite scenes were captured the affected areas. Anguilla being a limestone bedrock has a very permeable geology, therefore standing water does not normally remain for a long time on the surface. With this in mind, caution must be exercised when assessing the comparison between visible damage and the inland flooding model, where nearly 80% of the visible damage fell outside of the areas deemed 'at risk' (Figure 15). Further development of the inland flood risk model is therefore desirable.

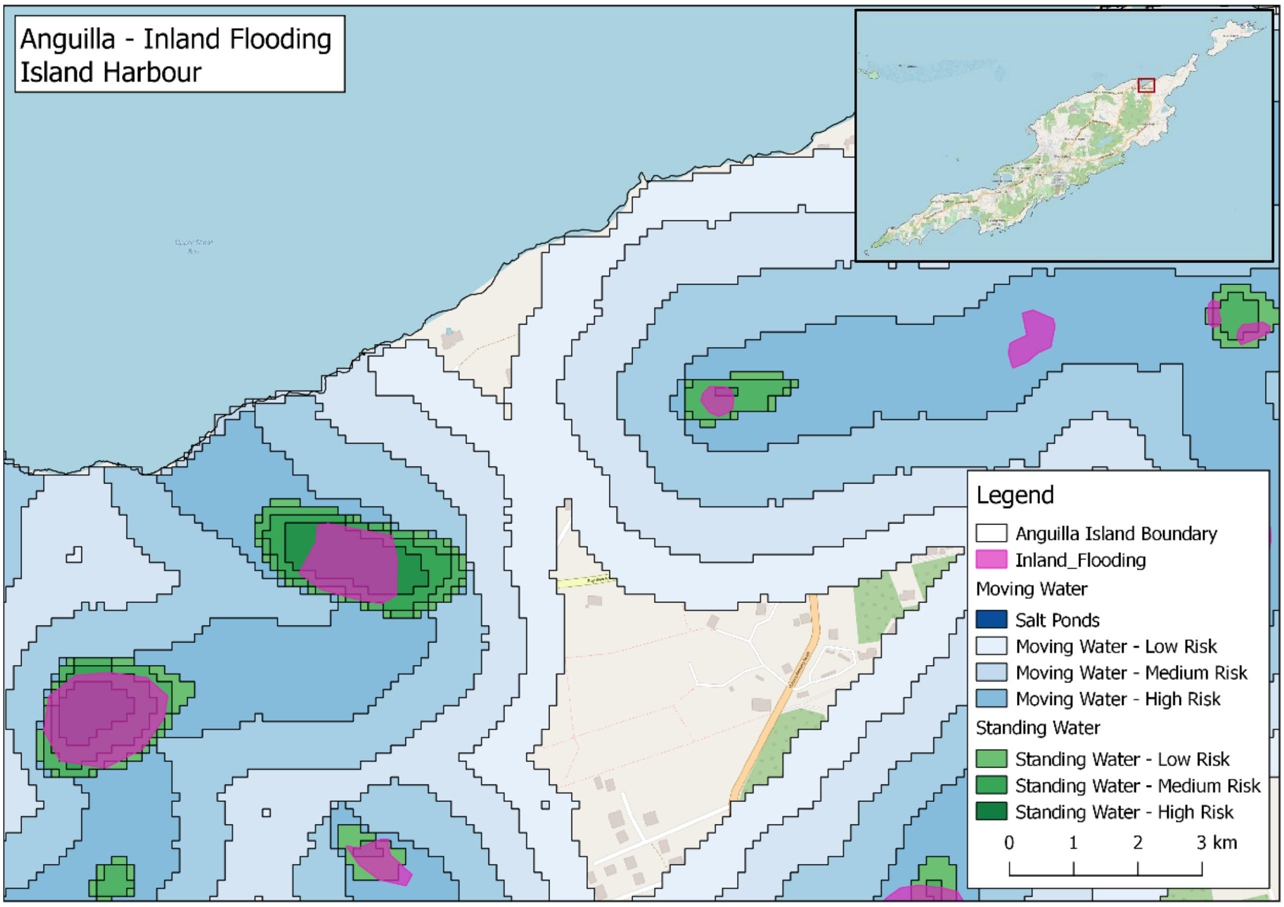

Figure 15. Example of a higher value area of inland standing water captured by the visual damage mapping, compared to the inland flood model risk extent.

Validation of the Model by local stakeholders

During the visits to demonstrate the model and validation on Anguilla (See Stage 6) a range of local stakeholders were asked to assess the model. The stakeholders included members from Department of Environment Department of Physical Planning, Department of Disaster Management, Department of Agriculture and Department of Fisheries. Local Wildlife Trust and Local press officers. The following points were made.

- For the storm surge model there was widespread agreement that areas that received significant damage were accurately illustrated in the high-risk areas and moderate-risk areas from the model.
- The model was deemed more accurate than the contour line Disaster Management Department currently use and was received well for planning disaster management strategies.
- Natural Capital, especially mangroves and reefs, were acknowledged as having an important role in protection. A number of areas were pointed out where the vulnerability risk model had accurately shown these features.
- The most significant area where the model was deemed to be less accurate against events that had occurred was over the areas of salt ponds. During hurricane Irma, the salt ponds seemed to have played a very strong protective effect on the land behind them. This was not accounted for in the models and would be worth more research to ascertain if it is a known phenomenon. However, it was acknowledged by all stakeholders that the ponds were at a very low level before the hurricane. Following the hurricanes, they were at a very high level, and the role as protective features if they are full was widely discussed, with many people fearing that they would not fulfil this purpose if they were already at full capacity. Further research is recommended into this aspect. The model could be updated following the results of this work.

Stage 4: Opportunity mapping for Anguilla

Opportunities for nature-based resilience

As well as showing where the existing natural capital occurs and areas of risk, SENCE (Spatial Evidence for Natural Capital Evaluation) methodology allows for the examination of opportunity spaces, which is where it might be biophysically possible to re-establish a particular habitat to help enhance the resilience of the natural capital on the island. In this instance we examined where it was possible to re-create mangrove by considering the correct slope and distance to water (Figure 17). The model needs to be refined by adding in soil types, which we did not have at a sufficient scale to build into this model, but it provided a good indication of 'areas of search' to ascertain on the ground if mangroves could be established. The Figure 17 shows changes to the level of potential risk if the mangroves were planted and had become established. It demonstrates that by establishing mangroves in the opportunity areas, they would lessen the 'risk' of serious damage for a number of properties (Figure 18).

