Joint Nature Conservation Committee

An assessment of the value of natural capital in the protective service against coastal and inland flooding in the UK Overseas Territory of the British Virgin Islands

Final Report

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Report for

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Executive summary

Purpose of this report

The British Virgin Islands (BVI), like many of the UK Caribbean Overseas Territories, is highly dependent on the natural environment for its economic and social well-being. Because of the recognition of the role of the natural environment can play, the Government of BVI (GoBVI) is looking to incorporate socio-economic values of natural resources into its policy and decision making. In particular, there is an objective of better incorporating the natural environment in fiscal planning through instruments such as the Medium-Term Fiscal Plan and budget, and the proposed Environment Bill.

To support these objectives, the primary purpose of this study is to assess the value of natural capital which mitigates the impacts of extreme weather on built infrastructure. Specifically, this relates to the provision of protection from coastal and inland flooding resulting from extreme weather events.

The natural capital estimates in this study reflect only one function – protection from flooding- provided by specific natural features in the BVI such as coral reefs. These same natural features contribute to the provision of other ecosystem services, such as a contributing source of global biodiversity, which may have a far greater economic value.

Natural capital and ecosystem services

The concept of natural capital is that natural features can be valued in terms of the services they provide both to people individually and to society and the economy. According to the World Forum on Natural Capital, natural capital can be defined as the stocks of natural assets found within the Earth's critical zone which includes living things, vegetation, and animals together with the geology, soil, air, and water. Natural capital constitutes renewable and non-renewable resources which combine to yield a flow of benefits to people in the form of ecosystem services categorised under the broad headings of cultural, provisioning and regulating services. Flood protection is a regulating service.

Key questions for people new to the concept are "Why has society not used natural capital before" and "Is this needed – isn't natural capital already accounted for in the real economy?" In essence, the approach is to trace selected impacts on society and economy back to their natural causes and instead of taking them for granted, seeks to value them, often in terms of alternatives. For example, a farmer with better crop yields than his neighbour would assign a natural capital value to the stream that is the source of better irrigation, the benefit of the service it provides being saved water purchases. The crop sales are already part of the economy. The natural capital of the stream is a previously unacknowledged part of the supply chain at risk of being overlooked because it was never recorded and assumed always available for free. The advantage is that dependencies on nature are more fully represented enabling better overall management and reduced risk.

Natural capital assessments require identifying natural processes and their links to the economy. The use of monetary metrics can further enhance understanding and simplify the analysis of trade-offs but the overall process should not replace the use of overarching environmental perspectives such as the precautionary principle. Environmental valuation is an inherently complex though well-established process. It requires selecting relevant natural features, assessing their effects and interpreting the impacts on the economy. These are not always separable or immediate. Although natural features are governed by natural processes, the services they provide may be prevented or accelerated by man-made action. Benefits may be captured by different parts of society and may take time to become available. There may be interactions between natural processes and people may not agree which should be included or which valuation techniques to use.

Stages in the project

The project was undertaken in three stages. The first stage comprised a literature review, to identify the natural features relevant to coastal protection and flooding and to review associated economic valuation approaches, focusing on the tropical coastal zone. In the second stage a selected valuation approach was applied in three case study sites with locations decided together with officials of the Ministry of Natural Resources and Labour during a visit by Wood to the British Virgin Islands in April 2018. In the third stage the approach was refined and extended to cover the whole BVI to provide a national level valuation.

Natural hazards

The BVI's steep topography and rugged interior have led to human settlement and physical development being concentrated in coastal areas. Being within the Atlantic hurricane belt, the population and infrastructure are exposed to the hazards of storm surge, extreme rainfall and high winds. Evidence that the low-lying island of Anegada was over washed in the seventeenth and eighteenth century indicates an additional hazard of tsunami.

Storm surge is a temporary rise in sea level caused by the high winds and low pressure at the centre of a hurricane (an extreme tropical storm) and its movement forward which combine to push seawater into a mound at the centre of the storm. As a storm surge makes landfall, the water is pushed up the shore and causes coastal flooding which is exacerbated by large waves at the now elevated sea level. Coastal flooding is a cause of much damage in the BVI with both the intensity and frequency of hurricanes important to overall effects over the longer term. The frequency of tropical storms passing within 60 nautical miles of Tortola is approximately 1 in every 5 years. The storms significantly affecting the BVI tracked in a north westerly direction, with a few tracking north easterly.

Extreme rainfall has caused severe inland flooding events in recent years, most notably in 2003, 2010 and 2017. Of these, tropical storm Otto in 2010 had the most extreme rainfall, typical of a storm that occurs once every 75 to 100 years. In 2017, the flooding in Road Town, the capital of the BVI, was the worst in living memory and more severe than in 2010, despite the rainfall being typical of a more frequent storm occurring once every 25 years. High winds have been responsible for substantial damage in the BVI but are not assessed in the context of this study as they are not specific to coastal areas or to flooding.

The steep topography of the BVI is important to the scale of impacts from both causes. Human settlement and physical development is concentrated in low-lying areas near the coast which are more accessible but more exposed to the sea, while inland the slopes create fast run-off which quickly routes surface water flooding to these same centres of population. Both are exacerbated by urbanisation, through alterations to natural drainage flow paths and reclamation of land from the sea.

Flood mitigation from natural features

Two natural features which are known to play a key role in mitigating against coastal flooding are coral reefs and mangroves. Coral reefs protect by absorbing the energy of oncoming waves dissipating up to 97% of wave energy by creating a barrier which reduces horizontal wave movement and flats which reduce vertical wave movement. Reefs protect against less frequent high energy events such as Category 4 and 5 hurricanes, but also against more frequent lower energy events where they reduce the height of swell waves. Research has shown that mangroves can reduce the height of wind and swell waves over relatively short distances: wave height can be reduced by between 13% and 66% over 100m of mangroves or between 50% and 99% over 500m of mangroves. The edge of the mangroves has the highest rate of wave height reduction per unit distance. However, mangroves are required in thick belts (>1km) to reduce the much larger wave heights from storm surge.

Inland, the inclination of the natural slopes is the main determinant of the pattern of run-off. However, the interaction with and between a range of artificial and natural features may accelerate or reduce the speed of water movement and so affect flooding at the bottom of a catchment and temporary ponding at intermediate heights further up. Vegetation is a relevant form of natural capital as it provides interception and infiltration storage, stabilises soils, and prevents and traps sediment movements. Urbanisation of forested and vegetated areas removes these natural flood risk management benefits, increasing the volume of rainfall converted to runoff, and the speed water moves through the catchment.

Valuing natural capital

The valuation methodology used here follows established practice and assigns a natural capital value based on the future level of damage and associated monetary costs that are avoided as a result of natural processes and natural features. All elements that affect the likelihood of natural events and monetary values are potentially relevant to the valuation, including people's expectations for their continuing quality and condition. Hurricanes are as much a natural feature as coral reefs and will affect market prices for shore-side properties as will an attractive beach nearby. If expectations are low, then natural features will also have low values, while growth in the economy will mean higher values for the natural features on which it depends, unless these assets deteriorate.

Quantifying the natural processes which mitigate inland flooding

The protective benefit of vegetation results from its holding back water temporarily, mitigating peak flows that cause the greatest flooding. In the BVI, the canopy and characteristically thin soils quickly become saturated and no longer provide benefits of interception and infiltration although the vegetation still provides physical resistance to flows. In the extreme rainfall events of interest the buffering capacity is soon exhausted and 100% of rainfall is converted to runoff flows. Flood depths and velocities were compared for current conditions and a scenario with vegetation cover removed, represented with a lower parameter for surface roughness. As flooding is related to extreme events with saturation the difference in buffering was considered minimal. Detailed hydraulic computer models for each catchment and a simpler model nationally reflecting available data were developed which use:

- Design rainfall storms based upon the intensity-time profile of the August 2017 event as reported in records from the Department of Disaster Management, GoBVI and from Caneel Bay in the US Virgin Island and scaled to represent 1 in 5, 25 and 100 year rainfall events.
- Elevation data based on LiDAR (Light Detection and Ranging) data;
- a detailed geographic representation of the location, elevation, use and attribution of economic value of individual buildings;
- Land use information across the study area used to assign roughness values; and
- Representation of the costs of loss and disruption

Quantifying the natural processes which mitigate coastal flooding

The approach used for the representation of protection provided by coral reefs follows the method of van Beukering *et al.* (2012) and van Zanten *et al.* (2014) applied in the US Virgin Isles. The valuation reflects the economic impacts of differences between a baseline of current reef conditions and two scenarios where reefs are firstly degraded and then lost. It is based on:

- a storm surge dataset developed for the GoBVI's Regional Risk Reduction Initiative (R3i) identifying coastal vulnerability to flooding at a resolution of a 50 metre spatial grid around the coastal zone;

- estimates of the effect of reefs on wave energy in the US Virgin Isles taken from van Zanten *et al.* (2014)[23];
- mapping of the location, depth and typology of coral reefs surrounding the BVI using datasets provided by the National Parks Trust and UK Hydrographic Office;
- the buildings dataset as highlighted above;
- representation of frequency of storm surge events over a 160 year period;
- representation of the costs of loss and disruption including bottom up estimates of market values for the BVI by Wood

The coastal protection function of mangroves is explored in the case study site of Paraquita Bay by interpolating the change in wave height observed over an area of mangrove using the R3i storm surge dataset.

Assigning economic values to the impacts of mitigation

The scale of the BVI economy provides a benchmark and maximum for the degree of protection that natural capital could theoretically provide. The BVI has an annual GDP of US$1,027m and largely depends on tourism and financial services –known as the "twin pillars" of the economy, each making up roughly 50% of the economic activity. Tourism-related activity is estimated to be worth US$484m annually.

For simplicity, land area is taken in this study as a basic metric for quantity because it is fundamental both to descriptions of natural processes and is long-established in economics. The 2 metre contour line provides a simple tool to provide a broad appreciation of the exposure of the economy to flooding. The 2 metre contour line includes 14% of the total property footprint in the BVI. However, the differences in the exposure of different types of economic activity vary substantially. Only 6% of residential property is below the 2m contour. In contrast, over 40% of bars and restaurants, of offices and of retail premises, transport and infrastructure (gas, electricity, water) are below the 2m contour. Even though residential property makes up over half the total footprint area, the exposure of business activity to coastal flooding is marked.

As the value of any form of natural capital which provides protection is the avoided costs of flooding, the specification of the definition and assumptions used for costs are as critical a component to final estimates as the quantification of the natural processes. The key underlying assumptions are that the value of lost economic activities scales with the proportion of buildings affected and that the loss can be represented by current market prices. The costs included are those that fall directly on occupants and users, estimated as repair and disruption, and indirect costs that fall across the broader economy. These costs provide a basic estimate of the unit cost for each square metre of land that is affected and the multiplication of the two the aggregate monetary impact.

The repair costs are estimated using the market price of US$300/ft^2 for reconstruction in UK Overseas Territories quoted in previous work for the JNCC multiplied by a 15% factor estimated by FEMA to represent the judgement that full reconstitution is not usually required, but there is a minimum level of cost for a flood of even minimal depth. After application of this factor, this cost is US$484/m^2 per flood event.

The costs of disruption were calculated for bar and restaurants using bottom up estimates based on seating capacity and occupancy for the sector by Wood for the BVI and amounted to a net annual margin (profit) of US$1,400/m^2. The duration of business interruption was estimated as one year. The costs of disruption for residential property was based on average rental rates in the current market with costs assumed as one third of rental rates (in line with bars and restaurants). The net annual margin was US$415/m^2 and the duration of interruption was estimated as 6 months. In addition, indirect costs were assumed to add a further 65% above the direct level of costs, based on standard multipliers.

Results of flooding projections and differences due to natural features

Inland, widespread flooding occurs even in the pluvial event expected most frequently, every 5 years, primarily due to the intensity of rainfall and the steep topography. More intense events expected every 25 or 100 years do not show significantly higher numbers of flooded properties.

Degrading the environment by removing the mitigating effect of vegetation leads to significant increase in modelled water velocities across the catchment. These are assessed as significantly contributing to scour of the slopes and transport downstream of sediment load (mud, clay and rocks). Increased water velocity also increases the risk of landslides, and likelihood of damage to infrastructure such as roads. This is important mechanism by which flooding can cause damage and hazard is not valued as part of this study, but qualitatively shown to be positively impacted by the presence of natural capital. The degradation of the environment did not produce a worsening in terms of flooding depths primarily due to the already saturated conditions in the baseline. In less extreme events, the canopy and soil are expected to reduce flooding, though.

Extensive coastal flooding occurs in the baseline for a Category 4 storm due to the many properties in low-lying areas. The additional impact from reef degradation through death of the live coral is comparatively small as many properties are already flooded. This is particularly apparent in the case study sites of Paraquita Bay and at Anegada. There is variation in maximum water levels around the coasts for the case study sites and nationally which reflects the undersea conditions including the reef topology. With reef loss, maximum water levels rise substantially, particularly in areas previously protected and leads to a much larger increase in the number of buildings flooded. The effect is most pronounced nationally as then all locations previously protected by reefs are included.

The mitigating effect of reefs is substantially affected by the selection of the baseline event. A storm of a lower category would be associated with a lower storm surge and resulting lower maximum water level and only buildings at lower elevations would be flooded. Increases in maximum water level from both reef degradation and reef loss lead to a greater relative increase in the number of flooded properties as in this case more remain to be flooded.

National value of natural capital providing flood protection

The impact of loss of reefs is estimated at US$74.3m annually. For comparison, this is approximately 7% of total GDP in numeric terms and equivalent to the GDP attributable annually to all the bars and restaurants in the BVI – in short their annual profits.

Simple contrasts between the estimates made here and existing financial statistics are potentially misleading. The reefs can be seen as currently providing an equivalent to insurance and so avoid what would otherwise be an annual US$74.3m out-of-pocket insurance payment by BVI inhabitants. However, while notionally a source of reduced insurance costs, the reefs can be seen as the actual physical cause of protection and, if they were actually lost, no substitute provider of insurance might come forward at this (or any higher) price. Structural changes and complex knock-on effects would follow, such as abandonment of uninsurable low-lying areas and changes in land prices.

The valuation model used here only provides a value for a notional first step in a sequence of possible change. It assumes that in an economy with a GDP of US$1,027m, people would go on living exposed to US$74.3m of damage annually. Even if insurers could be found, this seems unlikely. While future steps are inherently uncertain and too subject to assumption for detailed quantification, the basic characteristics of the existing situation are clearly visible in the BVI, in particular, the concentration of economic activity near the coast, meaning that the costs of structural change will almost certainly be greater than US$74.3m. The unresolved question is how much greater.

The calculation of the US$74.3m is not an estimate of a 'replacement cost', such as the amount of investment that would be required should reefs disappear, but it is an estimate of the stream of benefits that flows to BVI under current conditions. Assuming the reefs continue to exist, the greater the protection they provide to society and the economy, the greater their value. Population growth and increasingly frequent and intense weather are just two factors which increase this value.

The degradation of reefs is a first step towards reef loss and arguably differs only in degree. The impact of degradation of reefs is much smaller at US$3.6m annually, reflecting a more minor physical change, though benefits from protection will arise from a similar set of reasons, such as population growth. The death of live coral is a trigger for long term impacts that may be irreversible.

The case study results show similar features to those calculated nationally when considered approximately in proportion of the degree of habitation. Notable features are:

- Cane Garden bay shows many of the features of the BVI nationally. The economic activities are dominated by tourism and properties are close to the coast. The bottom up estimates for earnings developed by Wood for bars and restaurants in Cane Garden Bay, when scaled exactly matched those reported nationally.
- In Anegada, the possibility of reaching a threshold of uninhabitability is much higher and the proportion of buildings affected is also greater than in steep sided areas.
- In Paraquita Bay, there is a particular business use of the lagoon for yacht storage out of season which is estimated in this study to provide US$2.5m of direct benefits annually. This may be at risk with even limited reef or mangrove degradation as it depends on insurance ratings for hurricane shelters. The potential losses are significant when compared with the national value of US$3.6m for losses from flooding

This study provides a very detailed property by property analysis which can aggregate the footprint area of individual buildings affected by floods of different depths. These areas and proportions reflect the unique characteristics of the geography and land use in the BVI, and are fundamental to the assessment of the economic impacts and monetary values.

The proportion of the total property area in the BVI lying below the 2 metre contour is 14% but differs substantially between types of building. 44% of the aggregate total floor area of bars and restaurants lies below 2 metres but only 6% of the floor area of residential buildings. Furthermore, there is high sensitivity of the commercial sector (bars, hotels, offices, infrastructure including retail and storage) to floods of even small depths. 1 metre of rise leads to an additional 20% of their aggregate floor area being exposed. In contrast, for residential properties, the increase in floor area for a 1 metre rise is never greater than 5% and can be as low as 2%.

Conclusions

The topography of the BVI in the coastal zone, both onshore and offshore, is the feature dominating this natural capital assessment. In particular:

- The rugged interior means that the main areas of economic activity are concentrated in low-lying coastal areas (primarily for ease of access and construction) and so are particularly vulnerable. In contrast, residents typically live, perhaps from long experience, further up in the hills;
- Maximum water level heights do not have to be great to cover the coastal flats, but then the increasing steepness of the slopes means that relatively few additional properties are flooded for even substantial increases in flood depth. Hence the mitigating impact of reefs and mangroves are relatively greater for lower category storms;

- Rainfall on steep slopes with limited soil depths leads to fast run-off with velocity dependent on the inclination of slopes which does not affect flooding depths but contributes to degradation through mechanisms such as sediment movement;

There is very little uncertainty in the assessment of the vulnerability of individual buildings and associated economic activity to flooding because of the use of very detailed GIS mapping. The main uncertainty is in the projections of meteorological effects and the physical effects of reefs and these, combined with the knowledge of vulnerability, are the basis of predictions of society's response. The degree to which a need for a response is avoided and society can continue to function as it currently does is the basis of the value of reefs.

Overall, reefs and mangroves are clearly of great value to the BVI and the assessment made here of their marginal value, excluding the structural changes that would follow their loss, shows them to have a value approaching 10% of GDP, which is assessed as a lower bound. While based on broad considerations only, a judgement made here of their potential value which also includes structural effects is that their value could be considered a factor of 2 to 4 times higher.

Contents

1. Introduction

This section seeks to introduce the project, its objectives and describes the overall aim of incorporating the value of coastal protection from natural capital into policy and decision making in the BVI.

1.1 Project Objectives

The British Virgin Islands (BVI), like many of the UK Caribbean Overseas Territories, is highly dependent on the natural environment for its economic and social well-being.

Since the advent of international travel in the 1950's and 1960's, tourism has become a dominant economic sector. Visitors are drawn to the island to enjoy its scenic beauty, undertaking activities such as diving and sailing, which directly benefit from the services provided by the rich variety of local. The natural environment can also play a key role in protecting built infrastructure and human well-being, so it is important that it is safeguarded against damage from human activities.

In recognition of the important role that the natural environment, the Government of BVI wishes to incorporate the socio-economic value of its natural resources into its policy and decision making. In particular, it is wanting to take into account the value of the role of the natural environment to support its fiscal planning instruments (e.g. MTFP and budget) and the proposed Environment Bill.

To support this process, the primary objective of this study is to assess the value of natural capital to mitigate the impacts of natural disasters on built infrastructure. Specifically, this relates to the provision of protection from coastal flooding and inland flooding as a result of extreme weather events.

The delivery to meet this objective was through the following three stages of work:

- Stage 1: Identification of economic techniques that have been or could be used to value the role of natural capital in the protection from coastal and inland flooding, with an emphasis on the tropical coastal zone;
- Stage 2: Assessing the potential application of valuation techniques identified in Stage 1 to case study sites within the BVI; and
- Stage 3: Application of the most appropriate techniques from Stages 1 and 2 to develop a detailed assessment of the economic value of natural capital in protecting built infrastructure across the whole of the BVI.

The purpose of this report is to provide a summary of the outcomes of each of these three Stages or work. Stage 1 was previously reported[1], but key outcomes are described below. The selected valuation technique is applied to three case study locations to provide a snapshot of the value of the protective services. This is then scaled up to provide an indicative value at a national level.

[1] Wood (2018) Stage One – Literature Review: "Approaches to valuing natural capital in terms of its protective service against coastal surges and inland flooding"

2. Context

This section provides a general introduction to the BVI discussing its geographic context, economy and key natural capital

2.1 Introduction to the British Virgin Islands

Location and Climate

The BVI is a group of over 50 small islands in the eastern Caribbean which form one of the British Overseas Territories. The islands are part of the Virgin Islands archipelago in the Lesser Antilles, located around 1000 miles south-east of Miami, Florida and 60 miles to the east of Puerto Rico. Many of the smaller islands and islets are uninhabited, while the main islands of the BVI include Tortola ($54km^2$), Virgin Gorda ($21km^2$), Anegada ($38km^2$) and Jost van Dyke ($9km^2$).[2] Tortola is the largest island at approximately 20km long, 5km wide and is where the capital, Road Town, is situated. The BVI comprises a total area of $151km^2$ and, as of 2017, supports a population of 31,000.

All the islands apart from Anegada (which is completely composed of coral and limestone) were tectonically uplifted from submerged volcanoes, formed from volcanic material and metamorphosed sediment. The terrain is dominated by steeply sloping hills surrounded by rocky coastlines which are susceptible to flooding.[3]

The BVI has a tropical rainforest climate with very little variation in temperature throughout the year. Road Town experiences daily maximum temperatures of around 32°C in the summer, and around 29 °C in winter. Average rainfall tends to be higher in the hill areas, but averages around 1,150mm per year with the wettest months generally being from September to November. Hurricanes and tropical storms with high winds and heavy precipitation are frequently experienced and the hurricane season extends from June to November. In 2017 the region experienced the full force of Hurricane Irma, the most powerful Atlantic hurricane ever recorded, preceded by a tropical wave and followed less than two weeks later by Hurricane Maria, causing extensive damage to natural and built infrastructure.