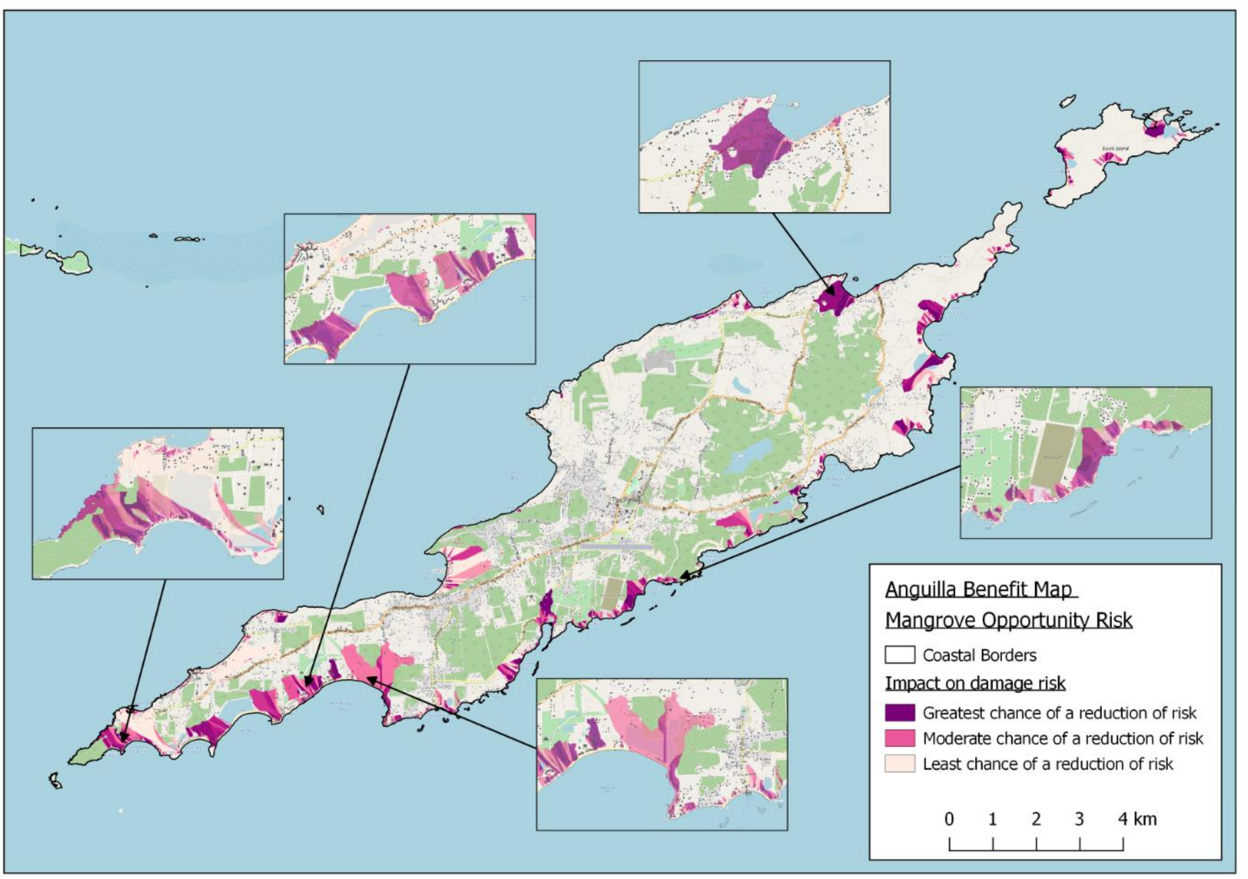

Figure 17. Opportunity areas for establishing mangroves, identified by considering the correct slope and distance to water, and the associated damage risk reduction from a storm surge event.

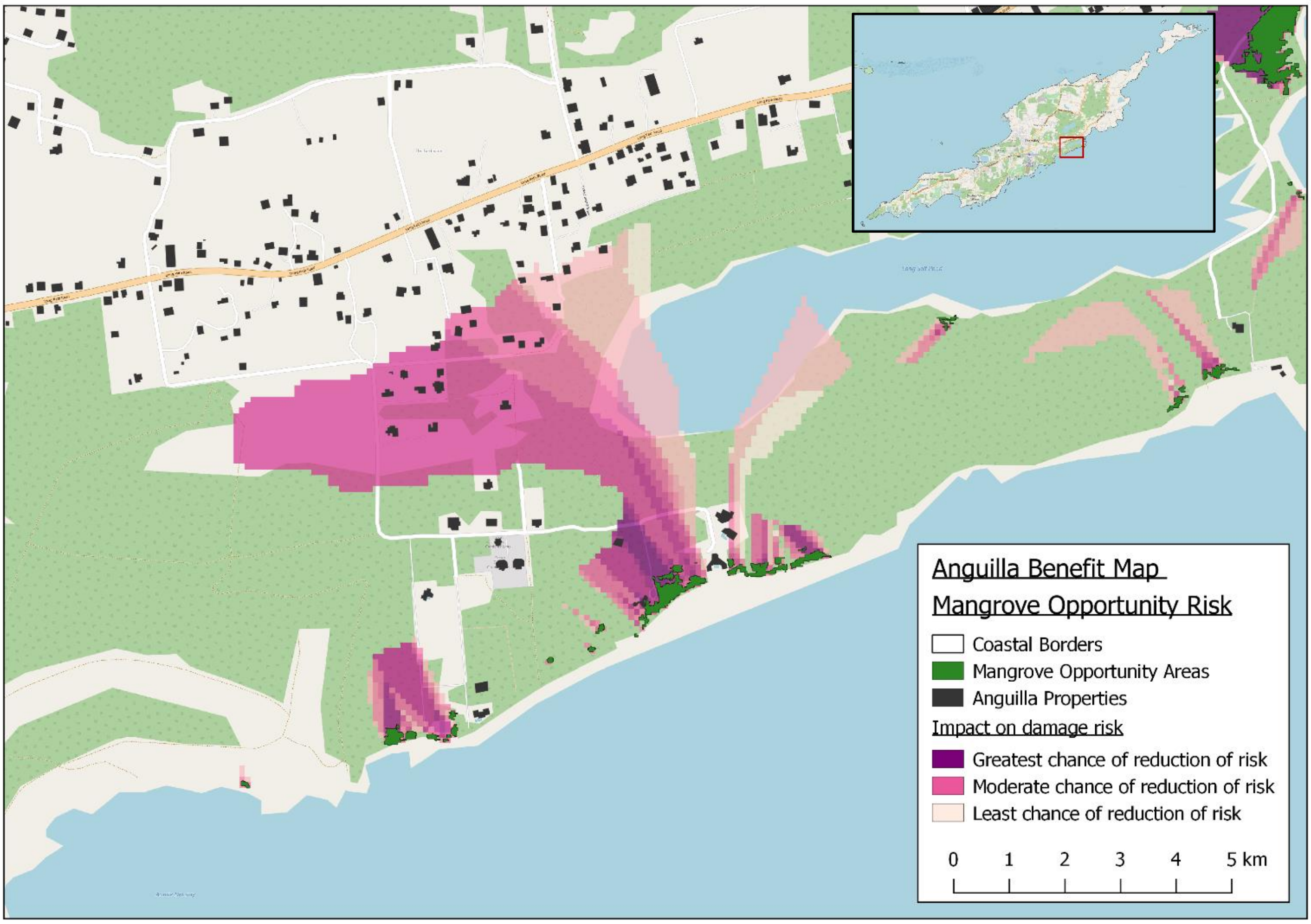

Figure 18. Close- up of Long Pond Bay showing the number of properties that move from a higher risk to a lower risk zone if mangroves can be planted in this opportunity space.

Stage 5: Application of the procedure – British Virgin Islands

Data assessment for BVI

JNCC acquired ultra-high-resolution imagery for BVI from the time between the two hurricanes and post hurricane Maria. Sentinel 2 imagery was also acquired. All was corrected, processed and added to the archives for BVI to use again.

In order to run the analysis for BVI it was necessary to create an up-to-date habitat map for BVI. The methodology used and map created can be seen in Appendix 2 and 3. The model was then run using the general track of Hurricane Irma and Maria to generate the risk outputs for BVI (Appendix 1).

For assessing the model, social media was used to help confirm damage lines using the methodology described in (Williams, *et al*. 2017). The detail of the methodology is available in Appendix 1.

To asses the damage on BVI the following tasks were created:

- The creation of the modelled damage line. Both the extent of the storm surge and flooding on inland areas was carried out by digitisation of experienced Satellite Image Interpreters.
  - The storm surge was reported by islanders to be approximately 6.2 metres.
  - Actual damage was defined as water or storm surge damage clearly visible in the imagery (seen from above).
  - Potential damage was defined where water or storm surge damage was likely but was not clearly visible in the imagery as it was obscured by vegetation, etc.

Storm Surge model BVI

The British Virgin Islands pilot study in Figure 19 shows the results of the risk of storm surge model from a storm coming from the south east, which is the most common direction from which storm surges originate for British Virgin Islands. The blue colours show areas of strongest wave action, whilst the red show areas most at risk of the storm surge from this direction. The northern island of Anegada is most at risk due to its low elevation and lack of surrounding islands to ease the storm's path.

The other islands of the British Virgin Islands have a steep elevation which reduced the risk factor for a great deal of the island. The clusters of islands closest to the hurricane's path, such as Virgin Gorda, also helped reduce the risk to islands like Tortola and have a higher damage risk.

A large amount of the built infrastructure is still in low lying land close to the coast, therefore storm events are highly likely to have a large economic impact over the British Virgin Islands.

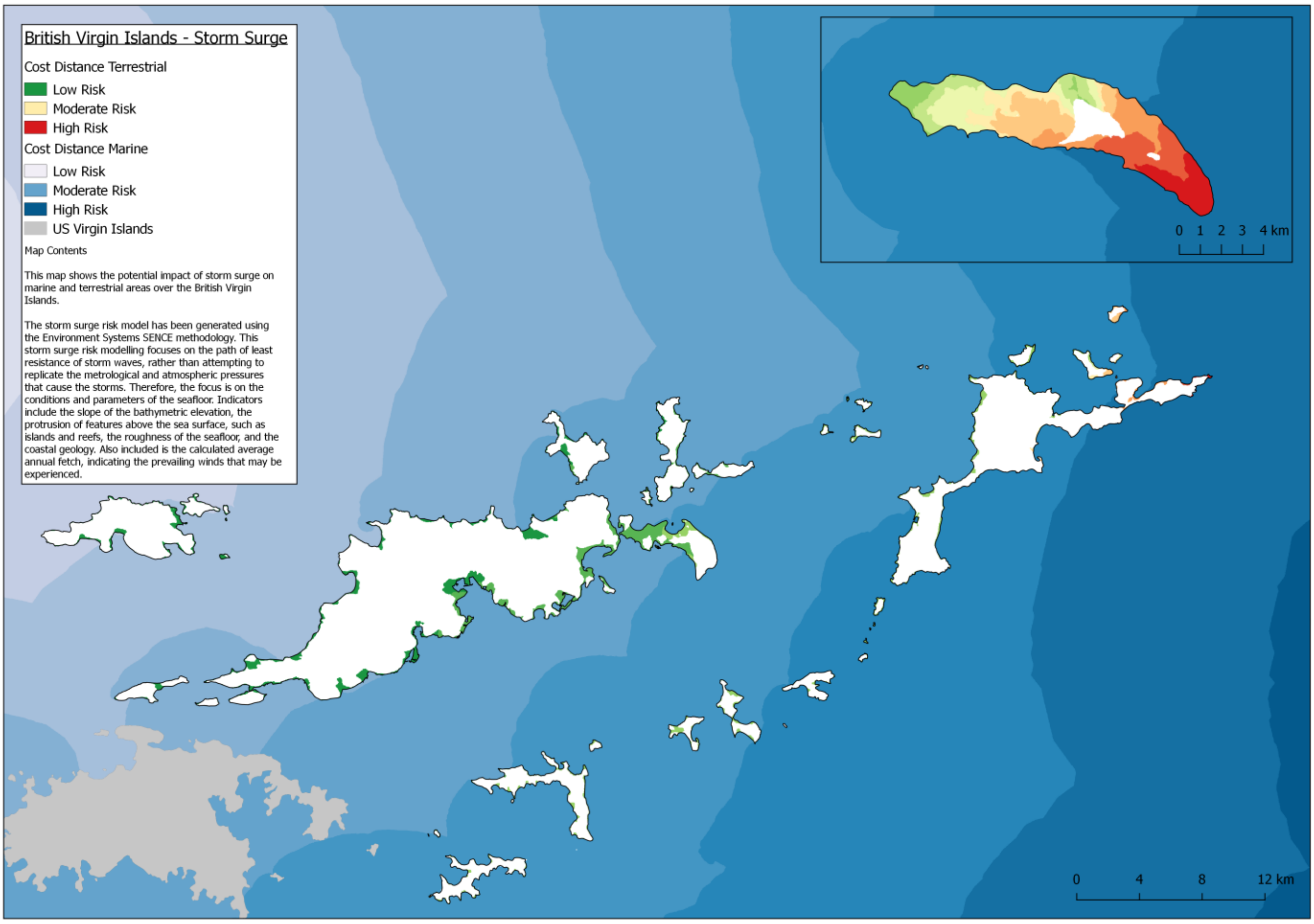

Figure 19. Map showing the damage risk from storm surge on the terrestrial and marine areas over the British Virgin Islands. The storm surge risk model has been generated using the Environment Systems SENCE methodology.

Comparison of risk model and visible damage post hurricanes for BVI

After the creation of a base data, including a habitat map (see Appendix 3), the storm surge model methodology was then directly applied to BVI (Figure 20 & 21). When the modelled storm surge risk map for BVI is overlaid with the confirmed and potential damage lines, it is apparent that the majority of damage lines fall within the model extent. Following stakeholder engagement, the model was deemed to show the areas in an accuracy that was deemed 'fit-for- purpose' by those who experienced the storm events on the islands, such as staff from Department of Environment and Disaster management. This subjectively demonstrates the potential transferability of the model to other Caribbean islands.

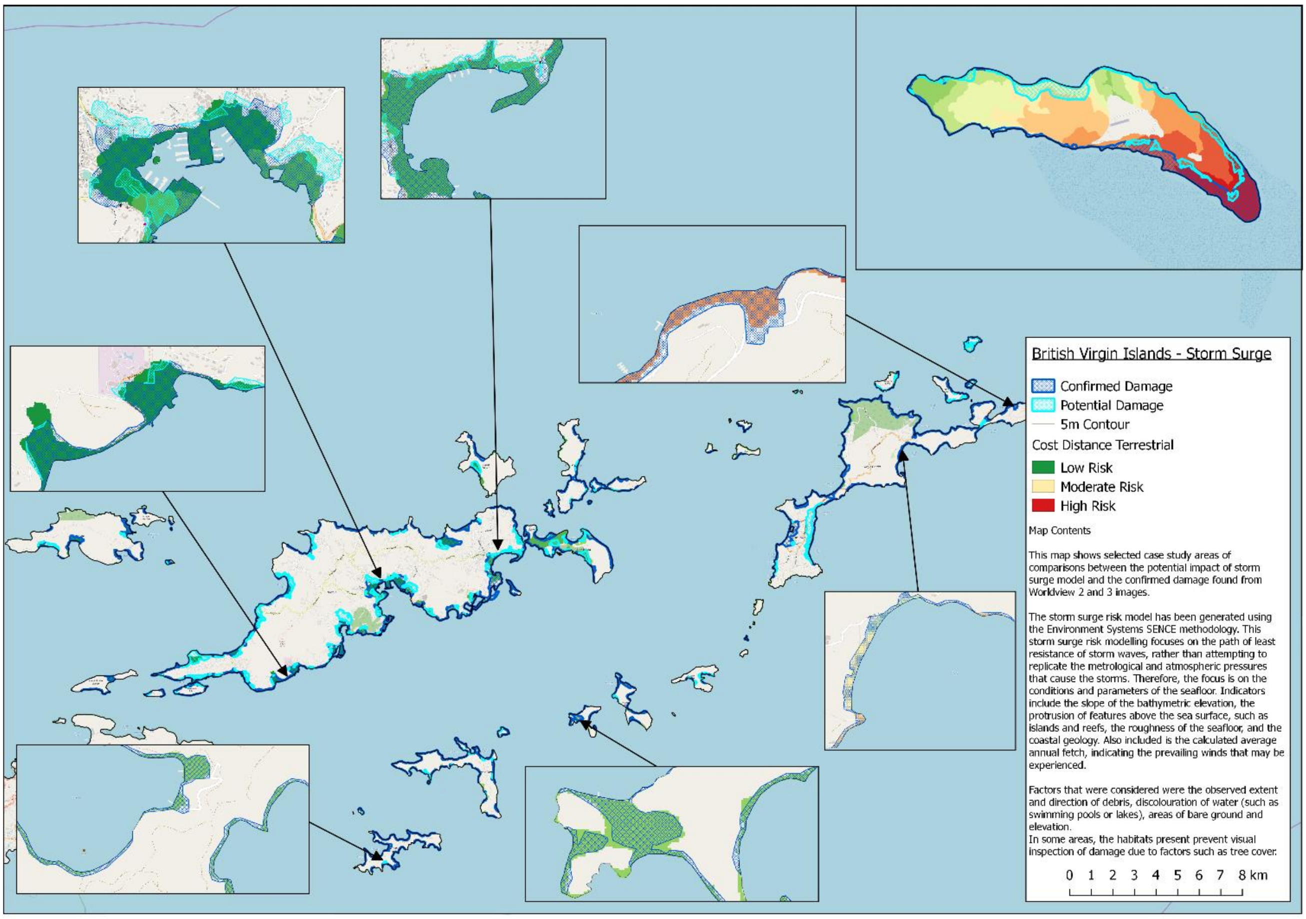

Figure 20. Damage Risk with case studies. Map -Selected case study areas were selected for comparisons between the potential impact of storm surge model and the confirmed damage found from Pleiades and Worldview 2 images.