Economy

The economy of the BVI is amongst the more stable and prosperous of those in the Caribbean. In previous centuries years it was intensively farmed for sugar cane, with extensive replacement of the original natural vegetation, followed by a period producing and exporting horticultural products within the Caribbean. Over the last 40 years, the BVI has evolved from an agricultural/subsistence economy characterised by local people leaving the islands in search of work, to an economy based on tourism. Accompanying diversification into the provision of financial services to an international business community means that the BVI economy is overall one of the more balanced of the Caribbean with strong business links to Asia/Pacific and the United States.[4]

BVI largely depends on tourism and financial services –known as the "twin pillars" of the economy, with each representing roughly 50% of GDP. According to Capital Economics (2017)[5], tourism accounts for 1 in 4 jobs, while finance accounts for 1 in 10. Despite the impacts of the global financial crisis, and being small in size, the BVI was able to maintain a sound fiscal position and levels of prosperity are among the highest in the

[2] Conservation and Fisheries Dept. BVI (2011) *British Virgin Islands: Between latitudes 18° 26′ N and 18° 44′ N and longitudes 64° 20′ W and 64° 37′ W.* http://jncc.defra.gov.uk/PDF/ot_biodiversity2011_britishvirginisland.pdf

[3] JNCC British Virgin Islands: http://jncc.defra.gov.uk/pdf/OT_BVI.pdf

[4] Foreign and Commonwealth Office (2012) *The Overseas Territories: Security, Success and Sustainability* http://www.bvi.gov.vg/sites/default/files/resources/The%20Overseas%20Territories%20Security%2C%20Success%20and%20Sustainability.pdf

Caribbean.[5] According to a summary of the budget for 2017 published by the Minister for Finance, GDP is currently US$1,027 million, while GDP/capita is US$34,246.[6]

As well as its direct economic impact, tourism has significant indirect and induced impacts. Taxes on goods and services represent the vast majority of government revenue in the BVI. The National Account Statistics[7] show that for two years following the year 2010, economic activities in the BVI had slowed, registering declines in Constant Prices GDP in both 2011 and 2012 of 0.69% and 4.5% respectively. The tourism sector, with a greater spread across economic activities, did not register a decline due to the nature of the business being driven by advance bookings. In 2012, the decline in the Wholesale and Retail industry narrowed to 7.4% and Accommodation and Food Services contracted by 14.8%. The contractions registered in these sectors were by-products of not only slowed global economic growth, but of contraction in the tourism sector from increased competition from other destinations, as well as issues with air and sea access in the BVI, including under-developed port facilities. This was seen in the 2014-2016 Medium Term Fiscal plan which indicated that in 2012, total tourism contracted by 9.4%, mainly due to the decrease in cruise ship passengers to the territory.

The economy began to recover in 2013, after two years of downturn. Increases were recorded in industries such as Transportation and Storage (11.1%), Financial and Insurance Activities (9.8%), Professional Services (5.6%), Public Administration, Defence and Social Security (2.2%). The stimulus for the increases in these industries (except for Financial and Insurance Activities) was the rise in overnight tourists, and high-end tourism.

These government and other data sources highlight the integral value of tourism, and by extension, tourism-related infrastructure (such as bars, restaurants and hotels) to the economy of the BVI. For example, Capital Economics report for BVI Finance Limited estimated that for 2016, there were over 1.1 million tourist visitors (a 22% increase from the previous year)[5] and according to the latest available statistics from the Central Statistics Office, tourism-related services accounted for export earnings of US$484 million.[8]

Economic impacts of extreme weather events

Climate-related events have been shown to have a direct impact on the BVI's economy.

Hurricane Otto

On 5th and 6th October 2010, the passage of Hurricane Otto over the BVI resulted in 25.68 inches of rainfall (652 mm) as recorded at the weather station at the Department of Disaster Management, leading to significant flash flooding and landslides, damage to utilities and pipes, and residences left without access to power or water supply. A state of emergency was declared and remained in place until 16th October. While no deaths were experienced, the financial impact was considerable. The Minister of Finance, Hon. Ralph T. O'Neal, stated that the damage was in excess of US$10.5m, not including the impacts from disruption to business. Emergency Powers Orders were signed by the Governor on 6th October to declare an emergency area with respect to Cappoons Bay, Pockwood Pond, and Prospect Reef to remove debris and allow for free flow of water in these areas.

August 2017 flooding

On 7th/8th August 2017 a tropical storm passed over the Virgin Islands bringing heavy rainfall and thunder storms. Up to 17 inches of rain (432 mm) fell in around 17 hours leading to significant flooding and a

[5] Capital Economics report BVI Finance Ltd. (2017) *Creating Value: The BVI's Global Contribution*
[6] Minister for Finance BVI (2017) *Budget in Brief 2017- Charting our course: positioning the BVI for the Future.*
[7] European Commission, IMF, OECD, UN and World Bank (2009) *System of National Accounts 2008* https://unstats.un.org/unsd/nationalaccount/docs/SNA2008.pdf
[8] BVI Central Statistics Office: http://www.bvi.gov.vg/sites/default/files/estimated_visitor_expenditure_2010-2015.pdf

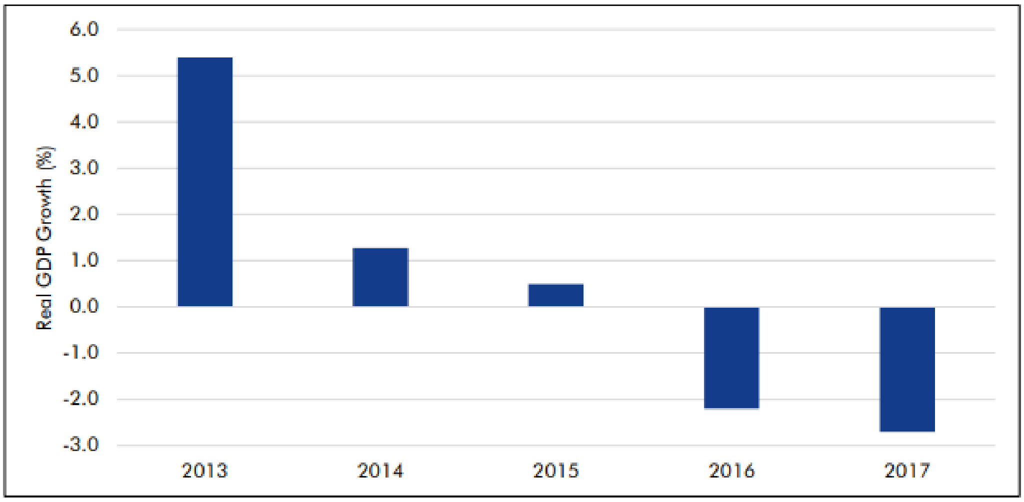
number of landslides, resulting in extensive damage to homes and properties, roads, schools and other public and municipal buildings.

Hurricane Irma and Maria

During September 2017 the British Virgin Islands experienced two 'category 5' hurricanes in rapid succession – Hurricane Irma, passing the territory on 6th September, and Hurricane Maria less than two weeks later on 19th September. Hurricane Irma was the strongest ever recorded Atlantic hurricane and passed directly over the British Virgin Islands, with the 'eye' of the storm passing directly over Road Town. Extensive damage was caused across the territory, with over 80% of buildings significantly damaged. A high storm surge was also experienced, causing rapid flooding of the low-lying areas of Road Town. Hurricane Maria did not pass directly over Tortola, but it was still a significant and dangerous storm It has been estimated that the damage caused by the hurricanes exceed US$3.6 billion which is equivalent to approximately 3.5 times the regions annual gross domestic product (GDP)[5]. The economy is estimated to have contracted by around 2.7% in 2017 as a result of the weather-related damage, following a decline of 2.2% in 2016, as illustrated in Figure 2-1.

The economic decline in 2017 has largely been attributed to the impact from the hurricanes on the tourism sector, which, along with financial services, is the main foundation of the BVI's economy. Hence, sustaining tourism in the BVI is integral to maintaining economic prosperity.

Figure 2-1 Real GDP growth 2011-2017 in the BVI



Source: Ministry of Finance, Dept. of Statistics referenced by the Caribbean Development Bank Country Profile of the BVI (2017)

Future climate change

As identified in the recent report by Wood on flood-risk in Road Town the effects of climate change mean that extreme events can be expected to be more frequent. The Government of the British Virgin Islands has assessed that the impacts of climate change on the Islands will be[9]:

- Increases to average temperatures of between 1.5°C and 5.0°C;
- Changes in rainfall patterns leading to more frequent and more intense storms, but also extended drought periods and reduced total precipitation in months that have historically experienced heavy rainfall;
- Stronger hurricanes; and

[9] Wood (2018), Road Town Catchment Characterisation Report.

- Rising sea level.

There is expected to be an associated rise in the risk and level of flooding and this has particularly deleterious effects on tourism. It has both direct impacts in the short term and, if not addressed, longer term reputational impacts.

Natural features

The diverse range of habitats in the BVI are a particular source of attraction for tourists as well as a benefit for local residents. Coastlines are generally rocky, dominated by white sandy beaches on the northern aspects. Coral reefs, salt ponds and some mangroves can be found in the coastal zone while the terrestrial areas on the steep slopes include vegetation from thicket to mixed forest.[10]

The beaches in the BVI are valued highly among tourists with popular destinations being Smuggler's Cove and Cane Garden Bay (Tortola), Loblolly Bay (Anegada) and White Bay (Jost Van Dyke). It has been noted by Gore *et al.* (2007)[11] that development pressure from tourism has been recognised as a potential ecological threat to beach health in the BVI. For example, it was estimated that land use change and recent natural hazards have caused beaches to narrow by up to 1m in the BVI (JNCC, 2017)[21]. The BVI includes 380km^2 of reefs which vary from small fragmented areas to the vast reefs of Anegada with made up of over 77km^2 of coral. The Horseshoe reef of Anegada is the third largest barrier reef in the world and attracts many divers and snorkelers every year.[12] Reefs in the eastern Caribbean region, including the BVI, are most at risk from over-fishing and coastal development. Development has led to increased sedimentation in the BVI which is a known cause of reef damage. Tourist activities such as yachting also put reefs at risk due to anchor damage and sewage.[13] The BVI has 53 separate mangrove systems comprising 5.8km^2, 75% of which are located on Anegada. The ecosystems of the BVI include many marine and terrestrial species, including over 100 species of tropical fish (e.g. flying fish & the wahoo), 50 species of birds (such as the brown pelican) and other marine animals (e.g. hawksbill turtle).

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[10] JNCC British Virgin Islands http://jncc.defra.gov.uk/pdf/OT_BVI.pdf

[11] Gore (2007) "Framework development for beach management in the British Virgin Islands" Ocean & Coastal Management (50) pp 732-753.

[12] Conservation and Fisheries Dept. BVI (2011) *British Virgin Islands: Between latitudes 18° 26′ N and 18° 44′ N and longitudes 64° 20′ W and 64° 37′ W.* http://jncc.defra.gov.uk/PDF/ot_biodiversity2011_britishvirginisland.pdf

[13] Burke and Maidens (2004) *World Resources Institute: Reefs at risk in the Caribbean*

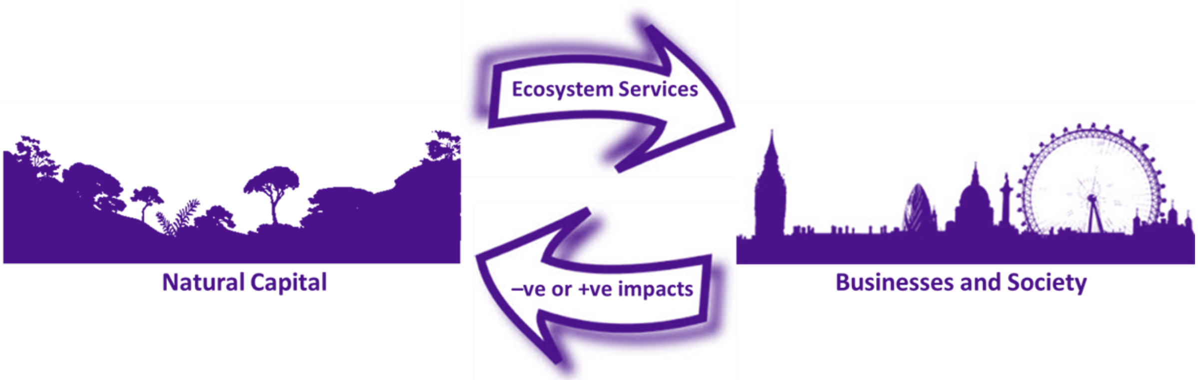
3. Approach

This section provides an overview of the current knowledge on natural capital, including the methods available for valuation and what has been applied thus far in the BVI and to the wider Caribbean. A description is provided on how the selected method has been used to assess protection provided by natural capital against inland and coastal flooding.

3.1 Natural capital and ecosystem services

According to the World Forum on Natural Capital, 'natural capital' can be defined as the stocks of natural assets found within the Earth's critical zone which includes living things, vegetation, and animals together with the geology, soil, air, and water[14]. Natural Capital provides the renewable and non-renewable resources that combine to yield a flow of benefits to people in the form of Ecosystem Services (Figure 3-1). Unsustainable use of Ecosystem Services can lead to negative impacts on the underlying Natural Capital and a reduction in benefits to people and wildlife.

Figure 3-1 The relationship between Natural Capital and Ecosystem Services



Natural Capital and Ecosystem Services such as cultural, provisioning and regulating services are potentially subject to a range of natural and anthropogenic processes and so may need to be protected and enhanced. Particularly close dependencies exist in small island states that rely on the natural environment. Figure 3-2 shows examples of cultural, provisioning and regulation services. According to the Millennium Ecosystem Assessment (2005) flood protection is an example of a regulating ecosystem service and demand for this service is likely to increase while provision is likely to decrease due to land use changes which enhance flood severity and the exacerbating effects of climate change.[15]

Coral reefs are examples of natural capital assets in the coastal zone which provide goods and services to society, a proportion of which are exchanged in markets on a local and global scale. They reduce the exposure and vulnerability of costal infrastructure to natural disasters along with other inherent advantages such as the provision of recreational opportunities for local people and tourists alike and opportunities for scientific benefits from academic research.[16] [17]

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[14] World Forum on Natural Capital https://naturalcapitalforum.com/about/
[15] MEA (2005) *Ecosystems and Human Well-being: Wetlands and water* https://www.millenniumassessment.org/documents/document.358.aspx.pdf
[16] Pascal et al. (2016) *Economic valuation of coral reef ecosystem service of coastal protection: A pragmatic approach*
[17] de Groot, R. et al. (2012) *Global estimates of the value of ecosystems and their services in monetary units*

The protective service of natural capital has been increasingly recognised since analysis of the Indian Ocean tsunami in 2004 and Hurricane Katrina in 2005 revealed damage to be less severe in areas surrounded by coastal ecosystems including coral reefs and mangroves.[18] Given the existence of coral reef and mangrove ecosystems in the BVI, the reliance of the economy on the natural environment, and the extent of damage caused by recent hurricanes, coral reefs and mangroves are vital natural capital assets which provide value to the BVI and its inhabitants while offering flood protection.

Figure 3-2 Important Ecosystem Services for the BVI with those prioritised in this Assessment highlighted.

Source: JNCC (2017) "Scope of a natural capital assessment in the British Virgin Islands" http://jncc.defra.gov.uk/pdf/OT_NCA_BVI_Scope_of_NCA.pdf

Valuing natural capital

Natural capital assets can be valued in a number of different ways because of the variety of roles they can perform and the intended use of the valuation estimate in decision-making or accounting[19]. Regarding the service of flood protection, there are a range of generic valuation techniques which can be deployed dependent on the circumstances. The principal generic methods relevant to this study are summarised in Table 3.1 but are discussed in detail in the final report for Stage One of the literature review.

[18] Barbier (2015) *Policy: Hurricane Katrina's lessons for the world* https://www.nature.com/news/policy-hurricane-katrina-s-lessons-for-the-world-1.18188
[19] https://naturalcapitalcoalition.org/natural-capital-protocol/

Table 3.1 Summary of generic methods to value protection against flooding from natural capital

Stated preference method	Stated preference methods are survey-based approaches which elicit the WTP (willingness to pay) value of a person for the provision of an ecosystem service. They are typically used to value ecosystem services which do not have a market value (such as informal recreation or biodiversity benefits).
Revealed preference method	Contrasts stated preference methods which are based on hypothetical scenarios. Revealed preference methods use observations of existing behaviour as proxies to understand the values that people implicitly ascribe (i.e. higher house prices where flood protection is greater).
Replacement cost method	The replacement cost method estimates the cost of an alternative to the natural capital asset which provides an ecosystem service such as coastal protection. A typical alternative is an engineered structure providing the same function.
Benefits transfer	Adapts readily available value estimates from the literature by identifying those which are most relevant for the service in question, and then makes adjustments to this value, making it useful for the area of interest. It involves an implicit 'transfer' of the estimated value of the service from one site to another.
Expected damage function	This was the technique selected to be applied and adapted to case studies in the BVI

Source: Wood (2018) Stage One – Literature Review: "Approaches to valuing natural capital in terms of its protective service against coastal surges and inland flooding"

3.2 State of knowledge

Previous work on natural capital in the Caribbean

Due to the significance of natural capital to tourism in the Caribbean, research has been conducted on quantifying the value of coral reefs and mangroves within the BVI and the wider Caribbean region. For example, Sipos et al. (2014) valued ecosystem services related to tourism in the BVI by assessing the WTP of tourists for management of marine/coastal ecosystems. Using this data, the tourism value of natural capital was estimated at around US$194 million per year.[20] This study did not include spatial data, or consider the protection offered by natural capital to tourist related infrastructure.

Despite the vulnerability of islands in the Caribbean to flooding and extreme weather events and the protection offered by reefs and mangroves to coastlines elsewhere in the world, few economic studies have been conducted to assess the value of flood protection from natural disasters provided by natural capital in the BVI.

The value of flood protection from natural capital in the UK Overseas Territories, which included the BVI, was estimated by JNCC (2017) using the avoided damage cost approach. The study combined radar-based terrain mapping and flood hazard risk models to understand the vulnerability and exposure of real estate infrastructure.[21] Depth-damage curves and functions were used to assess the expected damage and relative

[20] Sipos et al (2014) *The tourism value of nature in the British Virgin Islands" Institute for Environmental Studies.*

[21] JNCC (2017) *Using radar based terrain mapping to model the vulnerability of 5 UK OTs*

reconstruction costs used. It is reflective of the methodology recommended for this approach by WAVES (2016)[22].

The results highlighted that expected damages from a coastal flooding baseline can range from US$327 million for degraded ecosystems, to US$294 million for enhanced ecosystems. This was interpreted as yielding avoided damages of around US$32.5million in a scenario which enhances natural capital. Inland flooding was also assessed using the same approach, and damages were found to be higher than for coastal flooding. The costs of avoided damage by enhanced natural capital was estimated at over US$200 million for inland flooding. These figures did not provide an annual protection value but represents the value of protection from a low-probability, high impact event. The values represent aggregate damage for the OT's, and it is noted within the study that this should be considered as a lower-bound estimate – most likely representing an under estimation of total damages.

Costs of avoided damage approach

The expected damage function approach was the methodology chosen for this study. This method relates to a change in the output of a marketable good/service to a quantified change in ecosystem goods/services and its accuracy when compared to other methods has been highlighted by WAVES (2016)[22]. Hence, this section highlights previous studies which have use this approach (or similar approaches) to value coastal and inland flood protection.

Coastal flooding

A study conducted by Van Zanten *et al.* in 2014 applied the costs of avoided damage approach to assess coastal flood protection in the US Virgin Islands, by quantifying the physical link between hydrological services offered by coral reef ecosystems and flood damage to properties on the coastline.[23] In this study the main indicator for natural capital was coral cover while the ecosystem function was represented by the modelled wave energy dissipation offered by the coral. The ecosystem service being provided was quantified by reef-protected coastline and the economic value of avoided damage was represented by an estimated value of the infrastructure being protected. Hence, the three steps in the analysis addressed the following topics:

- Hazard
- Exposure and vulnerability
- Valuation based on risk indicator

WAVES (2016)[22] highlights the accuracy of this approach when compared to other valuation methods, though it is generally under-used due to the extensive site-specific data that is required. According to WAVES, data requirements include: 1) Offshore hydrodynamics 2) Nearshore hydrodynamics 3) Effects of the ecosystem on coastal hydrodynamics 4) Flooding and erosion in a BAU scenario 5) Assessment of expected damages vs the damages avoided due to protection from the ecosystem in question. According to WAVES, the value of avoided damages can also be expressed in non-monetary terms, such as the expected deaths avoided by coastal communities (Barbier, 2016)[27]. Alternatively, they highlight the possibility of using exposed populations as a translation of exposed assets by estimating the "Produced Capital per Capita" from the World Bank and the monetary value of property like hotels, retailers and businesses.

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

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

Thus, the general description of the methodology in WAVES is arguably more complex than the methodology outlined by Burke *et al.* for the coral reefs of Tobago, presented below.[24] In Burke's (2008) valuation of the protective service of coral reefs in Tobago and St Lucia, six steps were outlined to calculate the costs of avoided damage, which are highly comparable with the steps taken by van Beukering which assessed protection from coral reefs in Bermuda.[25] These are identified as follows:

- Develop an understanding of storm regimes and assess historic data reported by natural hazards in the past
- Identify areas that are vulnerable to damage
- Identify areas which are protected by the ecosystem
- Provide an evaluation of the shoreline's stability
- Assess the value of property in the study area that is protected
- Assess the extent that the ecosystem prevents any potential/modelled damage to property

While the methodologies followed by Burke and van Beukering are comparable, the economic value calculated different results. This has been attributed to the different storm return times used by the authors (Burke used 25-year storm period return times while van Beukering used a longer period of 52 years). According to van Zanten and van Beukering's 2012 report for the Institute of Environmental Studies[26], the data requirements for this approach include land elevation, shore type, coral reef cover and a metric of coral reef health as well as storm frequency, intensity, surge and historic wave heights, contrasting the data requirements suggested by WAVES (2016). A similar approach been used to assess mangroves ability to protect against extreme weather events.[27][28]

Storlazzi *et al.* (2017) modelled the production of "hazard risk reduction" from coral reefs in Maui, Hawaii. Figure 1.1 represents a schematic of the methodology used to evaluate the role of coral reefs in hazard risk reduction.[29]

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

[25] Van Beukering et al. (2010) *"Total economic value of Bermuda's Coral Reefs Valuation of ecosystem Services".*

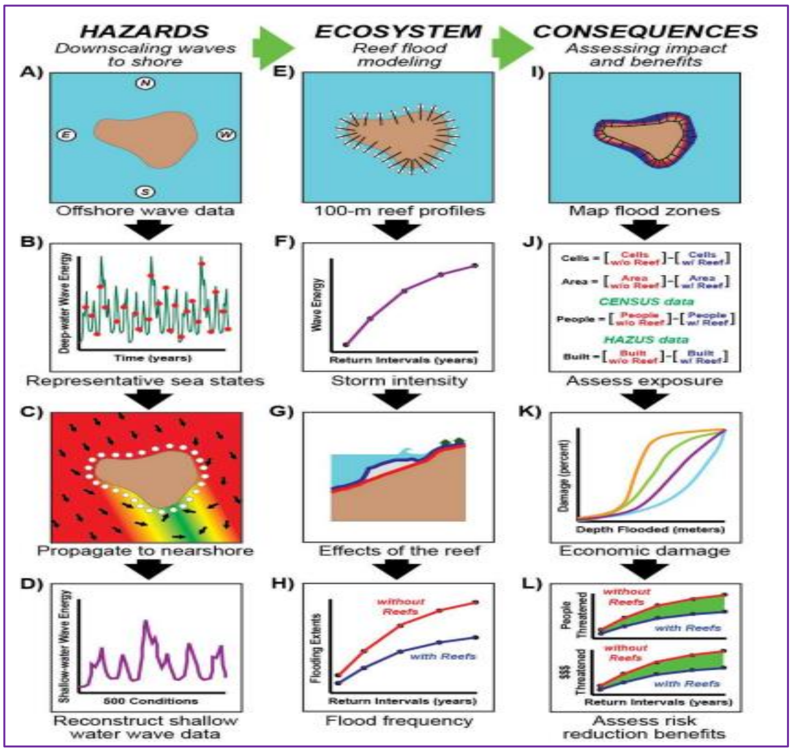
[26] Van Zanten & Van Beukering (2012) *Coastal Protection services of coral reefs in Bonaire. Economic values and spatial maps.*

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

[28]Hanley, N., and Barbier, E. (2009) Chapter 9-Valuing Ecosystem Services" in Pricing Nature: Cost Benefit Analysis and Environmental Policy

[29] Storlazzi et al (2017) *Rigorously valuing the role of coral reefs In coastal protection: An example from Maui, Hawaii, USA.*

Figure 3-3 Schematic of the costs of avoided damage approach used to value the protective service of coral reefs.