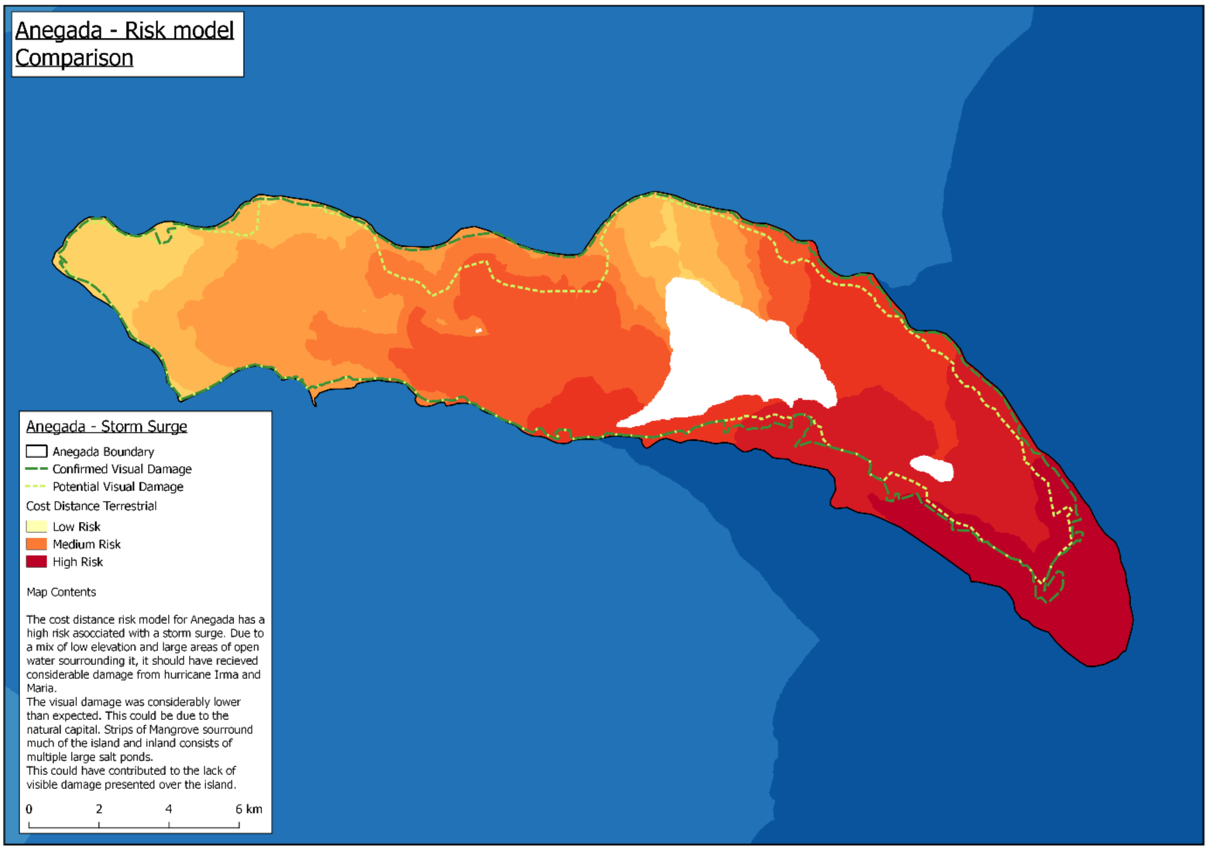

Figure 21. Damage Risk with case studies. Map overlaid with observed actual and potential damage lines.

Validation of the Model by local stakeholders in BVI

During the visits to demonstrate the model and validation on BVI (See Stage 6) a range of local stakeholders were asked to assess the model. The stakeholders included members from Department Planning, Department of Disaster Management, Department of Agriculture and Department of Fisheries, National Parks Trust and the Fire Department. The following points were made.

- For the storm surge model there was widespread agreement that areas that received significant damage were accurately illustrated in the high-risk areas and moderate-risk areas from the model.
- The model was deemed extremely accurate for the majority of areas which had undergone an unexpectedly large amount of damage.
- In a number of places more flooding was present than noted on the model, and this was deemed to be from in-land areas flowing onto the coastal belt especially from the storm on the 7th August, which had a very high rainfall and caused some flooding. The overland flow became restricted by coastal development/infrastructure and therefore unable to naturally output directly into the sea.
- The exceptions were the level of damage received on Anegada. Far less damage was experienced on this island than expected by our risk model or by the people on the islands. Two possibilities were suggested.

Stage 6: Demonstration in Anguilla and BVI

Workshops were held on BVI (Tortola) and Anguilla to demonstrate the model, get local feedback and ascertain their usefulness. The workshop on BVI ran on the 7-8th March, with individual meetings arranged on Friday the 9th March for representatives from the Department for the Environment who could not make the main meeting. On Anguilla the meeting was part of a larger suit of meetings and ran from Tuesday 13th March 2018 to Wednesday the 14th March 2018 (Figure 22)

The workshop included:

- A summary of the project for policy makers.
- A summary of how each stage of the model was created and a demonstration of how it could be recreated on the islands using open-sourced software (QGIS)
- Discussion on the accuracy of the model and the uses the island can make of it.

The following section documents the main impacts the data and models could have for Anguilla and BVI. Although there were some common themes there were also Island Specific features.

Impacts - BVI

As the model was deemed to show the areas in an accuracy that was deemed 'fit-for- purpose' by those who experienced the storm events on the islands, a number of uses were outlined for the data. Enhancement in the modelling were also suggested in order to build the technique into more projects on the island.

Uses of the vulnerability model and damage zone layers - BVI

Use of the risk zones and damage line documentation:

- The work is extremely useful to demonstrate to a wide audience the impact of the storms and the value of natural capital assets, such as salt-ponds, mangroves, and coral reefs, in slowing the energy of the storm surges. This includes key policy makers, government members, and the general public.
- The risk zones identified by the model will be useful for planning evacuation strategies.
- Planning relocation of fire engines and other emergency services, away from the danger zones, whilst allowing access to the largest number of people in an emergency.
- Identifying the infrastructure at risk and looking at key areas that would need to be targeted to maximise the speed of response, and the return to full functioning of the island.
- Using the risk zones in planning applications for further development, to make investors aware of risk and to build in suitable mitigations and ameliorations into their developments.
- To consider where current infrastructure functioning to prevent inland flooding exiting to the sea and consider these areas for further development.
- Highlighting the role that natural capital features such as salt ponds and mangroves has on reducing the energy of the storm surge and mitigating damage, so that their recovery is promoted rather than clearing of mangrove trees killed by the storm thus leaving the island more vulnerable.

Use of the erosion risk / channel layers:

- This layer was deemed to be particularly useful for land-use planning issues, showing landowners zones of risk and areas where small natural capital mitigation such as planting of native tress/scrub species will help prevent their property being subject to erosion.
- The level of detail of the risk zones was deemed to be a significant enhancement on the current model, which is based only upon the location of the main ghauts and does not consider the smaller channels.

- The layer was also deemed important to demonstrate the science and data behind existing policy of building away from ghauts and channels. Also, to highlight the risks for the property itself and to the rest of the island if the legislation is ignored.
- Using the data to calculate the economic value of the environment, helping investors to understand the significance of conserving key areas in good ecological condition, and promote the advantages of restoration to key areas in poor ecological condition. This will, in turn, show how natural capital is as significant as the other capitals, such as economic and social capitals, in protecting and maintaining the island's cultural, social, economic, and environmental well-being.

In conclusion, having models based on sound data from satellite imagery and on well-established science, has enabled a dataset which will be of key value to the island, for awareness raising, emergency planning, planning of future development, and highlighting the role of natural capital. Further refinement of the model was suggested in the light of new datasets acquired such as air-born LiDAR for BVI. There is an opportunity to take this forward and build on the success of this work in a Darwin Plus Project due to start in April 2018.

Impacts - Anguilla

Impact
During February and March 2018, the vulnerability model and the validation datasets were taken to both BVI and Anguilla. Workshops were held to demonstrate the model and to understand the uses that might be made of these data and the techniques.

As a first stage, the model was quality assured by the people present at the workshop, and both the modelled outline and the damage line were assessed against the participants experience and anecdotal evidence. The modelled line was acknowledged as being in line with the damage and flooding experienced. The main observed difference being in the areas around salt ponds, where damage was generally much less than expected. In some of the areas there was anecdotal evidence that the water did reach the end of the zone, but the damage was not extreme.

Uses of the vulnerability model and damage zone layers - Anguilla

Uses of the risk zones and damage line documentation:

- The risk zones identified by the model will be useful for planning evacuation strategies by disaster management.
- The work demonstrates to a very wide audience, including key policy makers, government members and the general public the impact of the storm and the value of natural capital assets, such as salt-ponds and mangroves, and coral reefs, in slowing the energy of the storm surges.
- The original work showing value of natural capital carried out as Phase 1 of this project, by Wolfs Company, was found to be particularly useful in communicating the evidence in a way in which developers and policy makers could readily identify with.
- Identifying the infrastructure at risk and looking at key areas that would need to be targeted to maximise the speed of response, and the return to full functioning of the island.
- Using the risk zones in planning applications for further development, to make investors aware of risk and to build in suitable mitigations and ameliorations into their developments.
- Designing these areas into any new Environmental Planning legislation for the island.
- Identifying economic and social capitals allowing the protection and maintenance of the island's cultural, social, economic and environmental well-being.

Inland flooding

- The inland flooding zones were generally thought to be accurate and useful for planning policy development and disaster management planning. However, the flooding of The Valley was debated. Ways of using and updating the model were discussed and further work was suggested to ensure its applicability for Disaster Management.

Erosion risk and Sediment

- The sediment plumes and erosion risk will be used by those working in the environment to target places for action to help mitigate erosion by planting native vegetation. The fact that the model proved the validity of the Opportunity maps created as part of the Anguilla NEA was especially welcomed. The data will be used to help inform land management actions.

In conclusion, having models based on sound data form satellite imagery, based upon well-established science, has enabled dataset which will be of key value to the island for awareness raising, emergency planning, planning of future developments and highlighting the role of natural capital.

Figure 22. Workshop Photograph Anguilla

Potential for Further work

It would be extremely useful to ascertain the damage inflicted on the marine environment, particularly the reefs, in the same way the damage to the coast was found. To do this it would be necessary to re-run the shallow water bathymetry and reef crest mapping from satellite imagery developed in the Darwin Plus project Mapping Anguilla's 'Blue Belt' Ecosystem Services: C6950.

To undertake this, it would be necessary to obtain from on-island, new post-hurricane point data for shallow water bathymetry, (for example from fishing boats which could be supplied with the depth / satellite tracking device) and suitable imagery with calm sea condition, the shallow water marine mapping underway for the Darwin Plus Project Mapping Anguilla's blue belt could be re-run to note any major changes. This would give a before and after comparison and to help validate the marine sections of the models.

The inland flooding model needs further development and refinement in order to accurately predict all areas flooded, this is because small building and engineering works at ground level are holding back water in a way it is not possible to judge from satellite imagery.

There is potential to extend the application of the model to the other Caribbean Overseas Territories using radar data or, where available, LiDAR data. These have been shown to have a wide level of impact for both emergency planning and for environmental planning.

Appendices

Appendix 1 – Methodology Purchase of satellite data

The project sort to obtain satellite data to both visually assess the accuracy of models developed in Williams *et.al.* 2017 using optical remote sensing and hold them in the archive for later exploitation.

JNCC sourced and processed new Worldview 2 and Worldview 3 VHR data. Environment Systems sourced and processed the Sentinel 2 and Landsat scenes from before and after the hurricane, include radiometric, geometric for BVI (where necessary topographic) and atmospheric correction. This ensured the scenes could be used for multiple types of analysis.

Inland flooding

The inland flood risk model was 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.

Two types of inland flooding were considered:

1. For BVI in particular but also in Anguilla we considered the role of channels / ghauts that run in storm conditions. In BVI where imagery was present between hurricane Irma and Maria the width of several of the ghauts was assessed to see if there was a difference in the effect of erosion form storm events with and without vegetation.
2. In Anguilla in particular the role of concavities (hollows) which fill with water in storm events was examined.

In Anguilla a method was used to find all those locations 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 A1). 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.

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.

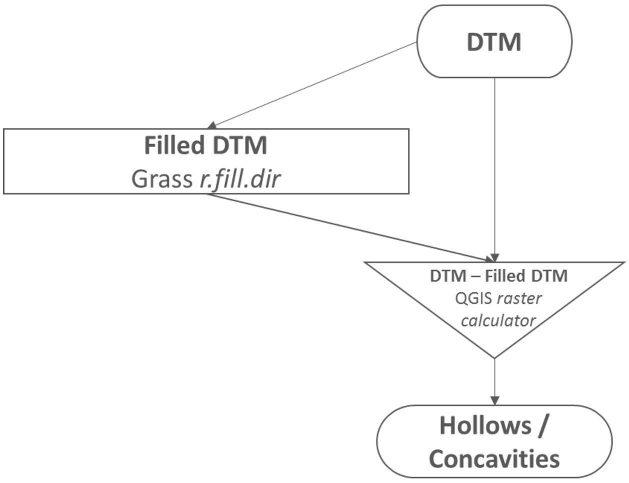

Figure A1 Work flow for identifying concavities.

Ground truth data

The validation dataset has been enhanced with an expert interpretation from ‘Caricom Disaster Assessment and Coordination Report’ (CDACR) produced by the ‘Department of Emergency Management Anguilla’. This dataset details the damage done to key buildings over Anguilla.

Supporting imagery has also been used to estimate the extent of damage from storm surge. This included media reports, social media data (such as Twitter) and images from Joint Nature Conservation Committee (Figure A2). Factors that were considered were the observed extent and direction of debris, discolouration of water (such as swimming pools or lakes), areas of bare ground and elevation. In some areas, the habitats present prevent visual inspection of damage due to factors such as tree cover.

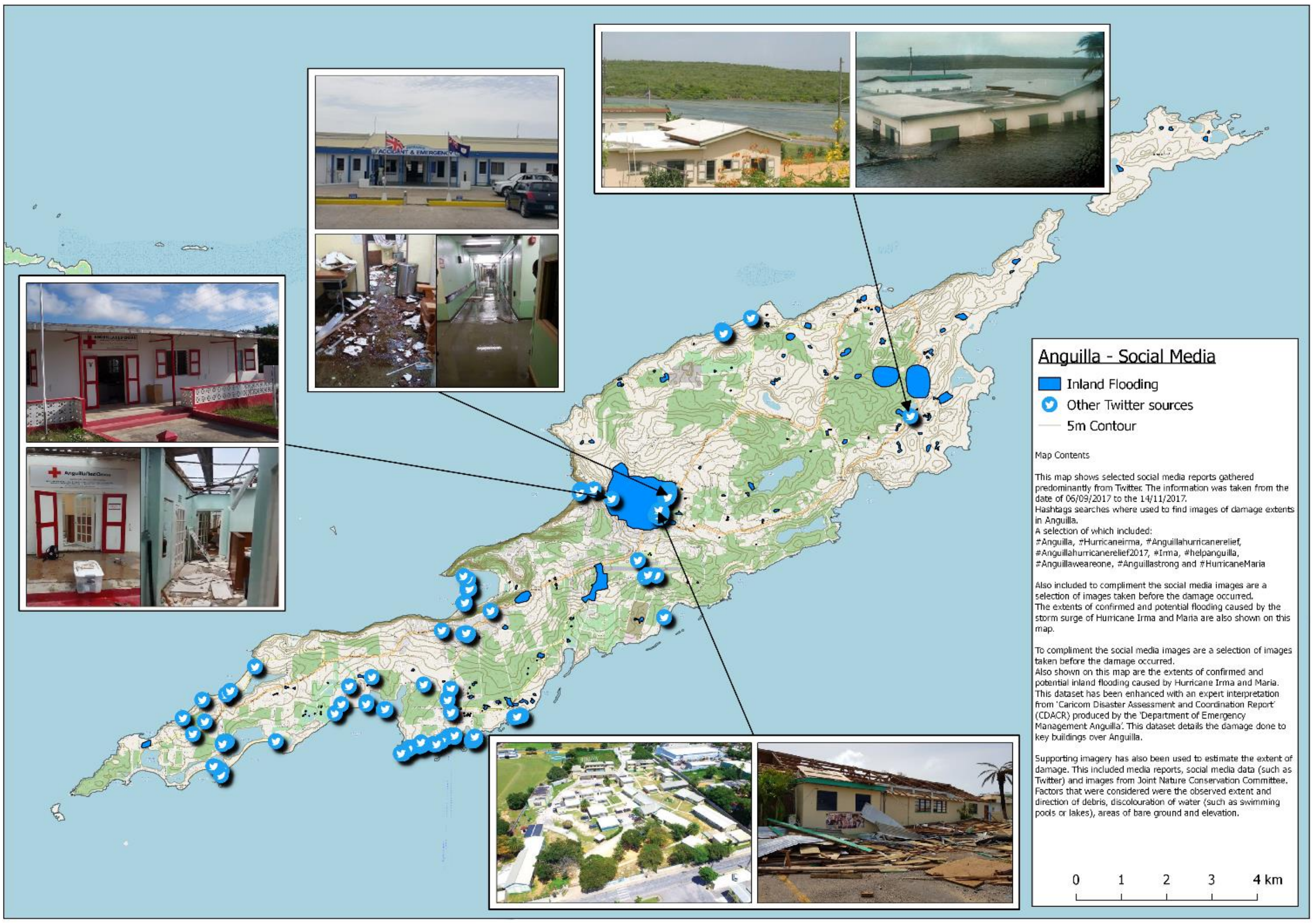

Figure A2. Spatial distribution of social media data of Inland Flooding.

Storm surge

Digitisation of storm surge

The storm surge damage extents aim to map damage risk zones over the islands of Anguilla and the British Virgin Islands[1]. This was achieved using the modelling approach developed in Phase 1 of the study but re-running the hurricane track for the same direction as Hurricane Irma, and at a 6.2m storm surge, which is the current accepted height of the surge observed in Anguilla.