Source: Storlazzi *et al.* (2017) *Rigorously valuing the role of coral reefs In coastal protection: An example from Maui, Hawaii, USA.*

Inland flooding

There are few studies regarding the value of natural capital for inland flood protection. However, recent studies in Europe have started this journey by attempting to value "green infrastructure" in the context of flood management plans, and this is also considered in the UK's national ecosystem accounting framework. The costs of avoided damages approach was identified as the most commonly used method for valuing flood mitigation, with cases from the UK and Mexico, as well as being used by the JNCC for BVI (2017).

The combination of hydraulic modelling and economic appraisal has been applied in Southwell, UK[30] in an area that suffers repeated flooding, which has become severe in recent years. A cost-benefit analysis compared the costs of planting woodland (enhancing natural capital) with damage to property and interruption to business from flooding and found that the benefits of natural protection consistently outweighed the costs of maintaining the woodland (replanting). This is an example where the natural capital is implicitly valued in terms of the avoided cost of damage.

A similar approach was used to analyse the cost of reducing flood risk to Tabasco state, Mexico.[31] This study modelled the expected annual damage caused by flooding in a situation where no measures were to be put in place, versus a scenario where adaption measures were considered, thus informing the costs of flood risk management. Scenario analysis was also carried out to value the flood mitigating service of Otter Creek wetlands and floodplains in Vermont, USA.[32] The authors emphasized the role of "green infrastructure" as a means of building resilience by quantifying the value of the ecosystem in reducing flood damage from a single historic event (Storm Irene – 2011) and by calculating the expected annual value of the ecosystem in mitigating flood damages.

[30] JBA Consulting (2016) *Flood management and woodland creation – Southwell Case Study*

[31] Haer et al. (2017) *Economic evaluation of climate risk adaptation strategies: Cost benefit analysis of flood protection in Tabasco, Mexico*

[32] Watson et al. (2016) *Quantifying flood mitigation services: The economic value of Otter Creek wetlands and floodplains to Middlebury, VT.*

Potential caveats of the costs of avoided damage approach

A limitation commonly associated with using the costs of avoided damages method is the difficulty in relating the damage prevention ability (i.e. of the coral reef or mangrove) with the quality of the ecosystem, as their ability to effectively protect the shoreline relates to ecosystem health[33]. This was accounted for by van Beukering by applying different scenarios for differing stages of ecosystem health, which included “degraded” and “full destruction” scenarios for shallow, deep, high density and low-density corals – this was also applied for each of the three case studies under this study.

This approach also requires substantial site-specific data (i.e. on the type and value of properties in the study, historic flood extents, quality of ecosystems) to provide a realistic representation of damages. The damage cost estimate is also likely to be less than the actual damage costs, as the modelled damage to property that is considered is often based on value of the building itself, and may not take into account lost business of the economic activities going on inside the property, or the non-tangible impacts to human well-being. However, the former can be considered if site-specific data on the impact of historic events to business revenue (i.e. hotels and restaurants) were available, or revenue of such businesses are modelled, as is the case with the three case studies assessed for this project (See Section 4 – Methodology).

[33] Waite, R., et al. (2014). *Coastal Capital: Ecosystem Valuation for Decision Making in the Caribbean.*

4. Methodology

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

4.1 Inland flooding

Amongst natural capital's wider benefits is the protection offered with regard to inland flooding. Vegetation cover is dense across much of the BVI, for example, evergreen, semi-deciduous and mixed forest combine to cover nearly 80% of the Cane Garden Bay catchment. There are several benefits that vegetation provides to mitigate flooding during rainfall events, including:

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

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

In 2017/18, Wood conducted a study in collaboration with the Government of the Virgin Islands and the Caribbean Development Bank into the hydrology and flooding issues in Road Town, the capital of the BVI (Wood, 2018)[34]. The study demonstrated that the extremely intense rainfall in large storm events in the BVI caused the interception and infiltration benefits of the vegetation cover to be insignificant relative to the volume of water in the storm; as the canopy and soil become saturated quickly, after which rainfall is converted to 100% runoff. The steep topography of much of the BVI causes rainfall to run off the slopes at high velocities, reaching the lower-lying areas from the tops of the hills very quickly. The study also revealed that in some cases, the mechanisms described above by which natural vegetation can help to mitigate flood risk, can also have the reverse effect and compound flood flows. It was observed that in Road Town, mangroves are blocking the dispersion of inland flood waters out to sea, and causing higher stream levels and increasing the susceptibility of infrastructure to flooding.

It was therefore proposed to use hydraulic modelling to assess the role of natural capital in terms of the protection offered by reducing the catchment response to a storm event; in slowing the passage of water through the catchment. The approach for hydraulic modelling is a 2-Dimensional (2D) hydraulic model, utilising the modelling software package InfoWorks ICM (Integrated Catchment Model). The model was used to compare the flood depths encountered in three scenarios:

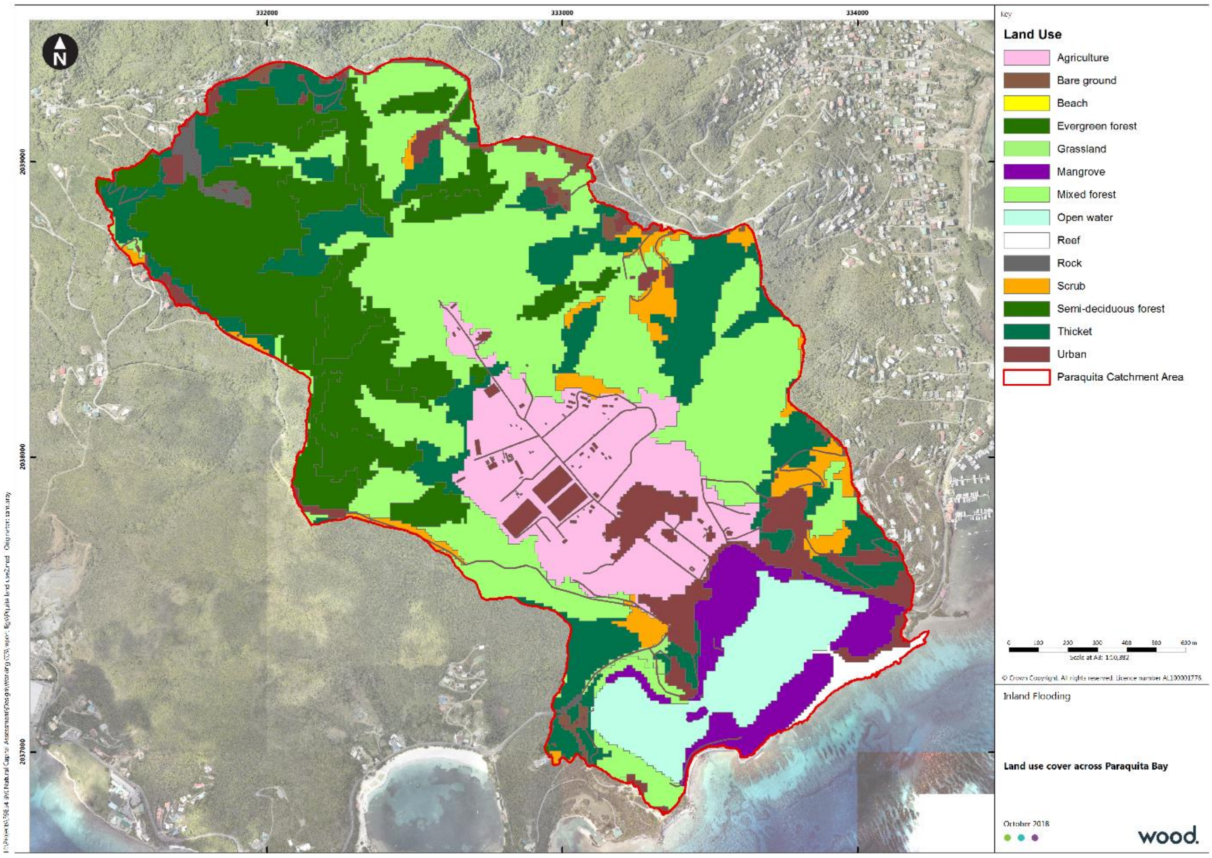
- Baseline scenario – where natural capital is represented within the model to best reflect the current condition;
- Economic Change scenario – where increased urbanisation is represented to reflect a future scenario in which there is increased development; and

[34] Wood (2018), Road Town Catchment Characterisation Report.

- Degraded Environment scenario – where the vegetation cover and its protection is removed.

The 2D model represents the land surface as an irregular triangular mesh. Each triangle is assigned an elevation, along with a range of other properties, forming a surface over which flood water can flow. Amongst those other properties is a value for land use cover, applied numerically as roughness. Roughness represents the energy losses due to ground friction, for example, dense weeds or brush in a channel will offer significantly more resistance to flow than a smooth, lined concrete channel. It is this roughness value that will be varied spatially to represent different land uses or degradation of the environment, to create the three scenarios listed above. Figure 4-1 below shows the distribution of land use across Paraquita Bay.

Figure 4-1 Land use cover across Paraquita Bay[35]



Note: Landuse/habitat data provided by Environment Systems

The key data requirements for the hydraulic modelling are as follows:

- Building information – including footprints and usage, to calculate flooding impacts
- Elevation data across the BVI – to define the model surface;
- Pluvial hyetographs - design rainfall storm events that can be applied to the scenarios, enabling the comparison of flood depths between them; and
- Land use information across the case study areas – to represent roughness.

[35] Land use information provided by Environment Systems

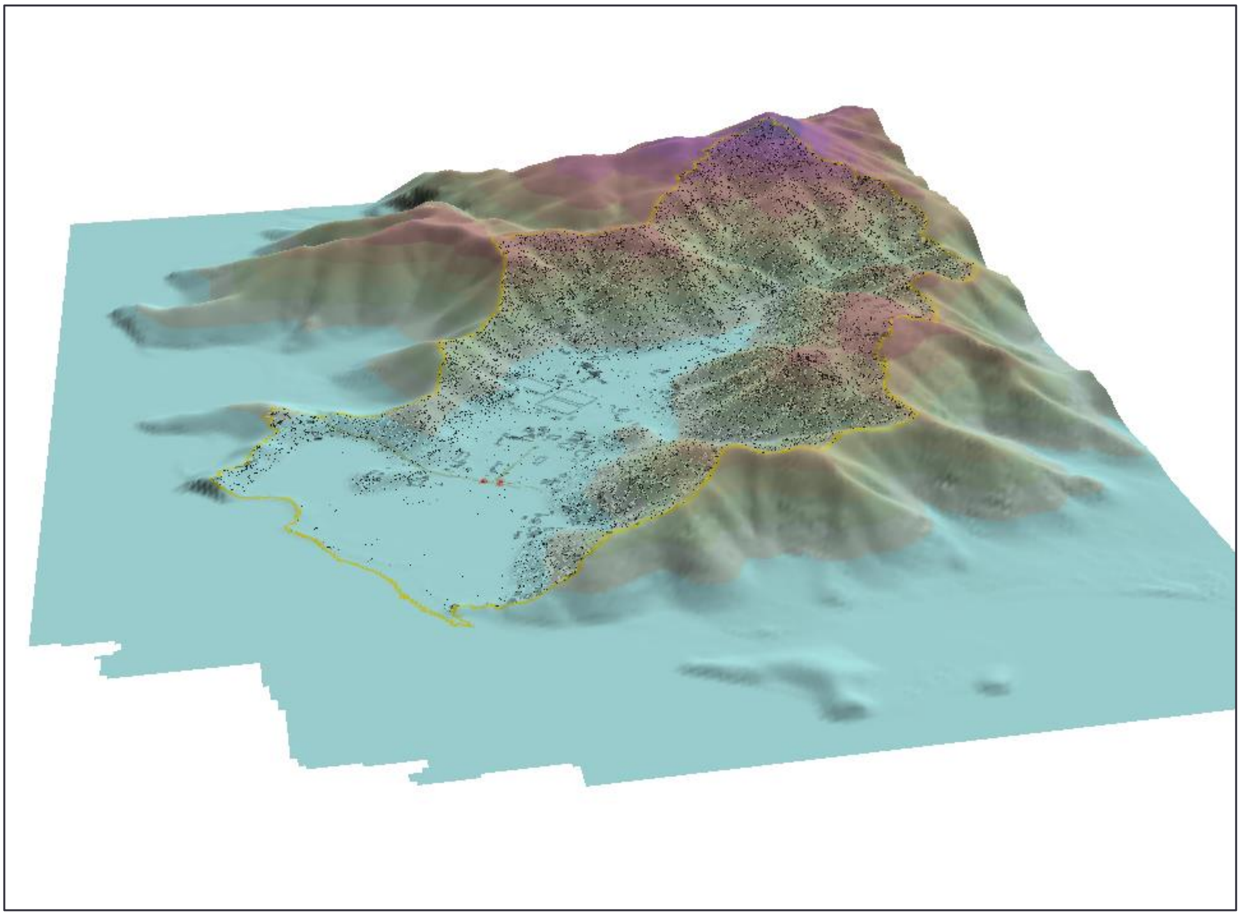
Buildings information

A buildings GIS (Geographic Information Systems) dataset was provided by the BVI Government for use within this study. The buildings were represented in the hydraulic model as porous polygons, with a porosity of 10%. This will enable some flood water to penetrate the perimeter of a building, but divert the majority of water around it. To assess the damage caused by a flood event, the maximum water depths either within a building or immediately outside it were compared across the various scenarios.

Elevation information

Elevation data for the case study areas in the form of LiDAR (Light Detection And Ranging), a remote sensing method used to measure the height of the ground surface. This provides elevation data on a gridded format at a resolution of 0.5m. This enables the hydraulic model to create the 2D surface using the irregular triangular mesh, as shown in Figure 4-2 below, showing the Paraquita Bay surface.

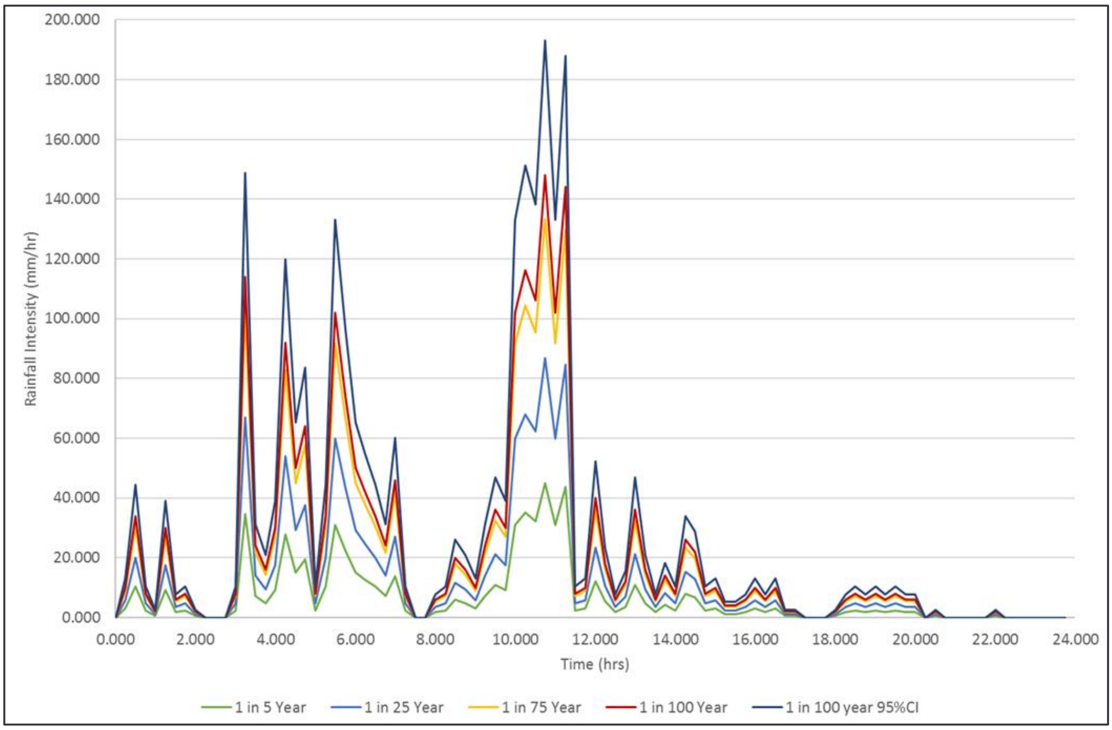
Figure 4-2 Paraquita Bay 2D surface



Pluvial hyetographs

As part of the Wood Hydrology Study (2018), a comprehensive assessment of extreme rainfall events was used to define design storm events. The analysis was based on rainfall records provided by the Department of Disaster Management, and supplemented by records from Caneel Bay in the US Virgin Islands. A range of storm events were defined, based on the rainfall profile of the August 2017 severe rainfall event, which caused widespread flooding across the BVI. The 1 in 5 year AEP (Annual Exceedance Probability), 1 in 25 year AEP, and 1 in 100 year AEP events, which have a 20, 4, and 1% chance respectively of being exceeded in any year, were used as the hydrological inputs to the natural capital hydraulic models. Figure 4-3 below shows the rainfall profiles generated.

Figure 4-3 Design rainfall-intensity hyetographs



Land use information

The land use and cover data used in this study was provided by Environment Systems in the form of a Land Use shapefile, which delineates the catchment into land cover by area. This dataset was used to create a series of roughness zones to represent the different land covers across the 2D model domain. Table 4.1 describes the different land cover classifications used in the model and their associated Manning's n roughness values. The Manning's n values selected for each land cover type were chosen based on published information[36,37,38], modeller experience and judgement.

Table 4.1 Roughness Zone classification and Manning's n roughness values

Land use coverage	Manning's N Roughness value
Agriculture	0.0350
Bare ground	0.0350
Beach	0.0350
Evergreen forest	0.1600
Grassland	0.0350
Mangrove	0.0700

[36] https://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/HecRAS/NEDC/lectures/docs/Manning%92s%20n-values%20for%20Kansas%20Dam%20Breach%20Analyses%20-%20Adopted%20071216.pdf

[37] Syme (2008) Flooding in Urban Areas - 2D Modelling Approaches for Buildings and Fences. Engineers Australia, 9th National Conference on Hydraulics in Water Engineering Darwin Convention Centre, Australia 23-26 September 2008.

[38] Chow (1959) Open-Channel Hydraulics. McGraw-Hill Kogakusha Ltd, 1959

Mixed forest	0.1600
Reef	0.0400
Rock	0.0350
Scrub	0.1000
Semi-deciduous forest	0.1600
Thicket	0.1600
Urban	0.0400
Open water	0.0400

The land use coverage across the model domain was altered to create the additional scenarios beyond the Baseline, the "Economic Change" and "Degraded Environment" scenarios. In the Economic Change scenario, the urban coverages of Paraquita Bay and Cane Garden Bay were increased to match the urban coverage in Road Town, representing a potential future development scenario. This was achieved by increasing the size of existing areas in development, typically centred at lower-lying areas and on the ridges, rather than the steep slopes. In the degraded environment scenario, the entire domain was assumed to have roughness value of 0.035, equal to the Bare Ground land use category.

Hydraulic model runs

2D hydraulic models were created for Cane Garden Bay and for Paraquita Bay. Due to the very flat topography, Anegada was considered to be more at risk of coastal flooding than inland, and as such not assessed using an inland flooding model. The two hydraulic models, three scenarios and three rainfall events combined to make 18 model runs, as shown in Table 4.2 below:

Table 4.2 Hydraulic model runs

Hydraulic model	Scenario	Rainfall event	Model run
Cane Garden Bay	Baseline	5	CGB_Base_5year
		25	CGB_Base_25year
		100	CGB_Base_100year
	Economic Change	5	CGB_EC_5year
		25	CGB_EC_25year
		100	CGB_EC_100year
	Degraded environment	5	CGB_Degraded_5year
		25	CGB_Degraded_25year
		100	CGB_Degraded_100year

Paraquita Bay	Baseline	5	Pquita_Base_5year
		25	Pquita _Base_25year
		100	Pquita _Base_100year
	Economic Change	5	Pquita _EC_5year
		25	Pquita _EC_25year
		100	Pquita _EC_100year
	Degraded environment	5	Pquita _Degraded_5year
		25	Pquita _Degraded_25year
		100	Pquita _Degraded_100year

Limitations of methodology

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

- Infiltration and interception are not considered; and
- Only depth is considered in the protection valuation.

Infiltration and interception are not considered as part of this study for two main reasons. Firstly, there is limited data available on soil infiltration capacity across the BVI, which would make choosing an infiltration rate, capacity and recovery rate difficult. Secondly, since pluvial hyetographs were made available to this study through the Road Town Hydrology Study, the rainfall profiles were extreme in nature. These extreme rainfall events are likely to cause saturation of the soil, after which rainfall is converted to 100% runoff. For this reason the role of natural capital for the purpose of this study was reduced to assessing the resistance to flow offered by vegetation, in slowing the passage of water through the catchment.

Flood depth in each building was the metric by which a valuation was placed on the potential damage caused by each model run. Depth is, of course, a key parameter in assessing the likely impact of a flood, however, the velocity is also key since this value may determine the scour of the hillsides, sediment load within the flood volume, and potential for landslides. Flood events in the BVI cause significant issues due to the mud, clay and rocks that are deposited in the lower-lying areas where the velocities drop, and as such, slowing the passage of water on the hillsides is likely an important factor in reducing flood damage, disregarded for simplicity in this study.

4.2 Coastal flooding

Coastal flooding is a cause of much damage in the BVI with both the intensity of tropical storms and their frequency important to overall effects on society. Increased water levels associated with storm surge is a primary cause of coastal flooding. Storm surge is a temporary rise in sea level caused by the high winds and low pressure at the centre of a hurricane (an extreme tropical storm) and its movement forward which combine to push seawater into a mound at the centre of the storm. As a storm surge makes landfall, the water is pushed up the shore and causes coastal flooding which is further exacerbated by large waves at the now elevated sea level. Mangroves and coral reefs are examples of natural capital assets or "green infrastructure" located in the coastal zone which have the ability to reduce exposure and vulnerability of property and populations to natural disasters (de Groot *et al.*, 2012[39]; Pascal *et al.*, 2016[40]).