The satellite imagery (Worldview 2 and Worldview 3) was then used to undertake a visual comparison, using expert staff, to assess the damage zone and where possible the cause of the damage. A line shapefile was then created, using the same projection as the island, to identify this zone along the coastline.

The validation of the storm surge was achieved primarily through the use of expert interpretation of VHR imagery, and where possible, supported by ground data.

Factors that were considered when undertaking the manual assessment of damage were:

- the observed extent and direction of debris,
- presence of standing water,
- dead or discoloured grass,
- dead or discoloured mangrove and coastal vegetation,
- discolouration of water (such as swimming pools or lakes),
- areas of bare ground.

[1]A new habitat map for BVI was produced as an input parameter for both the storm surge and inland flooding models.

Ground truth data

To further refine the classification, information from social media and news outlets were taken into account. Where damage was shown or reported in these outlets, the damage line was modified accordingly (Figure A3). This included searching on social media and news outlets for references of where buildings were recorded as flooded or having avoided the flood damage.

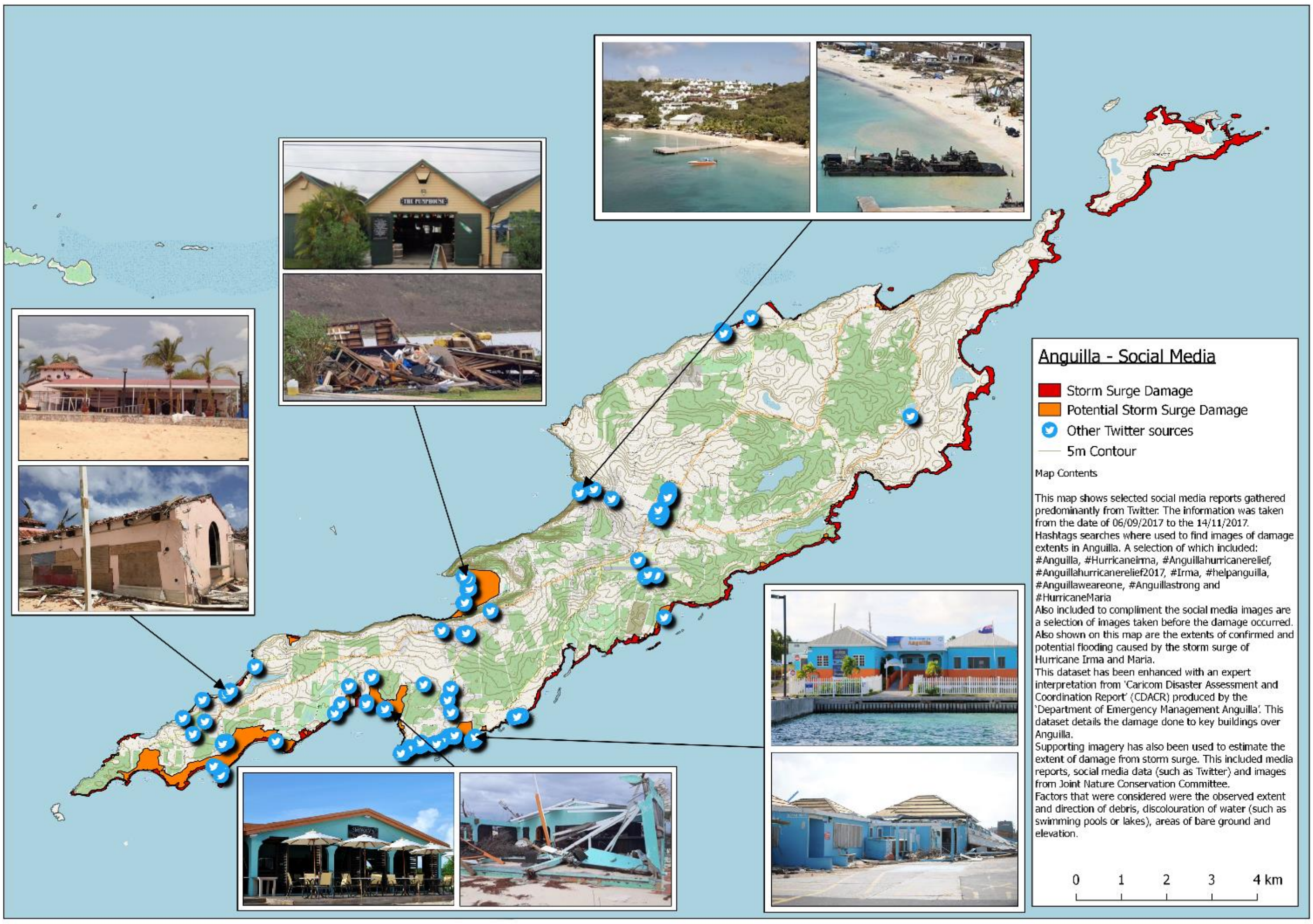

Figure A3. Anguilla Social Media Data (with Storm surge). Map showing selected social media reports gathered predominantly from Twitter. The information was taken from the date of 06/09/2017 to the 14/11/2017. Hashtags searches where used to find images of damage extents in Anguilla. A selection of which included: #Anguilla, #Hurricaneirma, #Anguillahurricanerelief, #Anguillahurricanerelief2017, #Irma, #helpanguilla, #Anguillaweareone, #Anguillastrong and #HurricaneMaria

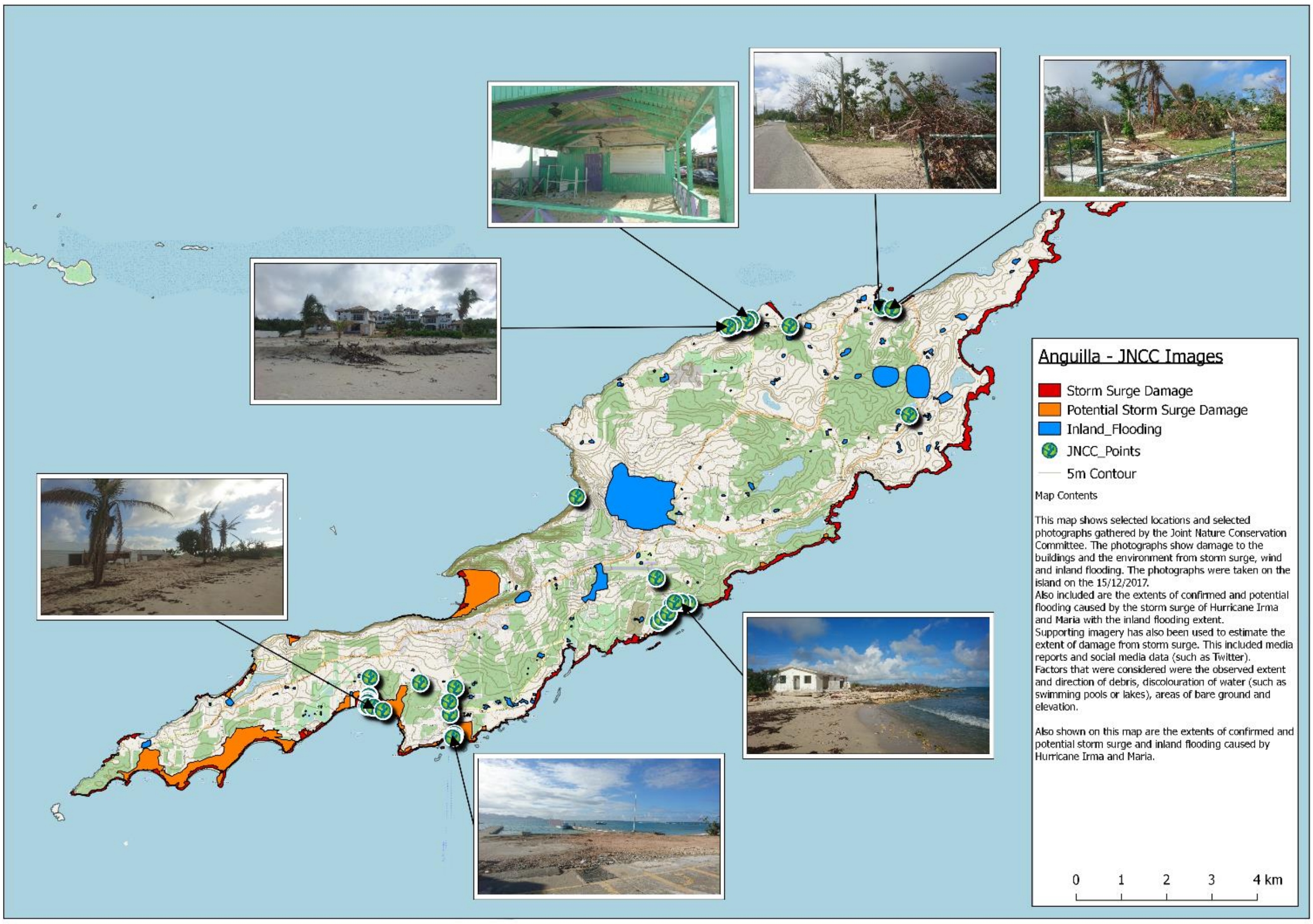

Figure A4. JNCC Data Anguilla. Map showing selected locations and selected photographs gathered by the Joint Nature Conservation Committee. The photographs show damage to the buildings and the environment from storm surge, wind and inland flooding. The photographs were taken on the island on the 15/12/2017.

Images from Joint Nature Conservation Committee (Figure A4) were also used as a means of supporting the validation process. For comparison purposes, a selection of images taken before the damage occurred was also gathered. The final ground truth dataset has also been enhanced with an expert interpretation from 'Caricom Disaster Assessment and Coordination Report' (CDACR) produced by the 'Department of Emergency Management Anguilla'. This dataset details the damage inflicted to key buildings over Anguilla.

Storm surge modelling

Storm surge modelling is normally predicated on understanding the complex meteorological processes involved in an individual storm, which include considerations 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 of where relative risk is greatest on the island.

The storm surge risk model has been generated using the Environment Systems SENCE methodology. This storm surge risk modelling focuses on identifying the path of least resistance of storm surge taking in to account the effect Natural Capital such as coral reefs, mangroves and forest could have on slowing the energy in the waves. The model is not an attempt to replicate the complexity of metrological and atmospheric pressures, and the exact line of Hurricanes Irma or Maria. Therefore, the focus is on the conditions and parameters of the seafloor. Indicators include the slope and bathometric elevation, the protrusion of features above the sea surface, such as islands and reefs, the roughness of the seafloor, and the coastal geology and vegetation cover. Also included is the calculated average annual fetch, indicating the prevailing winds that may be experienced. This storm surge risk model was scored and generated using the Environment Systems SENCE[2] methodology.

Fetch[3] was modelled to provide an indication of sheltered and exposed conditions, using the USGS Wind Fetch Model, alone with average wind directions for the study areas. This was based on the 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. To validate the model, the actual storm track (obtained from NOAH) was used, whereas in Phase 1 a generalized storm track was used.

All the input layers[4] are associated with a score of resistance to storm surge waves, and converted to raster format, where 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 (A5).

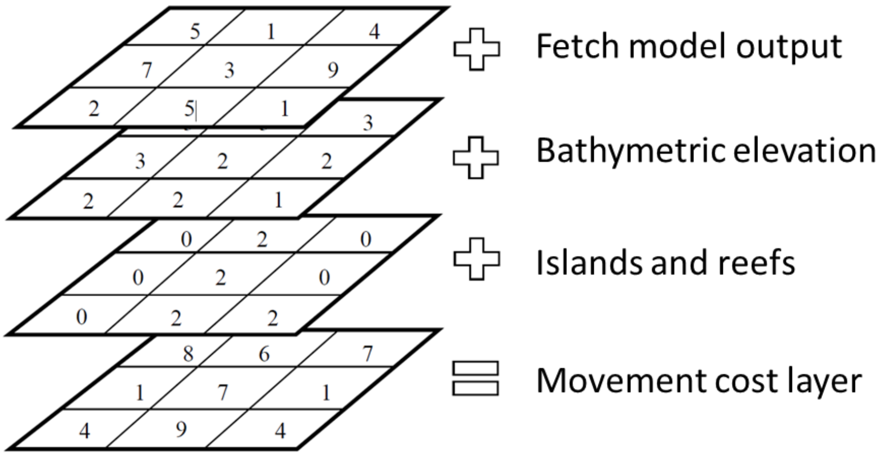

Figure A5. Conceptual diagram of additive raster model, creating the movement cost layer.

A storm course is traced 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 (Figure A6).

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 - 6.2 m 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.

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[2]Spatial Evidence for Natural Capital Evaluation http://www.envsys.co.uk/sence/
[3] 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
[4] 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.

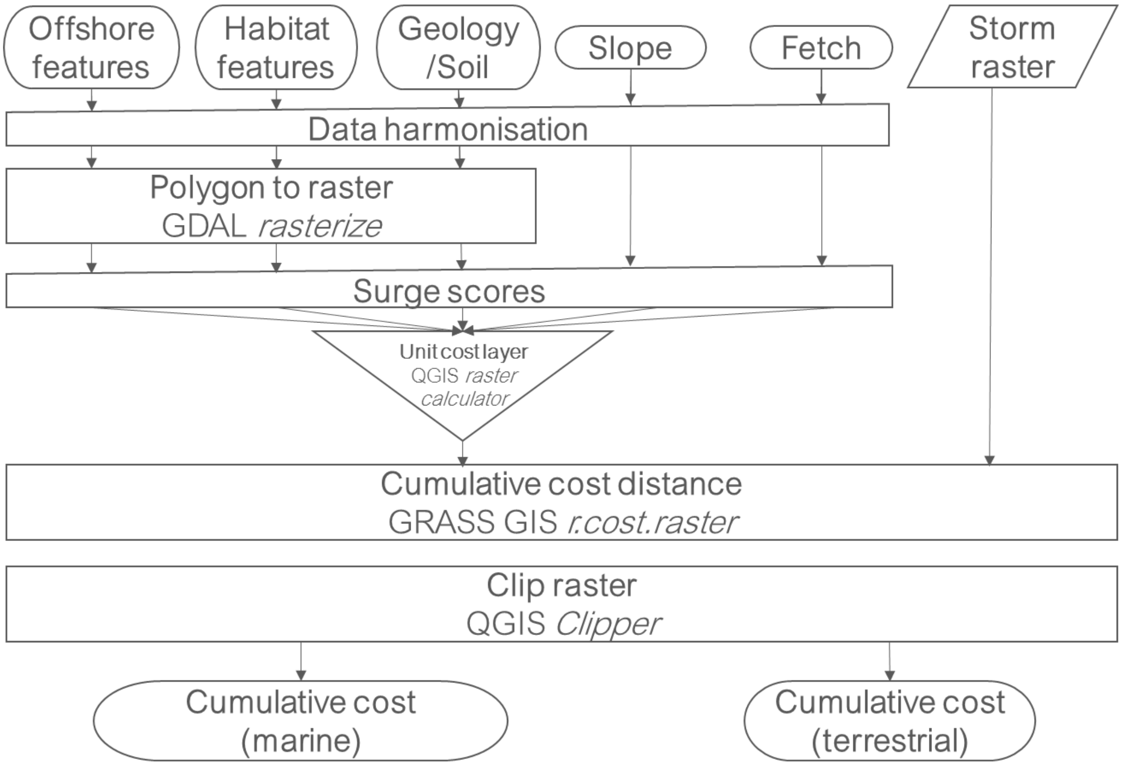

Figure A6. Work flow for producing storm surge risk map.

Sediment mapping

Sediment loads in the coastal marine zone show high temporal variability with respect to particle concentration and plume extent, and sediment plumes can be created or exacerbated by anthropogenic activities such as dredging or land clearance around drainage channels. Increased sediment load can have significant negative effects on water quality, affecting coral reef health by reducing their photosynthetic capability through smothering, and reduced coral recruitment (Richmond, 1993), with the most sensitive species exhibiting mortality following high sedimentation events lasting less than 24 hours (Erftemeijer *et al.,* 2012). An analysis was undertaken to define the extent of sediment plumes in the coastal waters surrounding Montserrat on different dates, to examine the feasibility for longer-term monitoring.

As light behaves differently in the marine environment, both on the water surface and within the water column, it is necessary to reduce the visual and spectral impact this has on the imagery. An example of this is sun glint, where a specular reflection of light from the sun is directed towards the sensor, reading as high digital values which can make it impossible to retrieve any meaningful information. To compensate for these affects, correction techniques following the method of Hedley *et al.,* (2005) were applied to the selected data, in order to reduce the impact of sun glint on the image values.