Coral reefs provide coasts with natural protection from erosion and flooding by absorbing wave energy. Coral reefs are capable of dissipating wave energy by up to 97%, with reef crests reducing on average 86% of incident wave energy by creating a barrier and reducing horizontal wave movement and reef flats, which reduce vertical wave movement and dissipate 65% of the remaining wave energy (Ferrario *et al*., 2014[41]). Reefs protect against less frequent high energy events such as Category 4 and 5 hurricanes, but also against higher frequency lower energy events by reducing swell waves. Provided they are healthy, they have the ability to accrete carbonate structures which keep in time with sea level and can provide a significant role in coastal protection even during cyclones. However, it is important to note that given the projected increases in ocean acidification and sea level rise, as well as the effects of coastal infrastructure on sediment availability, their protective function may be compromised as health deteriorates. (WAVES, 2016[22]; Ferrario *et al*., 2014[41]).

The coastal protection service provided by mangroves is related to the ability of the vegetation to act as a source of friction, which acts on a body of moving water, resulting in the reduction of wave heights and storm surges as they approach a shoreline, as well as their ability to buffer wind speed (Barbier, 2016a[27], 2016b[42]). Research has shown that mangroves can reduce the height of wind and swell waves over relatively short distances with attenuation wave height can be reduced by 0.0014/m and 0.011/m which indicate that over a 100m width of mangrove forest, wave heights can be reduced by between 13-66% and over a 500m width of mangrove wave heights can be reduced by 50-100% with the highest rate of wave height reduction per unit distance occurs near the mangrove edge (McIvor *et al.* 2012[43], Mazda *et al.* 2006[44], Quartel *et al.* 2007[45]). It is noted that studies of wave attenuation have been mostly focused on smaller waves with less during hurricane conditions[43]. To reduce storm surge peak water levels mangroves are required in thick belts of greater than 1km[22].

An existing method was used as the basis for assessing the impacts of an individual storm event, and the frequency of events derived from historical data.

Existing approach to assessment of an individual storm event

The method adopted for assessing the protective service of coral reefs is based on the approach described by van Beukering *et al.* (2012)[46] and van Zanten *et al.* (2014)[23] which presents a framework for the spatial assessment and economic valuation of the coastal protective service of coral reefs and was applied to the US Virgin Isles[46][47]. The framework was adapted for application with mangroves.

The analytical framework is shown in Figure 4-4 and comprises three key components: hazard, exposure and vulnerability, and valuation.

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

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

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

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

[43] McIvor, A.L., Möller, I., Spencer, T. and Spalding. M. (2012) Reduction of wind and swell waves by mangroves. Natural Coastal Protection Series: Report 1. Cambridge Coastal Research Unit Working Paper 40. Published by The Nature Conservancy and Wetlands International. 27 pages. ISSN 20507941.URL: http://www.naturalcoastalprotection.org/documents/reduction-of-wind-and-swell-wavesby-mangroves

[44] Mazda, Y., M. Magi, Y. Ikeda, T. Kurokawa, and T. Asano. 2006. "Wave Reduction in a Mangrove Forest Dominated by Sonneratia Sp." Wetlands Ecology and Management 14(4), 365 –378.

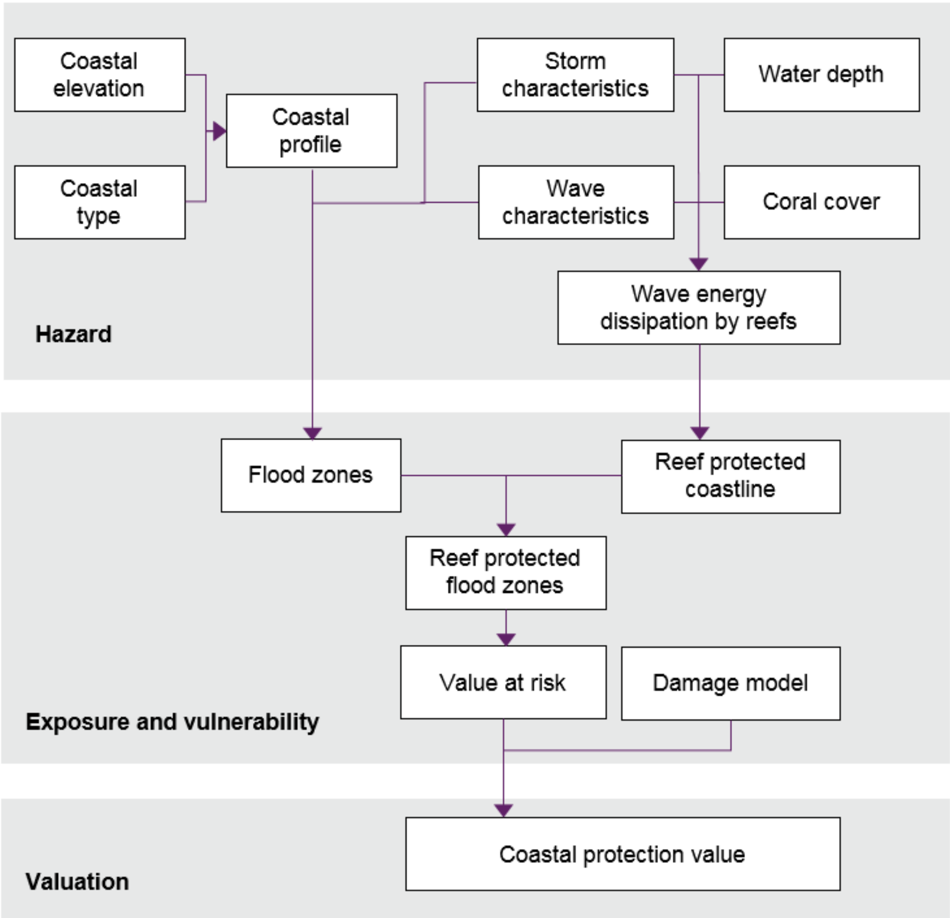
[45] Quartel, S., A. Kroon, P. Augustinus, P. Van Santen, and N. H. Tri. 2007. "Wave Attenuation in Coastal Mangroves in the Red River Delta, Vietnam." Journal of Asian Earth Sciences 29(4), 576–584.

[46] Van Zanten & Van Beukering (2012) *Coastal Protection services of coral reefs in Bonaire. Economic values and spatial maps.*

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

- The hazard component assesses the sensitivity of the coastline to flooding and how this is impacted by wave energy dissipation provided by coral reefs.
- The exposure and vulnerability component defines the areas of coastline which have some form of protection by coral reefs.
- The valuation component estimates the potential damage, in terms of damage costs that is avoided due to coral reefs.

Figure 4-4 Analytical framework as per van Zanten *et al.* (2014)



Reproduced from van Zanten *et al.* 2014

Component 1: Hazard - wave energy dissipation by coral reefs

In the approach originated by van Beukering in 2012, wave energy dissipation is calculated using a model designed by Gourlay (1996)[48] and further developed by Sheppard *et al.* (1995)[49] which uses information on coral reef cover, water depth on the reef and storm and wave characteristics. In this model, wave energy dissipation is calculated as a function of waves breaking on the coral reef and coral friction. Four different reef typographies are identified based on water depth and the density of coral cover (shallow high density - SHD, deep high density - DHD, shallow low density-SLD and deep low density- DLD) and in applying the approach to the analysis of the US Virgin Isles, the reefs were categorised into one four typologies according

[48] Gourlay, M.R., 1996. Wave set-up on coral reefs. 1. Set-up and wave-generated flow on an idealised two-dimensional horizontal reef. Coast. Eng. 27, 161-193.

[49] Sheppard, C., Dixon, D.J., Gourlay, M., Sheppard, A., Payet, R., 1996. Coral mortality increases wave energy reaching shores protected by reef flats: examples from the Seychelles. Estuar. Coast. Shelf Sci. 64, 223-234.

to water depth and reef type. Low density reefs were assumed to have 10-25% live or dead uneroded coral and shallow reefs were assumed to have a depth less than 8.3m. The figure of 8.3m was defined based on the deep water significant wave height for Puerto Rico and the US Virgin Isles following an approach by the US Army Corps of Engineers.

The total relative wave energy dissipation percentages for each of the four reef types from applying the model during a 1:100 year return flood are shown in Table 4.3, with the relative contributing proportions due to friction and breaking factors. The results show the shallow high-density reefs have the highest protective function with 95.5% of the energy from deep water waves not reaching the shore, followed by shallow low-density reefs. Deep water reefs have a lower protective value as waves do not always break on these reefs.

Table 4.3 Predicted relative wave energy dissipation before reaching the shore per reef type during a 100 year probability event and increased flooding levels without coral reef protection in flood zones

Reef Type	Coral friction energy dissipation	(1) Increased flooding without coral friction (m)	Total reef energy dissipation	(2) Increased flooding without coral reefs (m)
SHD	5.5%	0.33	95.5%	5.82
SLD	3.5%	0.21	90.0%	5.49
DHD	10.5%	0.64	38.0%	2.32
DLD	4.5%	0.27	32.0%	1.95

Reproduced from van Zanten *et al.* (2014)

Component 2: Exposure and vulnerability

In order to assess the areas of the shoreline that are protected by a reef, a spatial analysis was undertaken. Firstly, the areas of shoreline vulnerable to flooding were identified based on flood insurance rate maps by the Federal Emergency Management Agency (FEMA). The maps were created using historical storm data, storm surge analysis and coastal profile and differentiate those area of the coast that are vulnerable to flooding from storms of different return period and a distinction between high wave (V) and low wave (A) energy zones. Areas of the shoreline vulnerable to a 1:100 year flood with high and low wave energy zone were identified.

Secondly, a buffer is drawn 360° around each reef polygon where the buffer extent is based on the maximum distance from a shallow high-density reef to the shore. An intersect is then made between the two datasets to identify those areas vulnerable to flooding which are also protected by the presence of a reef. The resulting intersect areas are then ranked by reef type that provides protection.

The next step is to identify the total economic value at risk in each of the areas of the shoreline vulnerable to flooding and protected by coral reefs. This is assessed by using a maximum damage value/per hectare for five different land use types. In the highlighted study, maximum damage value estimates for five land use types from a Dutch study were identified and transposed for use in the USVI. Total areas for each of the land use types were identified for the intersect areas and then the damage value estimates applied. Damage depth functions were then applied to estimate how much damage is done by a flood relative to the total value of the property.

Component 3: Valuation

The avoided damage cost approach is used to calculate the coastal protection value of the coral reefs. This compares the storm damage from current coral reef conditions to two different hypothetical scenarios where there is less coastal protection provided by coral reefs. The scenarios considered were firstly, the short-term process of coral degradation where coral dies and starts to disintegrate and the coral friction element of protection is lost and wave energy increased as a result. The second, longer term scenario, is where the coral reef is eroded and lost completely. To translate these scenarios into values, energy dissipation rates of coral reefs are translated into increased flood depth, under the assumption that an increase of 5% wave energy reaching the coastline results in extra damage equal to 0.3m. The increased flooding levels are presented in Table 4.3.

Use and development of the existing approach in this study

The approach described in analytical framework above was adapted to the BVI in the following way.

Protection provided by coral reefs

The shoreline vulnerable to flooding was determined using a storm surge dataset derived as part of the Regional Risk Reduction Initiative for the GoBVI in 2013 (known as "R3i"). In this study, a Category 4 hurricane, according to the Saffir-Simpson scale, was modelled based on a wave climate obtained from a review of National Hurricane Centre historical data over the past 150 years with only hurricanes passing within a prescribed radius of Tortola considered. The numerical model used represented processes for energy loss including sea bed friction, refraction, movement of waves around reef structures and white-capping[50] .

The buildings information dataset obtained from the GoBVI was intersected with the storm surge dataset to determine those buildings that flood. The location of coral reefs surrounding the case study areas were obtained from a benthic dataset provided by the National Parks Trust derived from survey data. The dataset indicates the location, classification and relative density of different benthos. Water depth of each reef was interpreted from BVI bathymetry maps obtained from the UK Hydrographic Office. These datasets were used to classify the reef polygons into the four reef typologies (SHD, DHD, SLD, DLD) as described above. Buffers were created around each of the reef polygons to determine the shoreline areas and buildings they afford protection to, following the above approach.

The USVI are located within 2km of the BVI at the nearest point (St John to Tortola). Due to the relative proximity of the USVI and BVI they are likely to affected by the same hurricanes and the deep water significant wave height off each of the Islands will be similar. As a result of this, it was considered that the wave energy dissipation figures of coral reefs obtained from the USVI study could be used as proxies for the purpose of this assessment. The increased flooding levels associated with the two scenarios of live coral degradation and loss of reef shown in Table 4.3 were used to identify the additional buildings that would be flooded as a result.

It is understood that as part of the Regional Risk Reduction Initiative (R3i), a number of storm surge datasets were derived to represent storms approaching the BVI from different directions. Only one national dataset was provided by the GoBVI in GIS format, and this represented Saffir Simpson Category 4 storms tracking at 60 degrees with 1m of sea level rise. The dataset contained fields for maximum storm surge level and maximum significant wave heights above mean sea level and these were combined to provide a maximum water level through the following formula:

$$Max\ water\ level = \max storm\ surge\ level + \frac{max\ significant\ wave\ height}{2}$$

Protection provided by mangroves

The overall assessment framework highlighted above was used to assess the protective service from coastal flooding provided by mangroves at Paraquita Bay. To understand the flood hazard mitigation provided by mangroves, the R3i storm surge dataset was examined in Paraquita Bay and it showed a marked reduction in wave height over an area of mangrove with 260m width calculated at 0.0043/m which is consistent with

[50] Smith Warner International Ltd 2017. Engineering design and EIA report for the north shore coastal and watershed stabilisation project at Cane Garden Bay and Brewers Bay, Tortola, British Virgin Islands.

attention rates reported in the literatures of 0.0014/m to 0.011/m. This equates to maximum water levels increasing by 0.4m at the shoreline immediately behind the area of mangrove should they be lost.

Scenarios investigated

For all case studies investigated baseline flooding and the impacts of up to three scenarios: Scenario 1 which describes the case where reef degradation due to live coral die-off means the wave energy reduction from coral friction is lost; and Scenario 2, the long-term hypothetical situation where all the reefs disappear due to reef substrate erosion due to death of the living coral from a range of impacts including ocean acidification. For Paraquita Bay, an additional third scenario was investigated covering the hypothetical loss of the mangroves.

Frequency of events

The frequency of tropical storms used to estimate of future values in this study is based on records from 1851 to 2010 on tropical storm systems passing within 60 nautical miles of Tortola available from the website www.stormcarib.com. The storms significantly affecting the BVI tracked in a north westerly direction, with fewer tracking north easterly. Based on these records and the definition of hurricane intensity Table 4.4 shows the annual probability of storm surges of different heights. The probabilities sum to 0.19 which indicates that once every 5 years a hurricane of an intensity between 1 and 5 would be expected to affect the BVI significantly.

Table 4.4 Predicted Probability of hurricane and associated storm surge estimates

Saffir Simpson Hurricane Categories	Average storm surge (m)	Frequency in 160 years	Annual Probability of occurrence (100% = certain)	R3i modelled (m)	R3i + Degraded (m)	R3i + reef destruction (m)
H1	1.35	6	3.8%			
H2	2.2	12	7.5%			
H3	3.25	6	3.8%			
H4	4.75	6	3.8%	1.26	1.47	4.8
H5	6.3	1	0.6%			

Source: R3i scenario from the Regional Risk Reduction Initiative for the GoBVI (2013) and stormcarib.com

Limitations of methodology

The specific features of this methodology relevant to this assessment are:

- The approach has assumed that the wave characteristics around the BVI are the same as those for the USVI as reported by van Zanten *et al.* (2014)[23]. This information was used to determine the dissipation function of the coral reef, which has been used in our analysis.
- Only one storm surge dataset was available from the BVI Regional Risk Reduction Initiative for a Category 4 storm tracking at 60° and assuming 1m sea level rise. Additional datasets for storm tracking at 290°, at Category 5 level, with and without sea level rise are known to have been generated. If these datasets were made available, with information related around the frequency of these storms, the analysis could be further enhanced.
- The resolution of the grid used to derive the storm surge dataset was 50m on island and it is not known what data was used to characterise the topography. A smaller grid square and use of the latest LiDAR data would enhance the storm surge model results.

4.3 Economic valuation

Overview

The approach used to value natural features which provide protection such as coral reefs is the avoided costs of damage. The key underlying assumptions made are that the value of lost economic activities scales with the proportion of buildings affected and that the loss can be represented by current market prices.

The land area occupied by a property is taken in this study as a basic metric for quantity because it is fundamental both to descriptions of natural processes and is long-established in economics. A very detailed GIS dataset with accurate measurements of the location, elevation and spatial "footprint" (i.e. area in m^2) of individual properties is available from government sources discussed above.

The definition and assumptions made for the basic elements of cost are as critical a component of final valuation estimates as the quantification of the natural processes. The losses from flooding have been the subject of intensive research worldwide. In general, the cost of floods is broadly related to the quantity of area that is flooded and the typical levels of loss are often expressed using a unit value (a notional 'price' in US$/$m^2$) allowing the use of generic calculation of a quantity multiplied by a price (q * p) to derive a value, for example of damage to property. Unit values in US$/$m^2$ can also be derived to capture economic values impact in conditions without disruption and so can be used to estimate the costs during periods of business interruption.

The costs included are those that fall directly on occupants and users, estimated as repair and disruption, and indirect costs that fall across the broader economy. The overall costs depend on the repeated impacts from events and these can be estimated on an annual basis by further including an estimate of the frequency of events.

Because economic effects are assumed to scale pro-rata with the area flooded, the economic impact can be foreseen in statistics simply showing the areas flooded. For example, if the flooded area of bars and restaurants doubles the economic impact on bars and restaurants swill also double.

Characterisation of economic activity in the BVI

A characterisation of economic activity was conducted for property types in the BVI which was largely informed by data provided from contacts in the BVI and information gathered from the Central Statistics Office and the Dept. of Tourism, which included a GIS dataset of all properties, hotels, bars and restaurants in the BVI.

The GIS dataset of individual properties includes a range of other measures as well as footprint area. These were the basis of an interpretation of the economic use of the building and so make an assignment of building type. From an initial typology of over 400 distinctive land use types in the GIS dataset, eight aggregate categories were used to cover all buildings in the BVI: Residential, Infrastructure, retail, and industry, Bars & Restaurants, Hotels, Community facilities, Offices, Storage facilities and Other. Apart from recording the number of floors to allow verification that results are not significantly skewed by using only footprint areas, the types of economic activity and building type are not further distinguished in this analysis.

Estimation and validation of unit values (US$/$m^2$) for economic activities in the BVI

A unit value implicitly reflects a particular definition of an economic measures and/or impact. For example, the owner of a flooded bar will experience a direct loss of sales, but if tourists also then avoid the BVI, there will be other losses elsewhere in the country, as well as gains in the country chosen as an alternative destination. The direct costs of disruption were based on the characterisation of economic activity.

For the different land uses, two unit values were developed for this study, presented with the methodology used in Table 4.5 below. These unit values are the direct value of losses to the notional owner and would be equivalent to lost profits before tax for a business owner. Residents who live in their own property are assumed to have a personal benefit equivalent to the profits that would be made from renting the property and would experience a loss in welfare equivalent to these lost profits. Although only some of this would be experienced as cash or monetary transactions, for example where displaced people rent alternative dwellings, it provides a representative and transparent measure of real loss.

Table 4.5 Unit values developed 'bottom up' to assess value of flood protection in the BVI

Calculating unit values	Unit value (US$/m^2)	Description of methodology
Rental value of property	US$415/m^2	This represents the rental value of property and was derived from current market prices. One advantage of this measure is that rental values are the basis for the assessment of liabilities for government property tax and so are established measures of value within the financial context for the BVI.
Unit value of bars and restaurants	US$1400/m^2	This represents the value of the net margin (profit) earnt from bars and restaurants per unit area, and has been estimated for the BVI specifically. This was calculated by modelling annual revenue for bars and restaurants by estimating the seating capacity of each business and occupancy rate modelled over the year, reflecting seasonality of tourist arrivals to the BVI. The seating capacity was calculated for each restaurant, assuming 0.25 tables per m2 with an average of 2 seats per table. The value for an average mid-range meal in the BVI was estimated at US$20 in order to provide a tentative estimate of minimum revenue at 75% restaurant occupancy for 5 months of the year (to account for high-season) and 25% occupancy for 7 months of the year (to account for low season). Hence a crude estimate of yearly revenue was calculated. Costs of goods and labour were then subtracted in order to estimate total net profits generated.[51] This value was divided by the total footprint of all bars and restaurants in the BVI to provide a unit value.

The unit values were validated against the following estimates:

- *BVI government GDP estimates for the hospitality sector*: The breakdown of GDP for hotels, bars and restaurants match the annual values calculated here. The quantity data would be expected to be the same because the mapping data for floor areas is accurate and so this close correspondence indicates unit values are also close.
- *Estimates of costs of flood events by Van Zanten (2014)*: Van Zanten provides an estimate of unit values estimates of maximum potential loss (the economic value at risk) which reflects business as usual earnings. They are for a single event rather than for a year and adjusted for the US Virgin Islands from values originally derived for the Netherlands. The impacts from the event are likely to have a duration of approximately one year, and the values for commercial and the hospitality sector bracket the estimate above. The residential value is approximately double that estimated above but is a similarly lower than the commercial area and the Wood estimate is preferred as it is based directly on BVI market prices

These estimates were then used as a source of unit values for all building types identified in the GIS dataset in the BVI using the rationale shown in Table 4.6.

[51] Cost of goods and cost of labour assumed to be 1/3 of revenue each https://www.quora.com/What-is-an-average-profit-margin-for-a-typical-restaurant

Table 4.6 Unit values of economic activities in the BVI

Building type	Unit value (US$/m^2)	Rationale
Residential	US$415/m^2	Expected annual return from property rental as estimated using BVI market prices
Infrastructure, retail, and industry	US$1400/m^2	Value of operations in principle equal to competing businesses (bars and restaurants) and would be discontinued if interrupted as relocation is not possible
Bars & Restaurants	US$1400/m^2	Expected annual return from bar and restaurant operations in the BVI estimated using bottom-up (location specific) modelling
Hotels	US$415/m^2	Expected annual return from property rental as estimated using BVI market prices
Community facilities	US$415/m^2	Loss of facilities would require rental at market rental rate
Offices	US$415/m^2	Loss of facilities would require rental of space at market rental rate, but relocation would allow uninterrupted operations
Storage facilities	US$415/m^2	Loss of facilities would require rental at market rental rate
Other	US$60/m^2	Sales value of undeveloped land using. For abandoned property, represents a maximum loss. Other unspecified property assumed to be of similar low value

Further elements of the valuation methodology

Costs of restitution

While the frequency and severity of events varies, the *additional* impacts from changes in the protective function of natural features, such as degradation, are at the margin. It means that properties which were previously not flooded become flooded, and as such are expected to experience only shallow flooding. FEMA estimates for floods of even minimal depth are 15% of the costs of reconstruction and this value has been used as the basis of repair cost estimates. This approach neglects the additional flooding that occurs for properties which are already flooded but any increases are expected to be small compared to other known sources of uncertainty and variation.

The duration of events

The high level characterisation of an extreme climatic event is of a transient effect followed by a period of recovery. The key elements are the level and period of disruption and any additional recovery costs. For flooding the main impacts are felt directly and are assessed as per

Table 4.7 below.

Table 4.7 Main impacts of flooding

Impacts	Description
Cost of repair of damaged properties	The repair costs are modelled assuming only the repair costs from the additional properties which become flooded are included in the aggregate estimate. The repair cost is based on American Federal Emergency Management Agency (FEMA) estimates from 2011 and amounts to 15% of the construction value.
Interruption to business activities:	Interruption for an event of any severity is estimated causing a disruption to business of one year for coastal flooding and half a year for inland flooding.
Interruption to residential occupancy	For all events, disruption to residential occupancy is assumed to be 6 months for coastal flooding and 1 month for inland flooding.

The frequency of events

The probabilities of hurricanes are used to weight the impacts from floods with these levels of storm surge in order to derive a single representation of impacts which include both the frequency and impacts of the expected pattern of hurricanes of different categories. In very broad terms, and to provide a sense of scale, this composite representation has impacts which are approximately 30% greater than would be experienced if all properties below the 2 metre contour flooded, and the composite event would be expected to occur every 5 years. This is a simplistic representation and was not used for the valuation which is based on the detailed storm surge mapping.

Wider economic impacts

There is established evidence that direct impacts recorded in an economy, such as expenditure in a shop or hotel, is causally associated with wider economic impacts in supply chains and from induced impacts due to knock-on spending in these supply chains and elsewhere. These additional impacts increase the overall economic effect and are typically represented using an economic multiplier which is applied as a factor on the direct impacts and expressed in terms of expenditure or employment.

The economic multiplier is assumed here to be 1.65 based on a number of sources for what is an inherently difficult number to establish though of particular interest to governments and business and the subject of associated research.

Use of annualised values to represent the value of natural capital

Definitionally, natural capital is a ‘stock’ which leads to a ‘flow’ of ecosystem services. However, more generally, economic and financial values can be expressed in and converted into either stocks or flows, as when a house (stock) is purchased with a series of flows (annual mortgage repayments).

In this study, while the focus of the valuation is natural capital, the results are presented as annual values. This provides the simplest and most accurate representation and avoids the requirement for an additional assumption of discount rate to make the conversion to a total stock.

Presenting values as annual values also allows simple comparison with other relevant annual measures such as GDP. It also focuses attention on the long term and repeated costs of hurricane events and the ongoing value of protective services provided by natural capital. It implicitly requires and depends on the assumptions made for the frequency of events, but this is unavoidable and allows the value of natural features to be recognised as and compared with sources of insurance which have a pattern of regular often annual payments.

The presentation of results without use of ranges.

Ranges are not used to present results. Due to the types of projections and uncertainty involved, it is difficult to find a meaningful methodology (such as confidence interval) for specifying the ends of the range and they could show a specious accuracy. Consideration of the types of parameters and assumptions is arguably more important. For example, the degree to which Anegada would become uninhabitable if the surrounding reefs were lost is a judgement which would lead to suddenly greatly increased impacts. If such a change occurred, the timing of abandonment would also greatly influence the valuation.

4.4 Methodology for results at national level

Inland Flooding

The process for the assessment of the protection offered by natural capital used in the Paraquita Bay and Cane Garden Bay case studies was extended to enable a BVI-wide valuation. Due to the significantly increased scale, the method and data inputs were simplified to reduce computational load and to address data availability. The high-resolution LiDAR data was not available for all of the BVI, and as such a lower resolution dataset provided by the BVI government was used instead. This was a BVI-wide 2m interval contour dataset, which was converted to a 5m grid to provide the input to the hydraulic model software at national level.

The Baseline and Degraded Environment scenarios were simplified such that the Baseline was assumed to have 100% forest coverage (roughness 0.16), and the Degraded Environment 100% open space (roughness 0.035). Five models were created to provide coverage for the BVI, each with a Baseline and Degraded Environment scenario. Table 4.8 below shows the model domains and the islands included within each.

Table 4.8 BVI National-scale model domains

Model name	Islands included
Tortola	Tortola
Jost Group	Jost van Dyke, Little Jost
Southern Cays	Cooper Island, Norman Island, Peter Island, Salt Island
Beef Island Group	Beef Island, Scrub Island, Great Camanoe, Guana Island
Virgin Gorda	Virgin Gorda, Mosquito Island, Prickly Pear Island, Necker Island

As with the case study assessment, each model and its two associated scenarios were run using the three pluvial hyetographs, for a total of 30 model runs. The results of the runs and shown in Section 6.1.

Coastal Flooding

As highlighted above, one storm surge dataset was available that had full national coverage. This dataset was used to understand the coastal protection value of coral reefs at the national level. This was overlaid in GIS with the buildings dataset to identify the infrastructure that was flooded. As in the case studies, all reefs were classified as either high or low density based on their benthic characteristics. The national level hydrographic maps provided were in image format only, preventing an automated calculation of average reef depth to be made. Visual examination of the hydrographic maps against reef location showed that in most cases (with the exception of an area south of Paraquita Bay and Beef Island) the reefs were classified as shallow. As with the case study assessments, we assessed the impact of two degradation scenarios. The results of the runs are shown in Section 6.1. The impact of coastal protection from mangroves was not considered at national scale as local circumstances are important and using a proxy based on Paraquita Bay might be misleading.

Economic valuation

Economic valuation is often simpler at national level as statistics at a lower level are often not available. In this analysis, the case study for Cane Garden Bay was used at the level of individual businesses to derive bottom up estimates for earnings from bars and restaurants. When expressed as a unit value per floor area and scaled up to the footprint for all bars and restaurants in the BVI from the national GIS statistics, these matched independent GoBVI estimates for the sector well, providing confirmation that unit values were applicable for national assessment.

In the calculation of value (price multiplied by quantity), the price component – a 'per unit' measure, and quantity component – the area of flooding, are subject to different kinds of uncertainty). Of these uncertainties, the footprint area of buildings and their use types, however, are known accurately from GIS mapping and can be used at any scale. In contrast, the unit value will vary by location and a range of other short term and long-term influences on price.

5. Case study results

This section describes the results of applying the methodology outlines in Section 4 to the three case study sites.

Following discussion with the GoBVI, the locations of Cane Garden Bay, Paraquita Bay and Anegada were chosen as case studies for application of the valuation techniques. This choice was related to the locations and condition of natural capital, in addition to their economic importance. Cane Garden Bay is an important tourist destination, with coral reef coverage across its extent but human impacts on the reef are being observed. Paraquita Bay, a key marine shelter for the charter yacht industry, is flanked by coral reefs and mangroves and has suffered significant natural degradation following. Anegada is an important tourist destination, is Ramsar Site designated and is surrounded by the Horseshoe Reef, the largest barrier reef in the Caribbean.

Figure 5-1 Location of the case study sites of Cane Garden Bay, Paraquita Bay and Anegada in the British Virgin Islands.

5.1 Cane Garden Bay

Overview

Located on the north west of Tortola, Cane Garden Bay (CGB) has a catchment area of 2.06km^2 with a population of around 400 people. The catchment is characterised by very steep slopes and is dominated by evergreen, semi-deciduous and mixed forest which covers 78% of the area (see Table 5.1). The urban area and road cover account for approximately 13% of the catchment area, with development principally at low lying areas adjacent to the beach, at the north side of the Bay and at the top of the catchment to the west. The nearshore area of Cane Garden Bay is mainly comprised of sand with coral rock located at the northern end and with coral reefs located further offshore spanning almost the entire Bay (see Figure 5-2 and Figure 5-3).

It is one of the BVI's most popular tourist destinations with passengers disembarking from cruise ships visiting for the day, as well as from sailing boats from the many anchorages, to enjoy the beaches, the sea and views cross to Jost Van Dyke. The vast majority of accommodation, bars and restaurants associated with the tourism sector are located in low lying coastal zones directly adjacent to the beach. Due to their location, they are at potential risk to climate change impacts (SWIL, 2016[52]) such as:

- Coastal/beach erosion due to sea level rise
- Flooding and sedimentation events due to heavy rain and stronger hurricanes
- Stronger storm surges and coral reef degradation

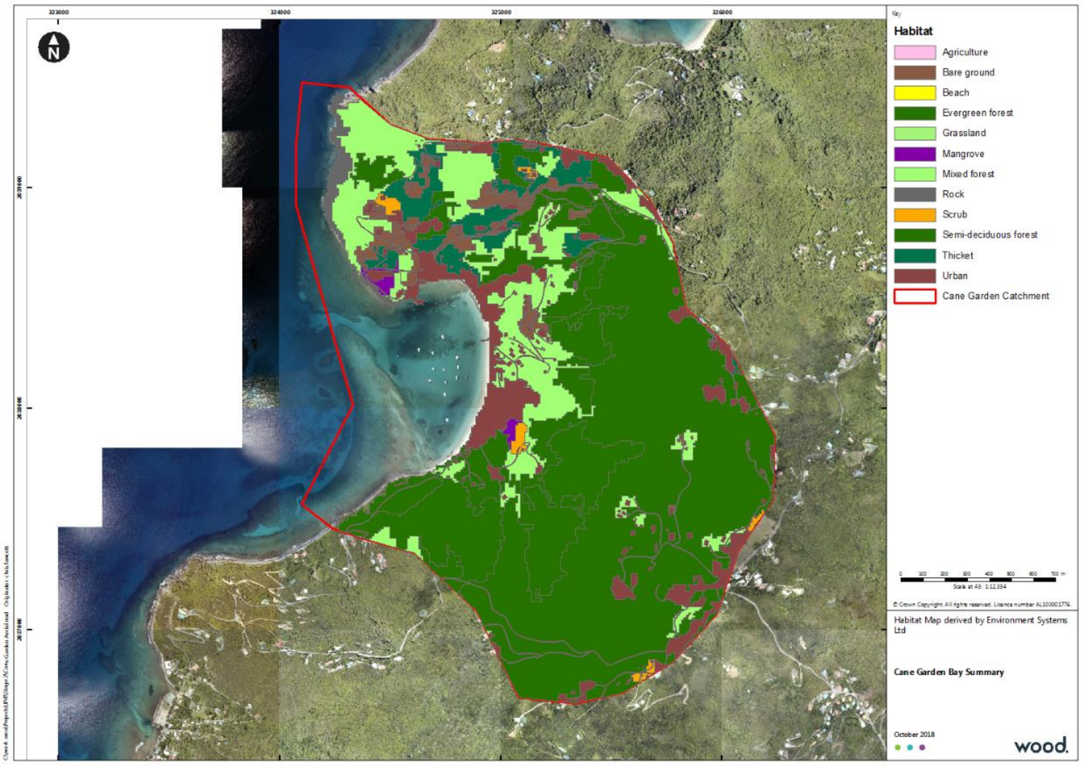
In addition to climate-related impacts, flooding and sedimentation in CGB are exacerbated by improper development, road building and land clearance[52]. For example, naturally-occurring coastal salt ponds acted as the bay's primary storm water retention and have been filled in, without being replaced with infrastructure to fill this function.

Table 5.1 Habitat coverage in Cane Garden Bay catchment

Habitat	Area (hectares)	Cover %
Evergreen forest	159.4	49%
Semi-deciduous forest	48.5	15%
Mixed forest	44.8	14%
Urban and road coverage	40	13%

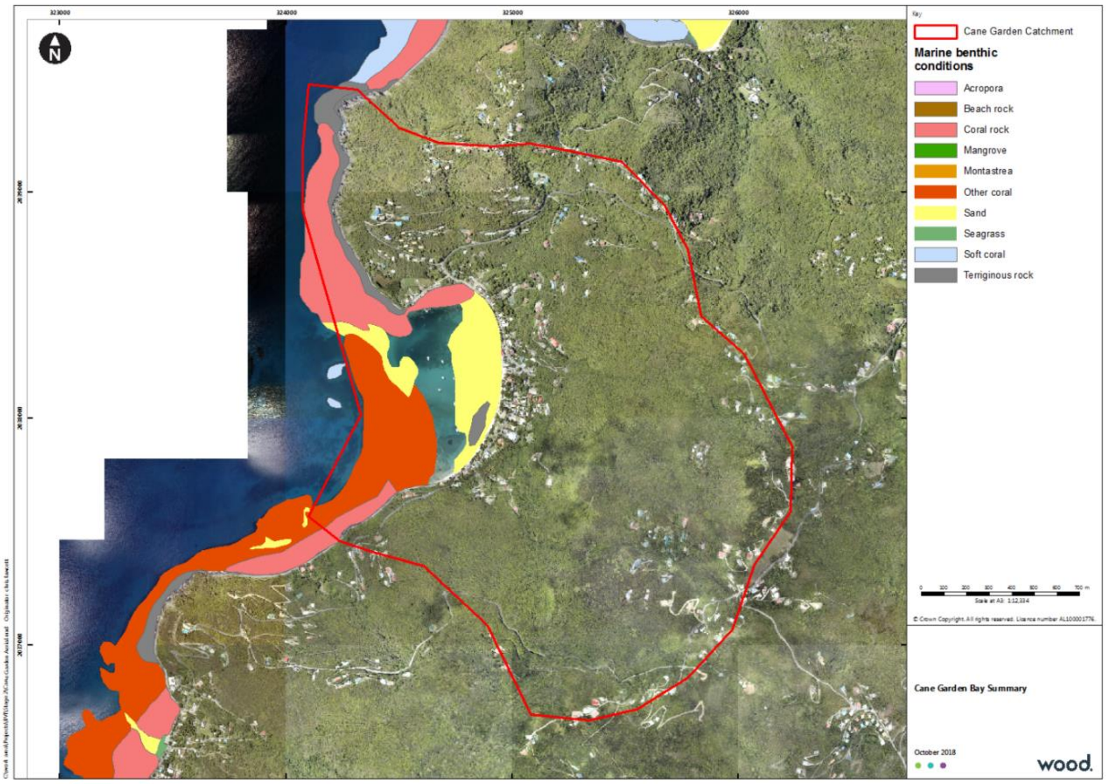
[52] Smith Warner International Ltd. 2016. Final hydrologic and coastal modelling report for the north shore coastal and watershed stabilisation project at Cane Garden Bay and Brewers Bay, Tortola, British Virgin Islands.

Figure 5-2 Land use in Cane Garden Bay catchment



Note: Land use/habitat data from Environment Systems

Figure 5-3 Marine benthic conditions in Cane Garden Bay



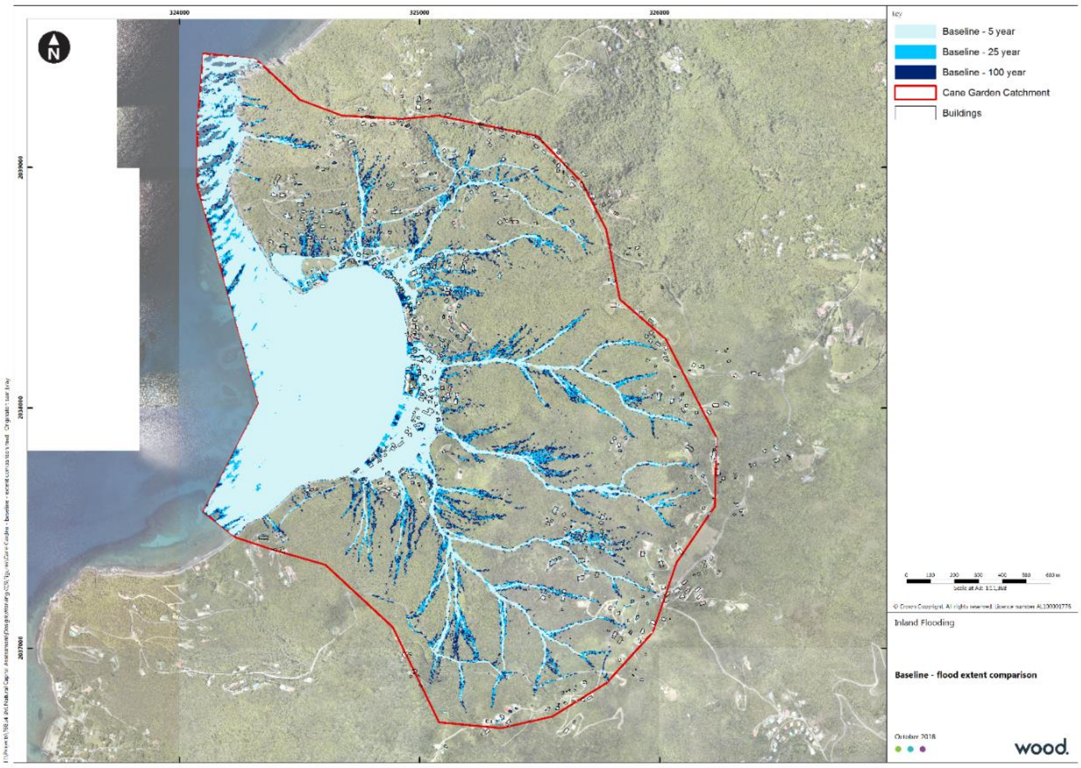
Assessment results

Inland results

The Cane Garden Bay model results were used with the buildings dataset provided by the BVI Government, to assess whether a building would be affected by flooding in each scenario. A threshold of 15cm was chosen as the depth above which a building was considered flooded. Below this depth, it was assumed that protective measures on an individual property level, such as flood boards and sandbags, would be sufficient to prevent serious damage to a building.

Figure 5-4 below shows the flood extents for the three different return periods under the Baseline scenario. As expected, the extents increase with event severity.

Figure 5-4 Extent comparison for the Baseline scenario, all return periods



The model has shown no difference to inland flooding when moving from the Baseline to the Economic Change scenario, indicating that the changes to the model setup were too subtle to create a change in flooding depths. As such, the remainder of the analysis focuses on the comparison between the Baseline and Degraded Environment scenarios.

The comparison of Baseline vs Degraded Scenario results for the 1 in 5 year AEP event, 1 in 25 year AEP event and 1 in 100 year AEP event are shown in Table 5.2, Table 5.3 and Table 5.4 below, respectively.

Contrary to the anticipated outcome, the model results have not demonstrated a worsening in terms of inland flooding depths by degrading the environment. In moving to the Degraded Environment scenario, the number of properties affected by flooding has marginally reduced.

For the 1 in 5 year AEP event, the results in Table 5.2 indicate that 108 properties are susceptible to flooding under the Baseline scenario. Of those 108, 56 are residential, with 17 properties listed as retail, bar, restaurant or hotel use. The total number of properties affected reduces to 93 under the Degraded Environment Scenario.

The 1 in 25 year and 1 in 100 year AEP event results show a similar reduction in the number of affected properties when moving from the Baseline to the Degraded Environment scenario. In both events, the total number of properties affected is reduced by 3%.

Although the flooding depths did not increase as a result of degrading the environment, the simulated loss of natural capital caused a widespread increase across the domain in terms of maximum water velocities.

Figure 5-5 below shows the maximum velocities across the model domain for the Baseline 1 in 100 year AEP event, with Figure 5-6 showing the same for the Degraded Environment 1 in 100 year AEP event. In comparing the two figures, it can be seen that the removing the resistance to flow offered by the presence of vegetation cover significantly increases the maximum velocities.

Figure 5-5 Maximum velocity - Baseline 1 in 100 year AEP

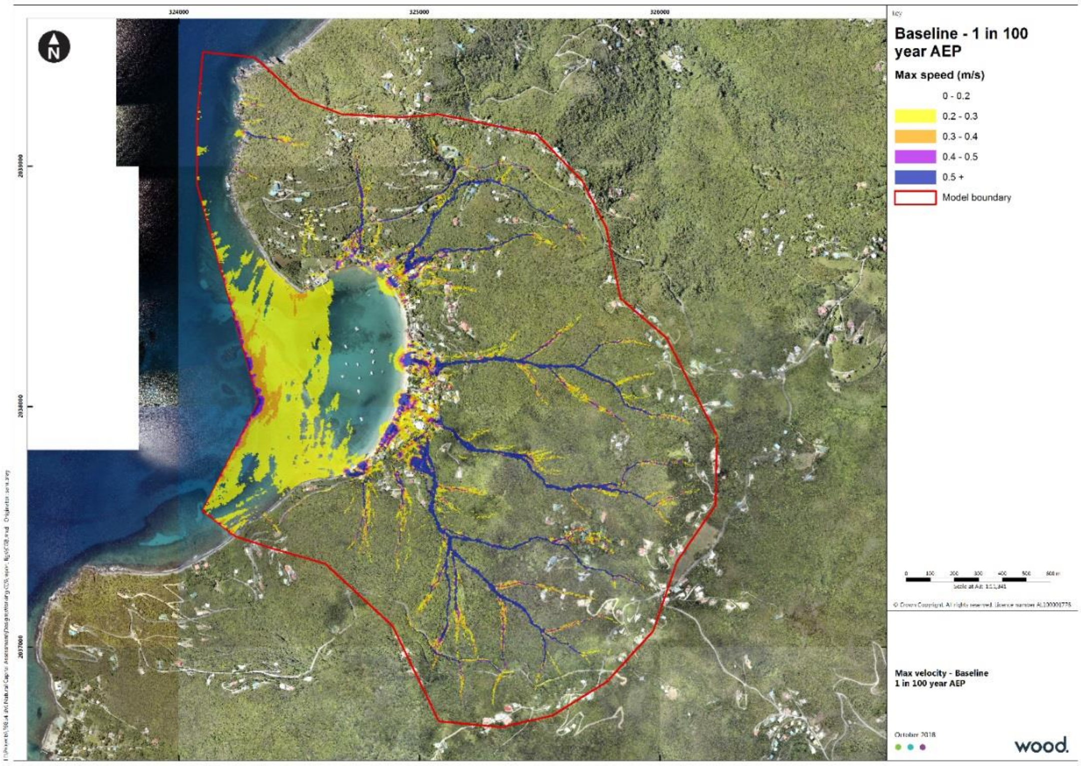
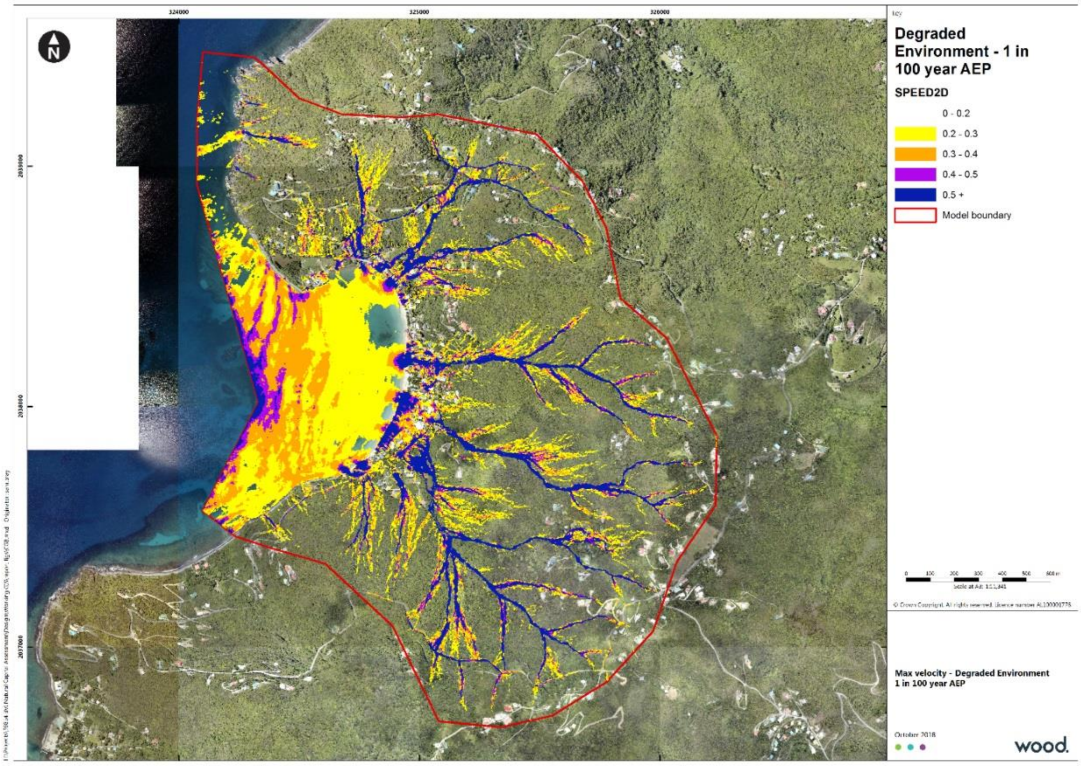


Figure 5-6 Maximum velocity - Degraded Environment 1 in 100 year AEP



Coastal protection

The Category 4 storm surge dataset for Cane Garden Bay, were overlaid on the buildings dataset in GIS to identify those individual buildings that were flooded by the storm based on the maximum water level calculations (see Figure 5-7). The maximum water level varies around the bay but approximates to the 2.7m contour. Coral reefs located in Cane Garden Bay identified from the benthic dataset and water depth data were used to classify the reefs using the four typologies. The most protective reef typology was SLD. Buffers were drawn around the reefs to understand those buildings that are afforded protection by the reefs.