In order to model Total Suspended Solids (TSS) from an aquatic environment, the reflectance values of the data must be converted to remote sensing reflectance (Rrs) products (Pahlevan *et al.*, 2017). This ideally requires measurements taken in the field which was not feasible, so the method as proposed by Watanabe *et al.* (2015) was used as an alternative, by which the image values were divided by pi (π). Suspended sediment algorithms were applied based on the findings of Ouillon *et al.* (2008) using Rrs at 0.560nm. Ideally the suspended sediment outputs would be regressed against field values, but in the absence of field data the outputs were viewed as relative concentrations. Threshold values were assessed to extract TSS from oceanic water, then converted into a binary mask.

Mangrove opportunities modelling

The mangrove opportunities modelling uses indicators to identify areas of potential mangrove establishment which would have the most benefit to areas of high risk, from a storm surge. Indicators include the slope and proximity to saline water, and current habitat.

This mangrove opportunities risk model was scored and generated using the Environment Systems SENCE methodology. Soil was not included due to a lack of detailed information currently available.

Appendix 2 - BVI habitat map

A habitat map covering the British Virgin Islands was require as an input to the storm surge model (Figure A7). The map has been generated using segmentation and random forest modelling with the aid of ecologists. The ground control points were gathered using he existing habitat map of the island (Kennaway *et.al.*, 2008) and existing data of specific island habitats. The dataset consists of 19 separate habitat types and includes open street maps urban shapefile layer to better classify the urban areas of BVI.

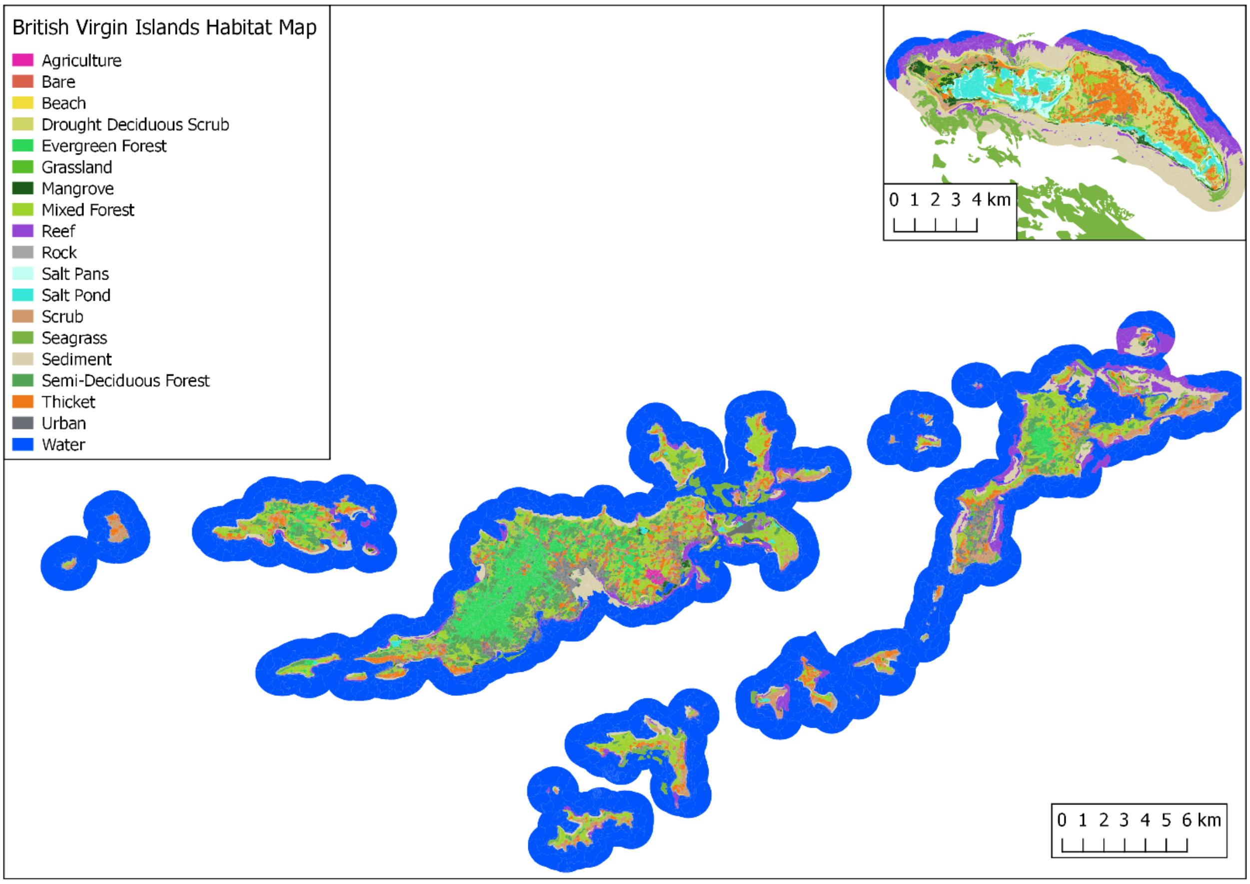

Figure A7. Habitat produced for BVI, as an input parameter to the storm surge and inland flooding models.

Appendix 3 – BVI Storm surge model method statement

The following table shows the factors taken into consideration. Each of these factors were used in the report to build the rule base model showing the effect of wave action, habitat, slope, elevation, and sea bed obstructions.

Data type	Attribute	How does it impact a storm surge?
Bedrock	Boulder Coral Rock Rock layer	An increase in surface roughness and structural complexity increases the amount of energy required by the storm surge to overcome the seafloor obstacle. As an example, coral provides a better resistance to an oncoming storm surge than seagrass or sediment. (Spalding *et a*l,. 2014)
Elevation	Height, metres (m)	Higher terrestrial elevations result in more force required by the storm surge to continue its path.
Fetch	1 - 10 (sheltered to exposed)	Higher fetch values can result in the storm surge having an increased level of energy when approaching the shore. (Fagherazzi and Wiberg, 2009)
Habitat	Agriculture Bare Beach Drought Deciduous Scrub Evergreen Forest Grassland Mangrove Mixed Forest Rock Salt Pans Salt Pond Scrub Semi-Deciduous Forest Thicket Urban	Vegetation provides structural diversity, and increases the number of obstacles in the path of the storm surge. Trunks, branches and leaves all help to reduce the wave energy, and also catch large moving objects and debris. The more complex the vegetation structure, the greater the resistance against the storm surge. As an example, mangroves are well documented as attenuating storm surges (Zhang, *et al*., 2012), and have a higher resistance when comparted to drought deciduous scrub Areas of bare ground, agriculture and manmade substances have relatively open structures, and can let storm surges pass through more easily.
Islands	0 -1, where 1 is an island	Where there is an island, regardless of size it is assumed it will form an obstruction to the path of the storm surge; forcing the tide to expel energy going either over or around.
Seafloor	Reef Seagrass Sediment	An increase in surface roughness and structural complexity increases the amount of energy required by the storm surge to overcome the seafloor obstacle. As an example, reefs provide a better resistance to an oncoming storm surge than seagrass or sediment. (Spalding et al,. 2014)
Slope	Angle, degrees (°)	The steeper the angle of ocean bottom, the lower the storm surge. The steeper the angle of the terrestrial slope, the more force is required by the storm surge to continue its path.

Data	Value	Score
Fetch	1 (very sheltered)	Very high attenuation of storm surge
Slope	40 - 90 degrees	
Fetch	2	
Elevation	6 - 7 metres	
Fetch	3	
Elevation	5 - 6 metres	
Fetch	4	
Slope	30 - 40 degrees	
Elevation	4 - 5 metres	
Fetch	5	
Elevation	3 - 4 metres	
Fetch	6	
Slope	20 - 30 degrees	
Elevation	2 - 3 metres	
Fetch	7	
Elevation	1 - 2 metres	
Fetch	8	
Elevation	0.1 - 1 metres	
Fetch	9	
Slope	10 - 20 degrees	
Elevation	0 - 0.1 metres	
Fetch	10 (~ very exposed)	
Slope	00 - 10 degrees	
Habitat	Evergreen Forest	
Habitat	Mangrove	
Habitat	Mixed Forest	
Habitat	Semi-Deciduous Forest	
Habitat	Thicket	
Bedrock	Boulder	
Bedrock	Rock	
Bedrock	Rock layer	
Habitat	Scrub	
Bedrock	Coral	
Habitat	Drought Deciduous Scrub	
Islands	Islands present	
Seafloor	Reef	
Seafloor	Seagrass	
Elevation	0 metres	
Habitat	Agriculture	
Habitat	Bare	
Habitat	Beach	
Habitat	Grassland	
Habitat	Rock	
Habitat	Salt Pans	
Habitat	Salt Pond	

Data	Value	Score
Habitat	Urban	
Seafloor	Sediment	
Slope	00 degrees	Very low attenuation of storm surge

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