Table 5.5 provide a summary of the infrastructure that is impacted by this baseline flood and two scenarios of (1) without coral friction and (2) the hypothetical situation where all the reefs have been eroded.

For the 60° storm at the baseline, a total of 110 properties are flooded located immediately behind the beach. For Scenario 1, a total of only 4 additional buildings are flooded. For Scenario 2 an extra 40 buildings are impacted with most of these being residential properties (20) and 3 additional hotel/restaurants/bars.

A key sensitivity is the baseline maximum water level that is reached. If the maximum water level reached the 2m or 2.4m contour instead of 2.7m, the number of properties flooded would be 30 and 97 respectively, compared to 110. This sensitivity will subsequently cause a larger variation on the impact on Scenario 1, as there are more buildings that could potentially flood.

Figure 5-7 Infrastructure flooded from Category 4 hurricane with storm of 60° mapping

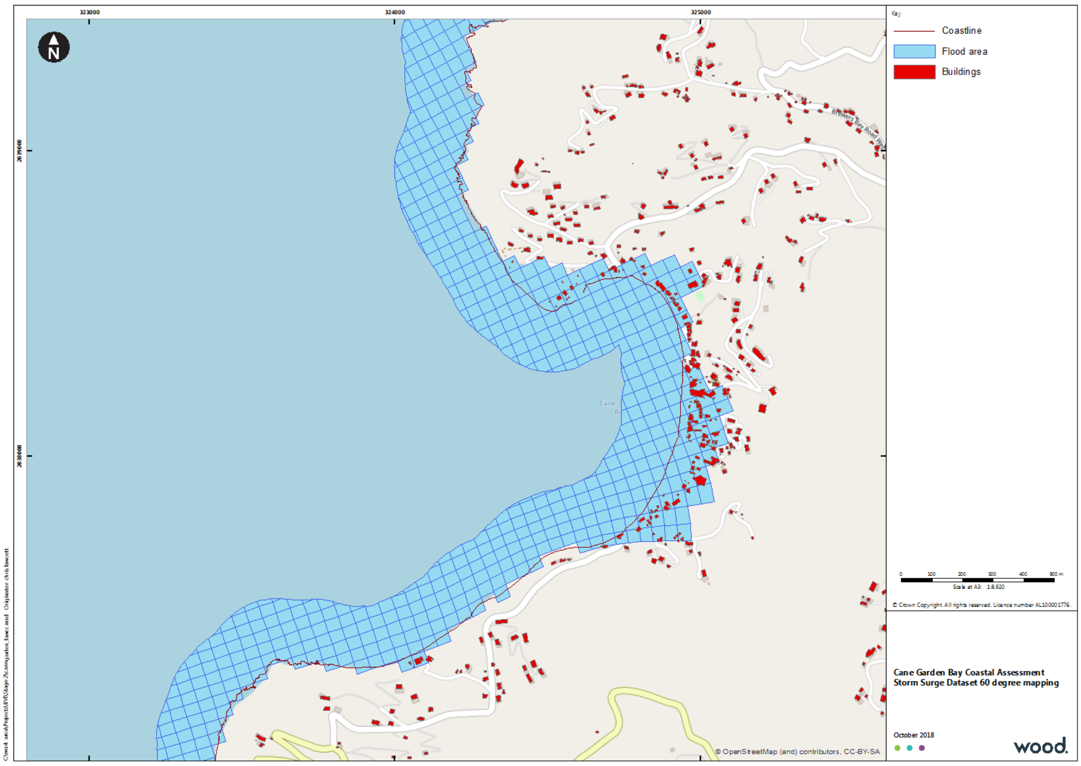


Table 5.2 Cane Garden Bay, 1 in 5 year AEP, inland flooding results for Baseline vs Degraded Environment scenario

	Total	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown
Total number of buildings	580	368	18	14	13	14	15	4	6	49	33	3	42	580
Flooded buildings:														
Baseline – 1 in 5 year	108	56	4	7	6	7	2	1	2	11	5	1	6	108
Degraded Environment – 1 in 5 year	93	48	2	7	6	7	2	1	1	10	5	1	3	93
Baseline -% buildings affected	19%	15%	22%	50%	46%	50%	13%	25%	33%	22%	15%	33%	14%	19%
Degraded Environment - % buildings affected	16%	13%	11%	50%	46%	50%	13%	25%	17%	20%	15%	33%	7%	16%

Table 5.3 Cane Garden Bay, 1 in 25 year AEP, inland flooding results for Baseline vs Degraded Environment scenario

	Total	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown
Total number of buildings	580	368	18	14	13	14	15	4	6	49	33	3	42	580
Flooded buildings:														
Baseline – 1 in 25 year	140	75	8	8	6	10	2	1	3	12	6	1	8	140
Degraded Environment – 1 in 25 year	123	68	4	7	6	8	2	1	2	11	6	1	7	123
Baseline -% buildings affected	24%	20%	44%	57%	46%	71%	13%	25%	50%	24%	18%	33%	19%	24%
Degraded Environment - % buildings affected	21%	18%	22%	50%	46%	57%	13%	25%	33%	22%	18%	33%	17%	21%

Table 5.4 Cane Garden Bay, 1 in 100 year AEP, inland flooding results for Baseline vs Degraded Environment scenario

	Total	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown
Total number of buildings	580	368	18	14	13	14	15	4	6	49	33	3	42	580
Flooded buildings:														
Baseline – 1 in 100 year	188	109	12	11	6	10	2	1	3	17	8	1	8	188
Degraded Environment – 1 in 100 year	167	97	10	9	6	10	2	1	3	13	7	1	8	167
Baseline -% buildings affected	32%	30%	67%	79%	46%	71%	13%	25%	50%	35%	24%	33%	19%	32%
Degraded Environment - % buildings affected	29%	26%	56%	64%	46%	71%	13%	25%	50%	27%	21%	33%	19%	29%

Table 5.5 Infrastructure flooded in Cane Garden Bay based on SLD reef based on storm surge dataset with storm mapping at 60° degrees for a single event

	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown	Total
Baseline 60° tracking storm														
No. of properties	38	11	13	6	9	3	0	0	4	13	4	3	6	110
Total floor area (m^2)	5273	599	3656	1145	2076	164	0	0	139	469	261	52	125	13,960
Scenario 1 without coral friction														
No. of properties	38	12	13	6	10	3	0	0	4	13	4	3	8	114
Total floor area (m^2)	5273	646	3656	1145	2618	164	0	0	139	469	261	52	194	14618
Impact														
No. of properties	0	1	0	0	1	0	0	0	0	0	0	0	2	4
Total floor area (m^2)	0	47	0	0	541	0	0	0	0	0	0	0	69	658
Economic value of impact (US$)	-	28,613	-	-	119,739	-	-	-	-	-	-	-	12,071	160,423
Scenario 2 without coral reefs														
No. of properties	58	13	14	8	12	3	1	0	4	19	11	3	8	154
Total floor area (m2)	8102	884	3688	1882	2893	164	133	0	139	615	773	52	194	19520
Impact														
No. of properties	20	1	1	2	2	0	1	0	0	6	7	0	0	40
Total floor area (m^2)	2829	237	32	737	275	0	133	0	0	147	512	0	0	4902
Economic value of impact (US$)	625,528	142,914	19,459	211,920	60,848	-	79,873	-	-	42,146	89,096	-	-	1,271,785

5.2 Paraquita Bay

Overview

Paraquita Bay is located on the south coast of Tortola east of Road Town and has a catchment area of 3.3km^2. The catchment has steep slopes dropping down to a flatter valley area where the land is used for agricultural purposes, covering 12% of the area. Mixed forest, evergreen forest and thicket dominate the land use, with a combined area of 240 hectares (see Table 5.6). The H Lavity Stoutt Community College, one of two tertiary institutions in the BVI, is located approximately 300m from the road crossing the bottom of the catchment. The College has a number of buildings including glass houses although these received substantial damage during Hurricane Irma. Adjacent to the college are a waste water treatment and desalination plant. A marine college is also located to the south of the road overlooking Paraquita Bay. There is a small residential area along Waterfront Drive to the north of the Bay and at the head of the catchment along the Ridge Road. Immediately beyond the coral rock that flanks the outside of the Bay are a series of reefs stretching out beyond 1.5km (Figure 5-8).

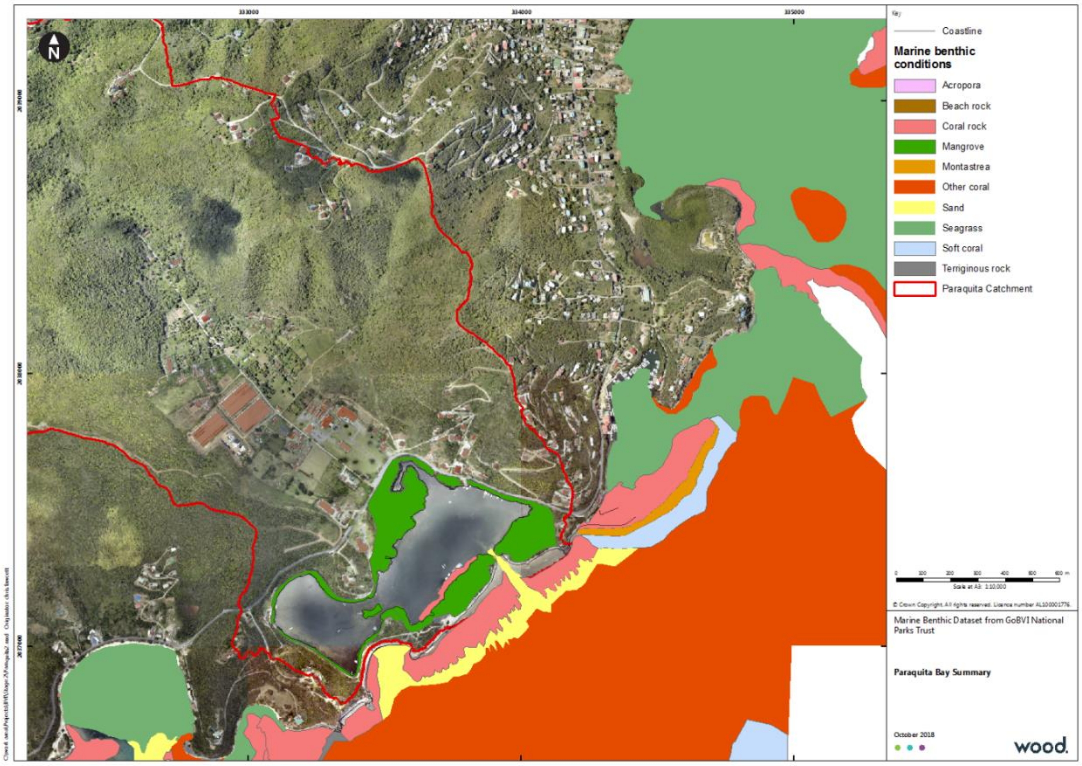
Paraquita Bay is one of the largest natural harbours in the BVI, with a barrier to the sea comprised of coral rock flanked by mangroves through which is a narrow entrance. Mangroves are also located along the north west of the Bay with a width of up to 200m. A small number of fishing boats operate from the Bay but due to its natural characteristics, its key use is a marine shelter for yachts during the hurricane season with moorings for up to 147 mono hull boats and 302 catamarans[53]. The value estimated by Wood of the lagoon as a hurricane shelter for the yachting industry is US$2.5m annually.

Table 5.6 Habitat coverage in the catchment of Paraquita Bay

Habitat	Area (hectares)	Cover %
Mixed forest	100	30%
Evergreen forest	49	15%
Thicket	50	15%
Agriculture	41	12%
Urban and roads	35	11%

[53] http://bvimarineassociation.com/downloads/1607PARAQUITA%20BASE%20PLAN%2026%20Jun17.pdf

Figure 5-8 Marine benthic conditions in Paraquita Bay



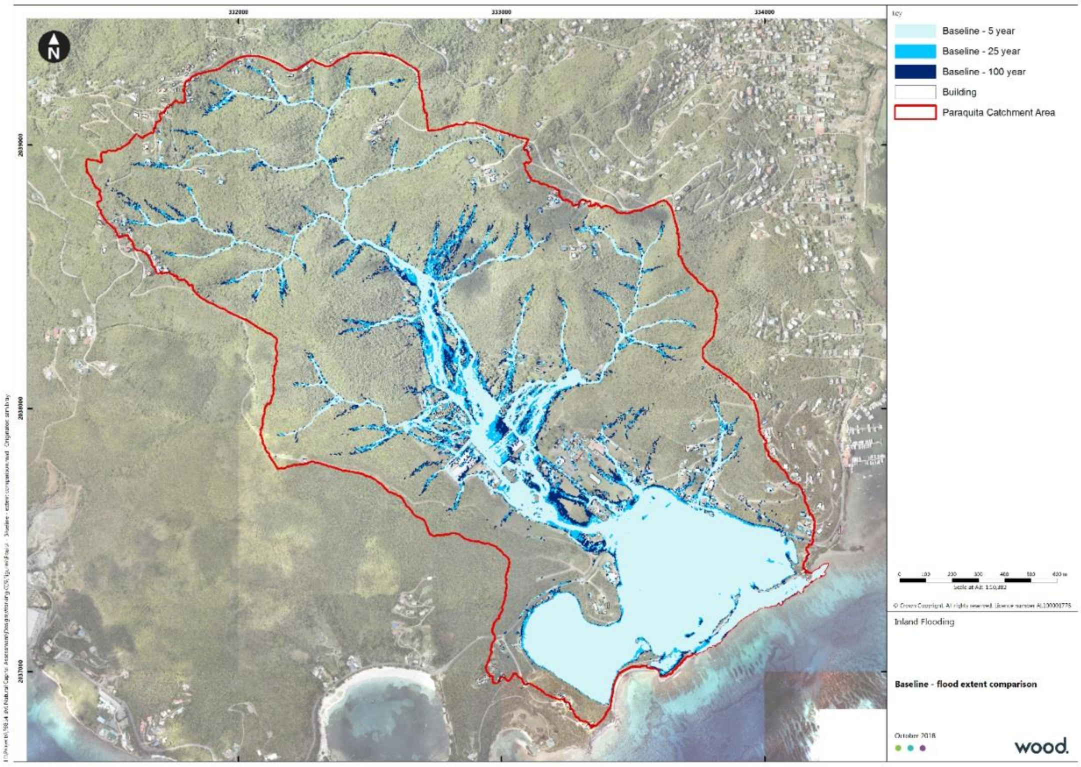
Assessment results

Inland results

Following the same method as for the previous case study, the Paraquita Bay model results were used with the buildings dataset provided by the BVI Government, to assess whether a building would be affected by flooding in each scenario. Once again, a threshold of 15cm was chosen as the depth above which a building was considered flooded.

Figure 5-9, below shows the flood extents for the three different return periods under the Baseline scenario. As expected, the extents increase with event severity.

Figure 5-9 Extent comparison for the Baseline scenario, all return periods



The comparison of Baseline vs Degraded Scenario results for the 1 in 5 year AEP event, 1 in 25 year AEP event and 1 in 100 year AEP event are shown in Table 5.7, Table 5.8, and Table 5.9 below, respectively.

As was the case in the Cane Garden Bay case study, the Paraquita Bay model results have not demonstrated a worsening in terms of inland flooding depths by degrading the environment. In moving to the Degraded Environment scenario, in general the number of properties affected by flooding has marginally reduced.

The 1 in 5 year AEP event sees a 3% reduction in the number of buildings affected by flooding when moving from the Baseline to the Degraded Environment scenario. The reduction is 4% in the 1 in 25 year AEP event, and 7% in the 1 in 100 year AEP event.

A similar increase in maximum velocity is seen in Paraquita Bay as in Cane Garden Bay when degrading the environment. Figure 5-10 and Figure 5-11 below show the maximum velocities across the domain in the 1 in 100 year AEP event for the Baseline and Degraded Environment scenarios respectively, again demonstrating that the removal of the resistance to flow offered by the presence of vegetation cover significantly increases the maximum velocities.

Figure 5-10 Maximum velocity - Baseline 1 in 100 year AEP

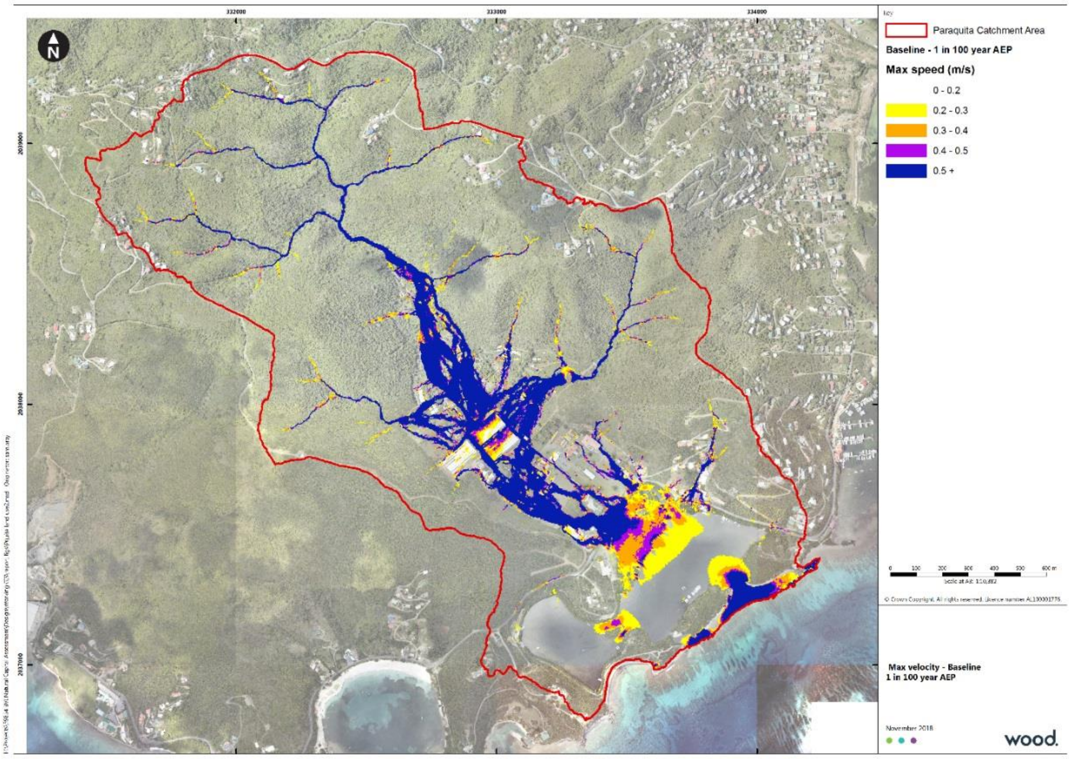
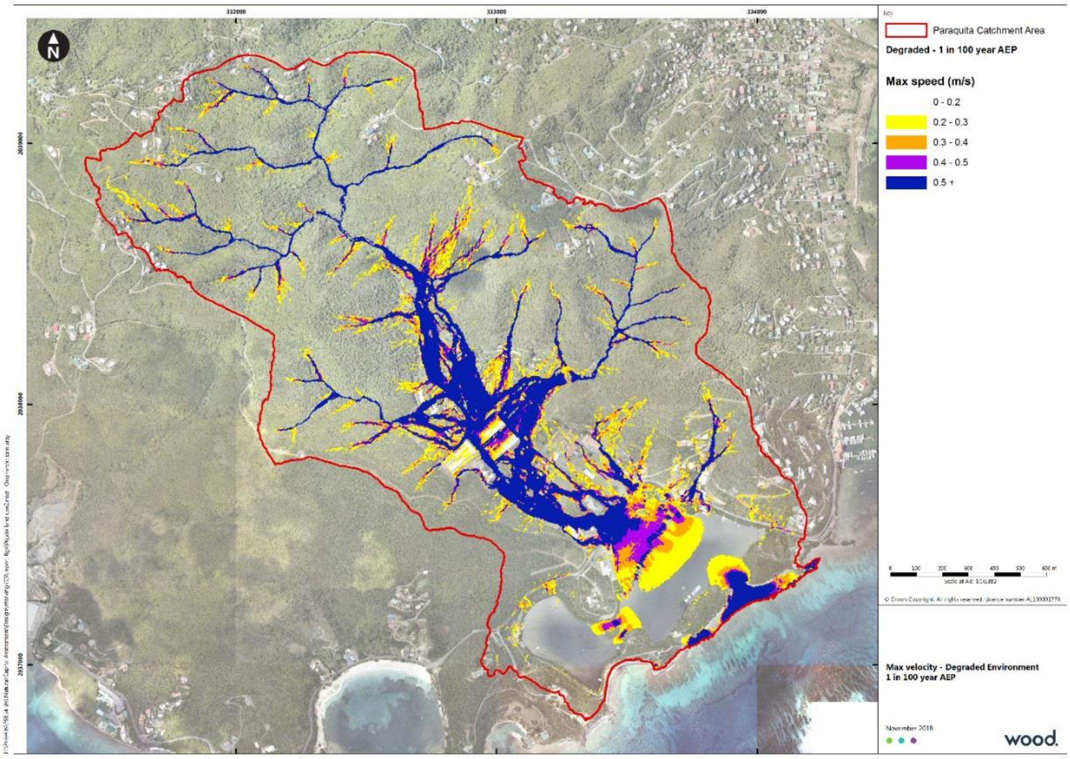


Figure 5-11 Maximum velocity - Baseline 1 in 100 year AEP



Coastal protection

The 60° mapping category 4 storm surge dataset was overlaid against the buildings dataset in GIS to identify those individual buildings that were flooded by the storm event (see Figure 5-12) with the maximum water level reaching approximately the 2.75m contour and across the Blackburn Highway across the Bay. In contrast to Cane Garden Bay, Paraquita Bay does not have may buildings immediately behind the bay. Table 5.10 provides information on the buildings flooded. Only a small number of buildings (19) are flooded with two bar/restaurants affected. In Scenario 1, only 7 extra buildings are flooded (including 2 residential, 1 bar/restaurant) and in Scenario 2 this increased to a 11 buildings including one extra bar/restaurant but included flooding of the desalination and waste water treatment plant.

In the scenario of loss of mangroves an increase in maximum water level of 0.4m results in 4 additional buildings being flooded (including 1 residential, bar/restaurant and community building) as shown in Table 5.11.

Figure 5-12 Infrastructure flooded from Category 4 hurricane with storm of 60° mapping

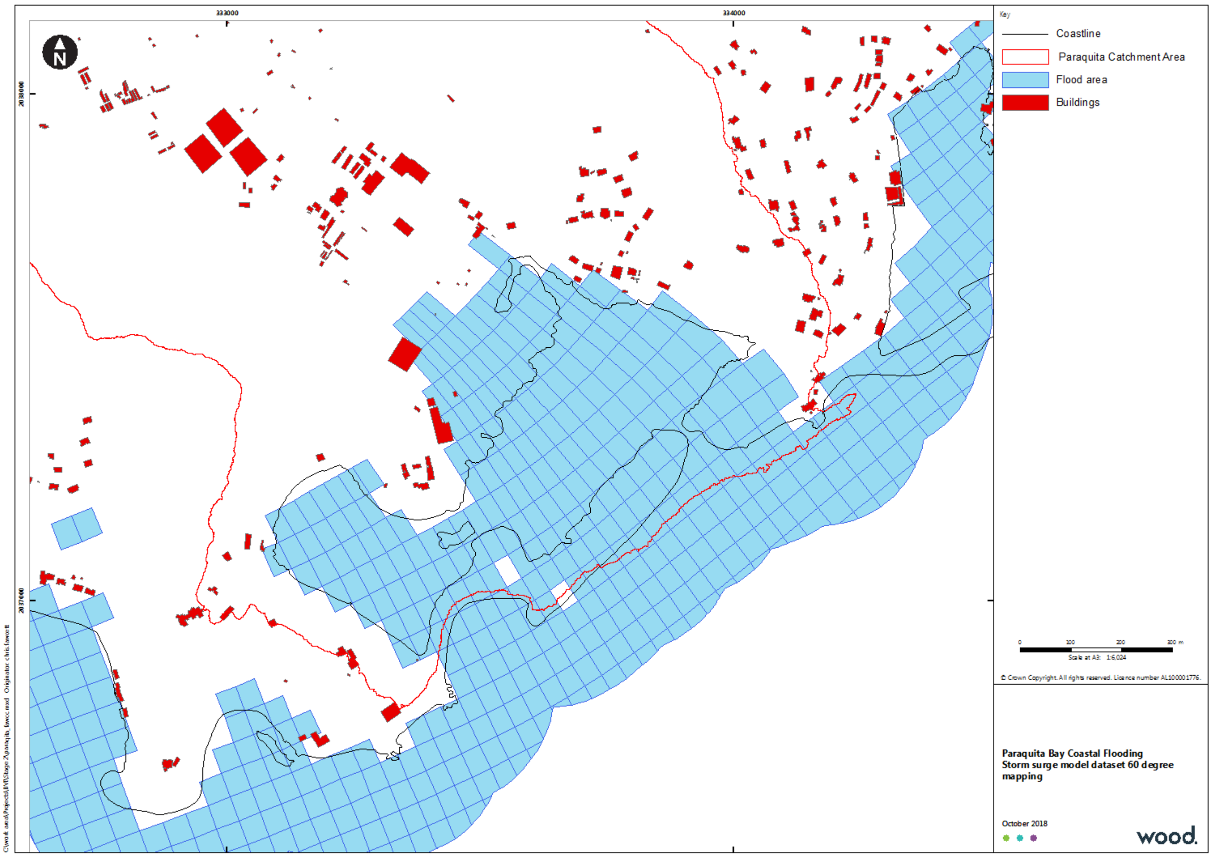


Table 5.7 Paraquita Bay, 1 in 5 year AEP, inland flooding results for Baseline vs Degraded Environment scenario

	Total	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown
Total number of buildings	342	134	5	4	19	5	1	64	2	24	19	47	18	342
Flooded buildings:														
Baseline – 1 in 5 year	40	8	2	0	1	0	0	15	1	5	0	8	0	40
Degraded Environment – 1 in 5 year	31	5	1	0	1	0	0	13	1	3	0	7	0	31
Baseline -% buildings affected	12%	6%	40%	0%	5%	0%	0%	23%	50%	21%	0%	17%	0%	12%
Degraded Environment - % buildings affected	9%	4%	20%	0%	5%	0%	0%	20%	50%	13%	0%	15%	0%	9%

Table 5.8 Paraquita Bay, 1 in 25 year AEP, inland flooding results for Baseline vs Degraded Environment scenario

	Total	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown
Total number of buildings	342	134	5	4	19	5	1	64	2	24	19	47	18	342
Flooded buildings:														
Baseline – 1 in 25 year	66	16	2	0	2	0	1	23	1	7	1	11	2	66
Degraded Environment – 1 in 25 year	51	13	2	0	2	0	0	16	1	6	1	8	2	51
Baseline -% buildings affected	19%	12%	40%	0%	11%	0%	100%	36%	50%	29%	5%	23%	11%	19%
Degraded Environment - % buildings affected	15%	10%	40%	0%	11%	0%	0%	25%	50%	25%	5%	17%	11%	15%

Table 5.9 Paraquita Bay, 1 in 100 year AEP, inland flooding results for Baseline vs Degraded Environment scenario

	Total	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown
Total number of buildings	342	134	5	4	19	5	1	64	2	24	19	47	18	342
Flooded buildings:														
Baseline – 1 in 100 year	102	21	2	0	6	2	1	38	2	9	3	15	3	102
Degraded Environment – 1 in 100 year	78	20	2	0	3	1	1	26	1	7	3	12	2	78
Baseline -% buildings affected	30%	16%	40%	0%	32%	40%	100%	59%	100%	38%	16%	32%	17%	30%
Degraded Environment - % buildings affected	23%	15%	40%	0%	16%	20%	100%	41%	50%	29%	16%	26%	11%	23%

wood.

Table 5.10 Infrastructure flooded in Paraquita Bay based on DHD reef, based on storm surge dataset with storm mapping at 60º degrees for a single event

	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown	Total
Baseline 60º tracking storm														
No. of properties	3	1	2	0	1	1	1	2	1	1	2	3	1	19
Total floor area (m^2)	506	7	159	0	198	13	16	376	20	12	564	40	61	1,972
Scenario 1 without coral friction														
No. of properties	5	1	3	0	2	1	1	2	1	1	2	4	3	26
Total floor area (m^2)	949	7	182	0	1,936	13	16	376	20	12	564	60	2,567	6,703
Impact														
No. of properties	2	0	1	0	1	0	0	0	0	0	0	1	2	7
Total floor area (m^2)	444	0	23	0	1,738	0	0	0	0	0	0	21	2,506	4,732
Economic value of impact (US$)	98,081	-	14,051	-	384,358	-	-	-	-	-	-	3,645	436,037	936,172
Scenario 2 without coral reefs														
No. of properties	5	1	3	0	3	1	1	2	1	2	2	5	4	30
Total floor area (m^2)	949	7	182	0	2,076	13	16	376	20	27	564	141	2,642	7,014
Impact														
No. of properties	2	0	1	0	2	0	0	0	0	1	0	2	3	11
Total floor area (m^2)	444	0	23	0	1,878	0	0	0	0	15	0	102	2,581	5,043
Economic value of impact (US$)	98,081	-	14,051	-	415,286	-	-	-	-	4,316	-	17,740	449,119	998,592

Table 5.11 Infrastructure flooded in Paraquita Bay – impact of loss of mangroves

	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown	Total
Baseline 60° tracking storm														
No. of properties	3	1	2	0	1	1	1	2	1	1	2	3	1	19
Total floor area (m^2)	506	7	159	0	198	13	16	376	20	12	564	40	61	1,972
Scenario 3 without mangroves														
No. of properties	4	1	3	0	2	1	1	2	1	1	2	3	2	23
Total floor area (m^2)	521	7	182	0	1936	13	16	376	20	12	564	40	149	3836
Impact of loss of mangroves – differences from baseline														
No. of properties	1	0	1	0	1	0	0	0	0	0	0	0	1	4
Total floor area (m^2)	15	0	23	0	1738	0	0	0	0	0	0	0	88	1864
Annual equivalent economic value of impact (US$)	3,309		14,048		383,941								15,302	416,600

5.3 Anegada

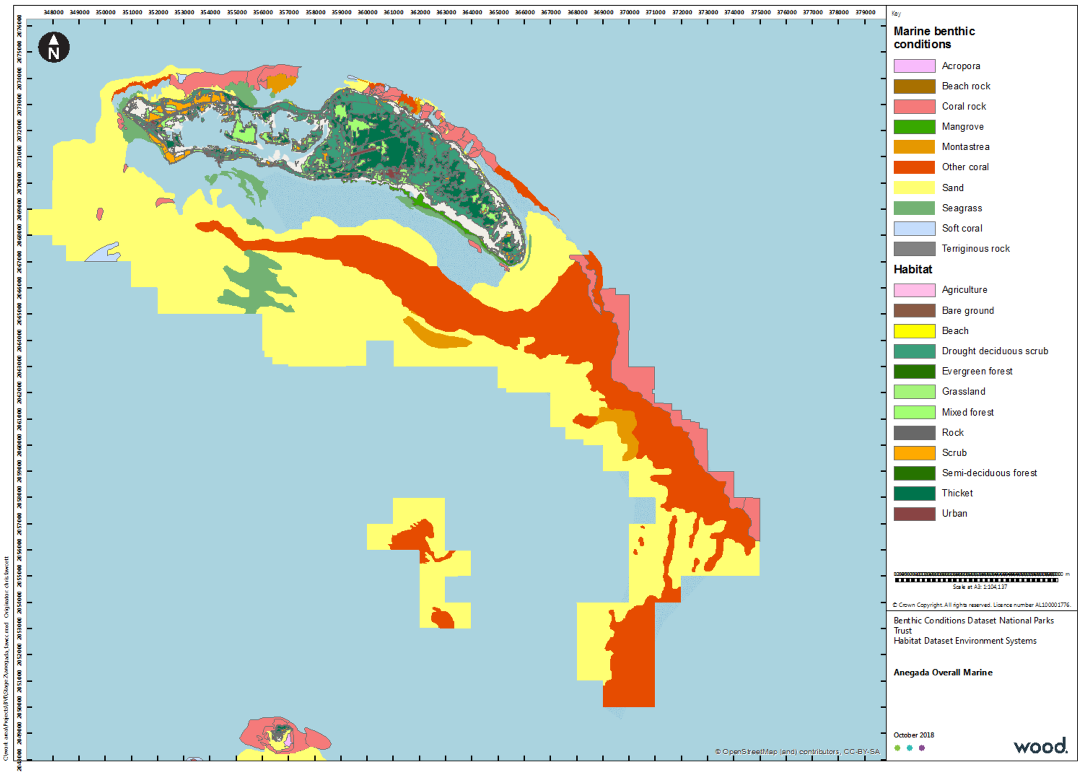
Overview

Anegada is the second largest of the British Virgin Islands at 38km^2 and lies 24km to the north of Virgin Gorda. Unlike the other islands in the archipelago it is flat and non-volcanic in origin, formed from coral and limestone. It is low lying with the highest point at 8.5m above sea level and it is estimated that 40% of the island is lies under 4m with western half of the island being below sea level. The Island has two distinct landscapes (IRF, 2013). The west of the island is formed by a series of sand dunes and beach ridges which protect an inland wetland system of interconnecting ponds which have been designated as a Ramsar Site. To the east, the island is comprised of flat reef limestone which is mostly exposed revealing sinkholes. To the north of the limestone plain are sand dunes and to the south a narrow band of wetland marshes and mangroves.

The island has an extensive coastal and marine environment with interconnecting habitats of reefs, seagrass, mangroves and beaches. The offshore coral reef protects the whole of the north coast of Anegada, whilst the Horseshoe Reef extends for 15km to the south east and covers a great area, providing protection from the prevailing winds and waves.

The population of Anegada is small with the 2010 census reporting a population of 285. The majority of development is located in "The Settlement" area of the island, but the island as a whole remains largely undeveloped. Tourism plays a key role in the economy with the population almost doubling in the tourist season through day visitors and charter boats.

Figure 5-13 Marine benthic and habitat for Anegada.



Habitat coverage

Table 5.12 summarises habitat coverage in Anegada, providing an indicative value of % cover. Anegada is dominated by natural vegetation with very little development. 72% of the area is covered by vegetation – with drought deciduous forest dominating.

Table 5.12 Habitat coverage in Anegada

Habitat	Area (hectares)	Cover %
Drought deciduous forest	976	25%
Thicket	787	20%
Salt pond	565	15%
Mixed forest	235	6%
Mangrove	222	6%

Assessment results

Coastal

The 60° Category 4 storm surge dataset is shown in Figure 5-14 for the whole island of Anegada. As can be seen large areas of the island are flooded with the exception of land with elevation of approximately >4m located at along segments of the north coast and centrally north of 'The Settlement' where the airport is located. Figure 5-15 provides a more detail picture around the Settlement with buildings overlaid. As can be seen in the baseline situation almost all of the buildings are flooded. Table 5.13 shows the baseline and results from Scenario 1 and 2. The impact of Scenario 1 is minimal as a result of so many buildings being flooded at the baseline, with only 1 additional building flooded. Scenario 2 has a slightly greater impact with 23 additional properties flooded with the majority being residential or 'unknown'.

The coastal flooding experienced in Anegada as a result of characteristics of Hurricane Irma was much less severe than that predicted from the Category 4 storm surge dataset. Environment Systems provided a Hurricane Irma visual damage line as a result from coastal flooding. Whilst there was variation in the height of damage line around Anegada, the average was 0.4m above sea level and averaged at 0.4m in the Settlement. At this 0.4m baseline in the Settlement, 90 properties were flooded, with an additional 50 and 166 properties flooded in Scenarios 1 and 2 respectively. This relative change is significant and demonstrates the sensitivity of lower baseline maximum water level.

Figure 5-14 Anegada infrastructure flooded from Category 4 hurricane with storm of 60° mapping

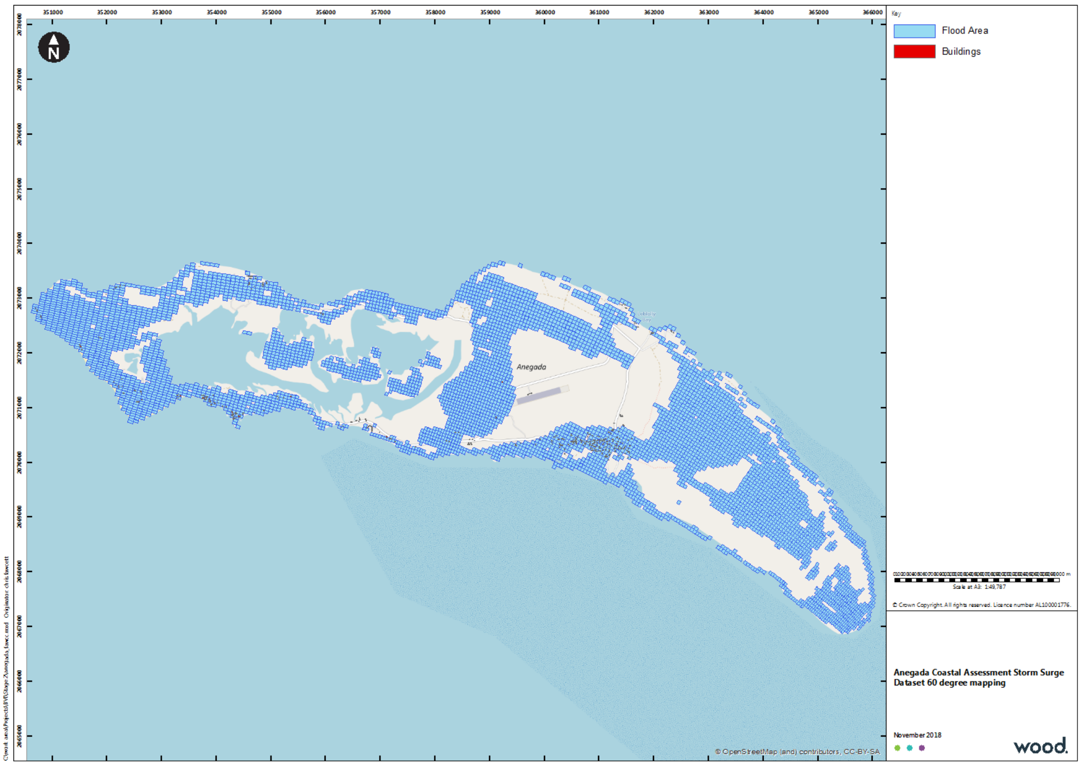


Figure 5-15 Anegada 'Settlement' infrastructure flooded, Category 4 hurricane with storm of 60° mapping

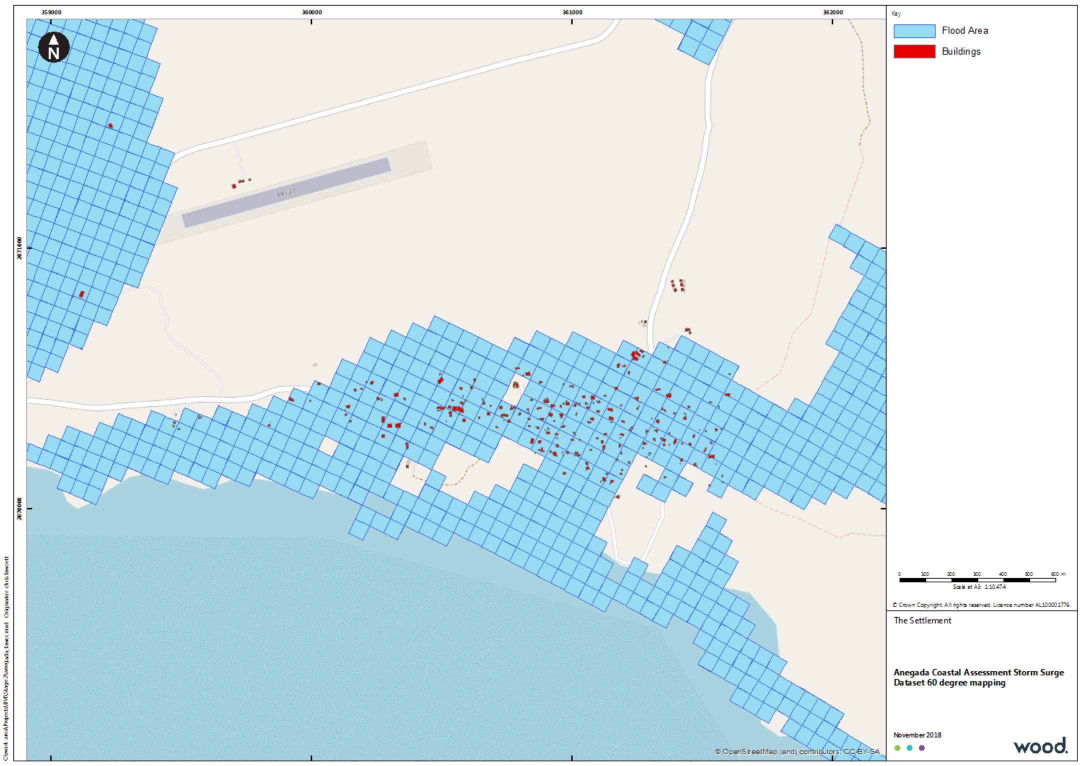


Table 5.13 Infrastructure flooded on Anegada based on SLD reef, based on storm surge dataset with storm mapping at 60° degrees for a single event

	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown	Total
Baseline 60° tracking storm														
No. of properties	151	21	30	42	18	10	0	1	13	62	19	0	127	494
Total floor area (m^2)	15185	1200	2873	5078	1351	88	0	48	1517	2166	1018	0	6098	36,621
Scenario 1 without coral friction														
No. of properties	151	21	30	42	18	10	0	1	13	62	19	0	128	495
Total floor area (m^2)	15185	1200	2873	5078	1351	88	0	48	1517	2166	1018	0	6201	36,724
Impact														
No. of properties	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Total floor area (m^2)	0	0	0	0	0	0	0	0	0	0	0	0	103	103
Economic value of impact (US$)													17,923	17,923
Scenario 2 without coral reefs														
No. of properties	160	21	32	42	18	11	0	1	16	63	19	0	134	517
Total floor area (m^2)	16333	1200	2999	5078	1351	99	0	48	1873	2319	1018	0	6592	38,909
Impact														
No. of properties	9	0	2	0	0	1	0	0	3	1	0	0	7	23
Total floor area (m^2)	1149	0	126	0	0	11	0	0	355	153	0	0	494	2288
Economic value of impact (US$)	254,037	-	75,841	-	-	6,627	-	-	102,150	43,978	-	-	85,962	568, 595

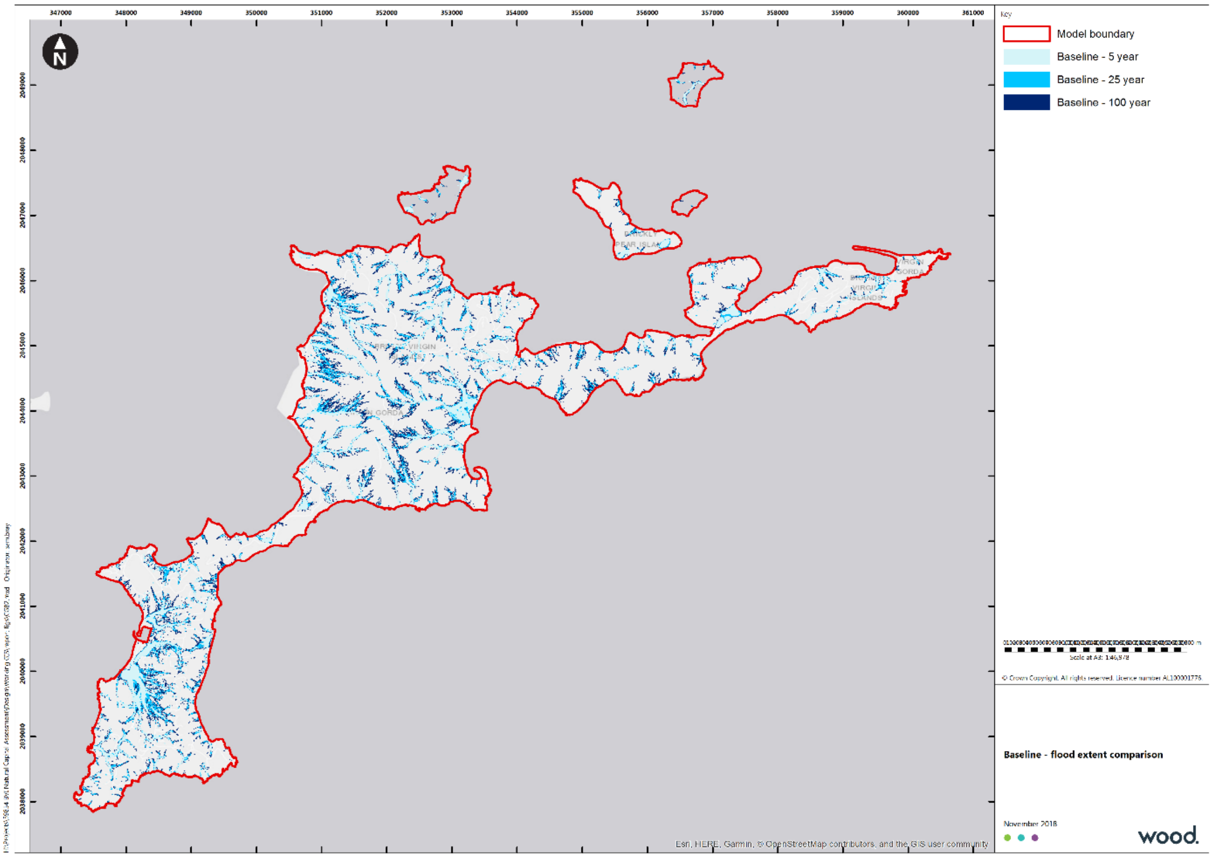
6. National perspective

This section provides an overview of applying the methodologies outlined in Section 4.4 to provide a national estimate of value natural capital provides for inland and coastal flood protection

6.1 Inland flooding

The results used to undertake the national assessment were produced following the method described in Section 4.4. The models produced flood extents, depths and velocities for the entire BVI. The flood extents for Virgin Gorda are shown as an example of the model outputs in Figure 6-1, comparing the extents for the 1 in 5, 25 and 100 year events.

Figure 6-1 Extent comparison for the Baseline scenario, all return periods (Virgin Gorda)



The results for the BVI-wide inland flooding assessment are shown in Table 6.1, Table 6.2 and Table 6.3 below, comparing the Baseline and Degraded Environment scenarios for the 1 in 5 year AEP, 1 in 25 year AEP and 1 in 100 year AEP events respectively.

The degradation of the environment has reduced the number of properties affected by a depth of flooding over 15cm in all three modelled AEPs. This reduction is 3% for the 1 in 5 year AEP, and 4% for the 1 in 25 and 100 year AEPs.

Although the modelling did not reveal an increase in flooding depths in any of the extreme events by degrading the environment, a widespread increase in maximum velocities is seen across the BVI, as with the case studies. Using Virgin Gorda as the example, Figure 6-2 and Figure 6-3 compare maximum velocities across the model for the Baseline and Degraded Environment scenarios respectively. The benefit offered by natural capital in terms of slowing the passage of water is once again highlighted by the marked difference in the figures.

Figure 6-2   Maximum velocity - Baseline 1 in 100 year AEP

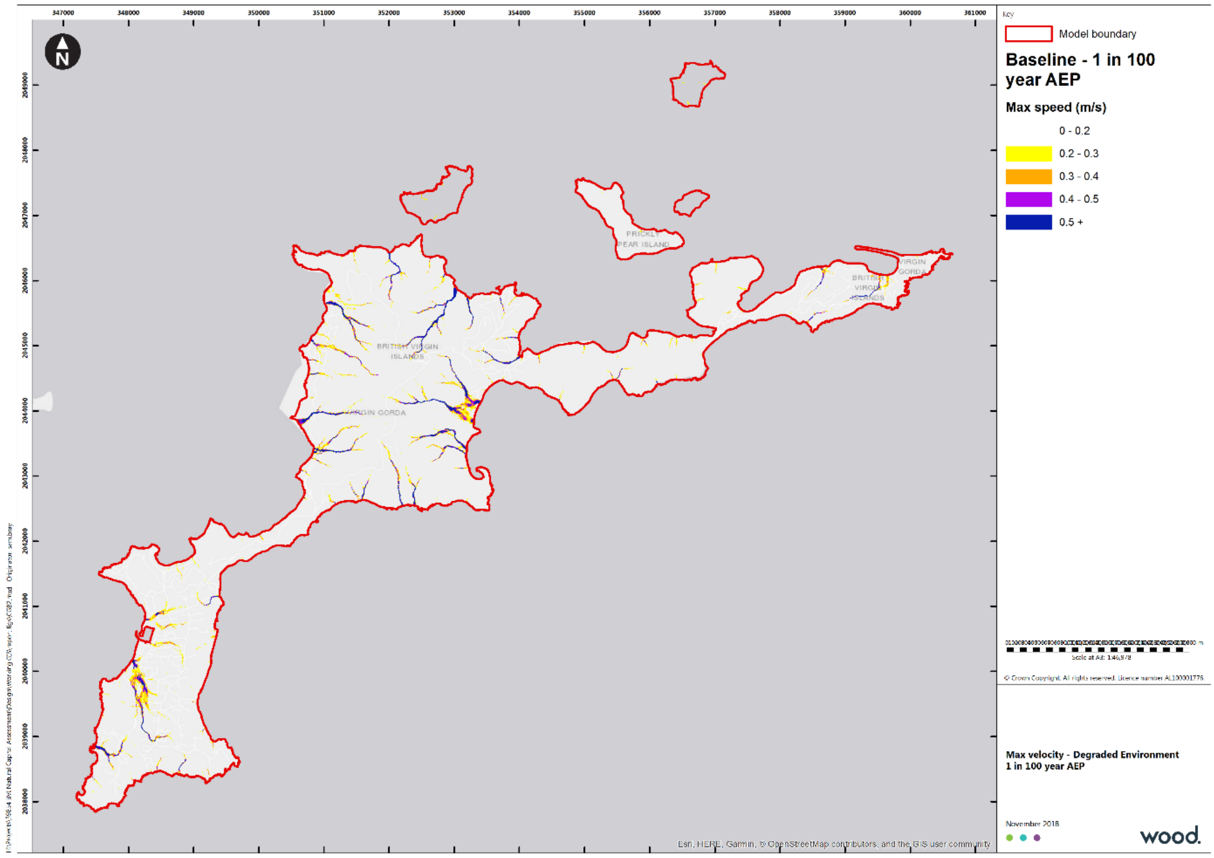
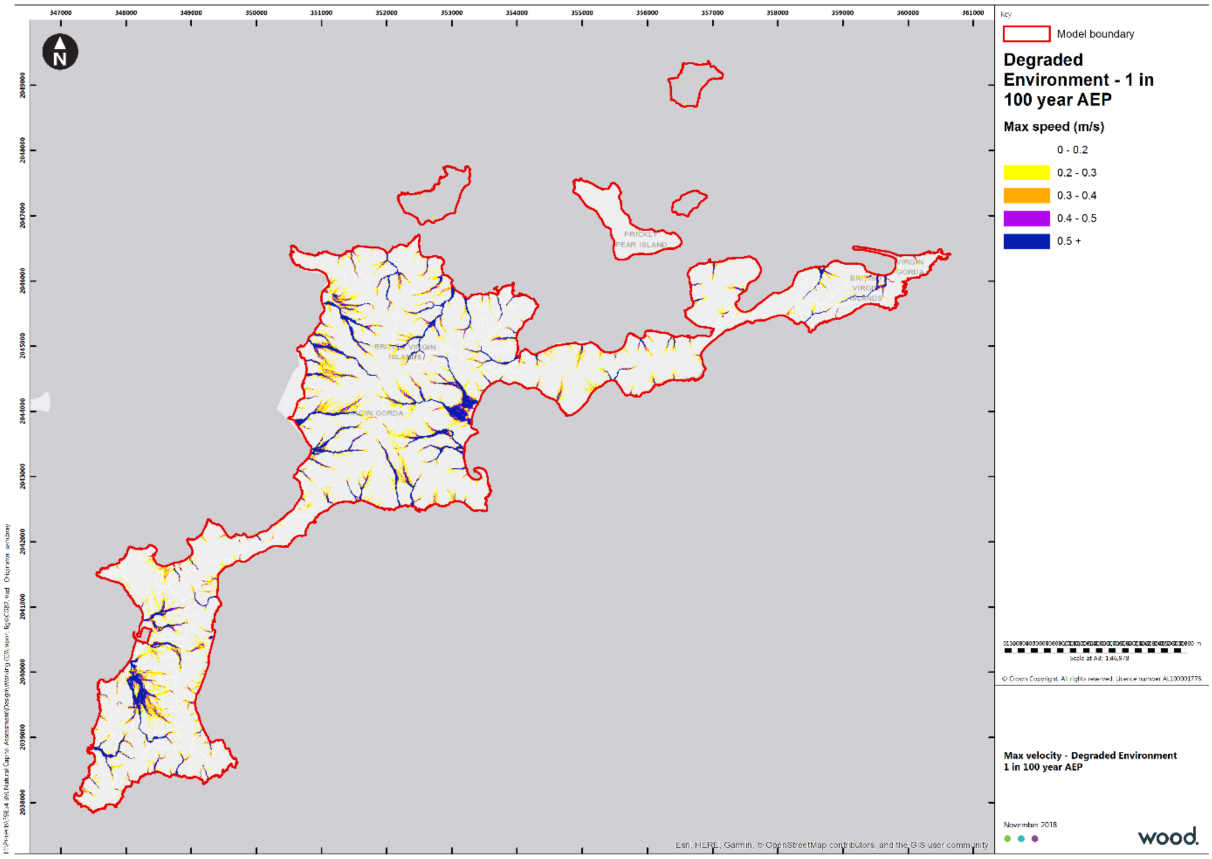


Figure 6-3 Maximum velocity - Degraded Environment 1 in 100 year AEP



Commentary on results

The hydraulic modelling demonstrated an increase in flooding depths and extents with event severity, as would be expected with heavier rainfall. In both of the case studies, however, and similarly to the Road Town Hydrology Study results[54], the increase in extent was limited due to the steep topography surrounding the flatter, lower-lying areas. This creates a "bucket-like" effect, where adding more rainfall increases the depth, but not necessarily the extent in all areas.

It had been anticipated that the reduction in the roughness value associated with the Degraded Environment scenario would increase the speed of the catchment response to rainfall, causing water to move more quickly from the steep slopes to the more populated lower-lying areas, increasing the flood depths here. Due to the very extreme nature of even the 1 in 5 year AEP event, the catchment response impact was limited, and the reduced roughness in fact improved conveyance of water to the sea. For that reason, the Degraded Environment scenario appears to lower flooding depths. This, however, does not necessarily indicate an improved or favourable position with regard to flooding as a result of degrading the environment.

In a severe rainfall event such as those modelled as part of this study, the depth of flooding is only one aspect of the risk and damage that the event may cause. The velocity of flood water is another important aspect, and one not considered for valuation here. The increase in velocity as a result of degrading the environment was shown in Sections 5.1, 5.2 and this section. It is clear that the velocities have been increased as a result of degrading the environment, due to the roughness values being lowered. The

[54] Wood (2018). Catchment characterisation report

increased velocities would contribute to more scour of the slopes and sediment load within the flood water, transporting greater volumes of mud, clay and rocks from the hillsides to the lower-lying areas where the velocity drops. Increased water velocity also increases the risk of landslides, and likelihood of damage to infrastructure such as roads. This important mechanism by which flooding can cause damage and hazard is not valued as part of this study, but qualitatively shown to be positively impacted by the presence of natural capital.

The result of reduced depths by degrading the environment highlights two key limitations of the modelling and assessment method, in that infiltration and interception are not incorporated, and that only extreme rainfall events were considered.

With data regarding the interception and infiltration capacities of the forested areas and soils in the BVI, these important protective characteristics of natural capital could be assessed by representing this data in the existing hydraulic models. Under the current assessment method, these factors are ignored, based upon the assumption that the rainfall events are so extreme that the soil would likely become saturated early on in any storm. In a shorter duration storm, however, or a less extreme event, this protection is likely to be significant, and if removed, may effectively turn more regular rainfall events that do not cause flooding into events that begin to cause damage.

6.2 Coastal flooding

The results used to undertake the national assessment of coastal protection were produced following the method described in Section 4.4 and the results are shown in Table 6.1. Flooding at baseline indicates 1,873 properties flood with a total floor area of 327,000m^2 with residential, retail and offices/banks each being the largest sectors effected (84,000m^2, 58,500m^2 and 54,800m^2) respectively. The results of Scenario 1 show an increased floor area flooded by 122% (73,000m^2) equating to 333 extra buildings. Residential properties and offices together contribute 42,683m^2 and bars/restaurants/hotels account for 6,566m^2. In Scenario 2, in the hypothetical situation where the reefs are destroyed, the impact is much more significant with an increased floor area of 426,865m^2 which is a 230% increase over the baseline and represents 19% of the total floor area of buildings in the BVI.

Commentary on results

At both case study and national level the modelling shows coastal flooding of built infrastructure from a Category 4 storm is considerable in the BVI, due to the high concentration of buildings in the flat areas that characterise the low lying coastal zone. In particular, the results highlight the importance of commercial losses in these areas while residential buildings are further up the steep hillside and are less affected.

Whilst our results indicate only a modest valuation associated with the reduced coral friction from live coral die back (Scenario 1) and mangrove loss at Paraquita Bay (Scenario 3) the significance of this should not be underestimated. The ill health and damage to live coral provides a key indicator to what could be instore for the future. If coral reefs are not protected and do not remain in good health and live coral is destroyed, the continued regeneration of the reef will not occur and over the long term the reef will erode. Whilst this impact will not be seen immediately, the analysis from Scenario 2 has shown the disappearance of reefs would have significant impact on increased flooding and economic impacts. Even short widths of mangroves provide high levels of wave attenuation and also reduce wind speeds. Whilst only a relatively small number of properties were shown to be flooded in the hypothetical situation of mangrove loss the protection provided by the mangroves and coral reefs at Paraquita Bay afford a level of flood protection which make it a safe hurricane shelter for the yachting industry demonstrating value and the need to protect and enhance the mangrove belts.

It is vital therefore that steps are taken immediately to safeguard the future health of coral reefs and to regenerate coral reefs which have been destroyed.

Table 6.1 BVI-wide assessment, 1 in 5 year AEP, inland flooding results for Baseline vs Degraded Environment scenario

	Total	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown
Total number of buildings	12389	6930	474	242	249	428	245	112	143	301	1041	432	273	1519
Flooded buildings:														
Baseline - 5 year	1931	853	158	74	33	123	45	31	26	123	193	77	45	150
Degraded Environment - 5 year	1556	670	122	67	30	99	37	27	22	108	153	64	37	120
Baseline -% buildings affected	16%	12%	33%	31%	13%	29%	18%	28%	18%	41%	19%	18%	16%	10%
Degraded Environment - % buildings affected	13%	10%	26%	28%	12%	23%	15%	24%	15%	36%	15%	15%	14%	8%

Table 6.2 BVI-wide assessment, 1 in 25 year AEP, inland flooding results for Baseline vs Degraded Environment scenario

	Total	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown
Total number of buildings	12389	6930	474	242	249	428	245	112	143	301	1041	432	273	1519
Flooded buildings:														
Baseline - 5 year	2931	1451	208	92	58	173	65	42	45	152	255	100	62	228
Degraded Environment - 5 year	2423	1179	172	84	50	145	50	36	32	134	213	91	50	187
Baseline -% buildings affected	24%	21%	44%	38%	23%	40%	27%	38%	31%	50%	24%	23%	23%	15%
Degraded Environment - % buildings affected	20%	17%	36%	35%	20%	34%	20%	32%	22%	45%	20%	21%	18%	12%

Table 6.3 BVI-wide assessment, 1 in 100 year AEP, inland flooding results for Baseline vs Degraded Environment scenario

	Total	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown
Total number of buildings	12389	6930	474	242	249	428	245	112	143	301	1041	432	273	1519
Flooded buildings:														
Baseline - 5 year	4015	2124	261	107	75	207	79	48	68	170	326	136	79	335
Degraded Environment - 5 year	3412	1810	222	95	64	182	68	44	51	158	264	116	68	270
Baseline -% buildings affected	32%	31%	55%	44%	30%	48%	32%	43%	48%	56%	31%	31%	29%	22%
Degraded Environment - % buildings affected	28%	26%	47%	39%	26%	43%	28%	39%	36%	52%	25%	27%	25%	18%

wood.

Table 6.4 National assessment of Infrastructure flooded based on storm surge dataset with storm mapping at 60° degrees for a single Category 4 event

	Residential	Retail	Bar/ Restaurant	Hotel/ Resort	Community, health and education	Utilities	Transport infrastructure	Agricultural Infrastructure	Offices, Banks	Storage	Abandon	Misc	Unknown	Total
Baseline 60° tracking storm														
No. of properties	527	197	112	83	109	68	29	3	120	228	71	24	302	1,873
Total floor area (m^2)	83,965	58,544	16,898	22,094	25,564	2,609	5,185	165	54,784	23,042	6,689	924	26,566	327,030
Scenario 1 without coral friction														
No. of properties	645	219	123	101	124	76	37	5	144	263	87	30	352	2,206
Total floor area (m^2)	105,703	62,871	18,283	27,275	31,079	3,224	5,973	542	75,729	28,814	7,933	1,170	31,536	400,132
Impact														
No. of properties	118	22	11	18	15	8	8	2	24	35	16	6	50	333
Total floor area (m^2)	21,738	4,327	1,385	5,181	5,515	615	788	377	20,945	5772	1244	246	4970	73,102
Economic value of impact (US$m)	24.8	13.5	4.3	7.7	6.3	1.9	2.5	0.4	31.1	8.6	1.1	0.2	4.5	106.8
Scenario 2 without coral reefs														
No. of properties	1,564	319	171	131	218	95	66	7	219	453	155	83	626	4,107
Total floor area (m2)	258,080	96,138	27,751	35,558	66,911	6,769	11,423	654	117,438	44,314	13,491	6,468	68,899	753,895
Impact														
No. of properties	1,037	122	59	48	109	27	37	4	99	225	84	59	324	2,234
Total floor area (m^2)	174,115	37,594	10,853	13,464	41,347	4,160	6,238	489	62,654	21,272	6,802	5,544	42,333	426,865
Economic value of impact (US$)	198.7	116.9	33.7	20.0	47.2	12.9	19.4	0.6	93.0	31.6	6.1	5.0	38.0	623.0

Note: The economic values reported here are for a single relatively extreme (Category 4) event. Elsewhere in the report, annualised values reflecting a frequency weighted composite of Category 1-5 events are reported.

6.3 Economic valuation results

Overview

The first part of this section discusses the headline results and their context. A second further section considers the relationship between land use by economic sectors and the depth of flooding. This allows an understanding of the effects in more general terms and shows how value of natural capital, particularly reefs, relates to the topography. The third section considers sensitivities of the results drawing on the understanding of the topography and influence of the natural capital. A final section compares these results with the values from other studies.

Headline results and the context

The scale of the BVI economy provides a benchmark and maximum for the degree of protection that natural capital could theoretically provide. The BVI has an annual GDP of US$1,027m and largely depends on tourism and financial services –known as the "twin pillars" of the economy, each making up roughly 50% of the economic activity. Tourism-related activity is estimated to be worth US$484m annually.

The inland hydraulic modelling showed that flood depths did not increase and hence very little change in the size of the area or number of properties flooded. Estimates of flood damage are primarily related to depth and so there is no simple link that can be made or quantified between the natural capital represented by vegetation and the capturing of changes to it in economic terms.

Qualitative analysis shows substantial impacts from natural processes related to faster water movements through a flooded area but these effects are not flooding per se, which is a rise in water above normal levels. These additional effects of scour, sediment movement and related impacts such as risk of landslide are therefore not valued within the scope of this work, but are believed to be significant.

The economic value of the impact of vegetation, and more broadly natural capital, on inland flooding is estimated as zero, but it is emphasised that vegetation provides many other benefits to natural processes in a catchment, particularly related to the transport of soil and other material under conditions of flood, drought and even in normal conditions). The example of the progressive silting of Paraquita Bay indicates that there are clearly observable effects which will have economic consequences and would be exacerbated with a reduction in the natural capital of vegetation.

For coastal flooding, a quantitative relationship has been estimated which takes account of the links between the physical processes which cause flooding and economic values. This enables natural capital to be valued in terms of the avoided costs of floods that the reefs prevent. When reefs are degraded or destroyed these costs are no longer avoided and become real. The estimate of these costs, which are presented and discussed below, is directly equivalent to the value of the reefs.

Using the relationship between physical change and economic values, the impact of loss of reefs is estimated as US$74.3m[55] annually including the indirect knock-on effects in the supply chain. It is approximately 2.5 times greater than the losses of US$30.3m that are currently expected with the protection of existing reefs (the reefs are not expected to avoid all flooding).

For comparison, the additional as US$74.3m is approximately 7% of total GDP of the BVI in numeric terms and also numerically equivalent to the GDP attributable annually to all the bars and restaurants in the BVI (approximately equivalent to their profits). While this may appear large, it is only one fiftieth of the reputed costs of hurricane Irma of US$3.6bn, a storm expected to occur less often than once in every 50 years.

[55] Additional analysis indicates that the swell-reducing features of mangroves could add, just for Paraquita Bay, approximately $0.5m to this figure. Datasets are not sufficiently developed to make a national estimate

Simple contrasts between the estimates made here and existing financial statistics are potentially misleading. The reefs can be seen as currently providing an equivalent to insurance and so avoid what would otherwise be an annual US$74.3m out-of-pocket insurance payment by BVI inhabitants. However, while notionally a source of reduced insurance costs, the reefs can be seen as the actual physical cause of a safer world and, if they were actually lost, no substitute provider of insurance might come forward at this (or any higher) price. Structural changes and complex knock-on effects would follow, such as abandonment of uninsurable low-lying areas and changes in land prices.

The valuation model used here only provides a value for a notional first step in a sequence of possible change. It assumes that in an economy with a GDP of US$1,027m, people would go on living exposed to $74.3m of damage annually (Table 6.5). Even if insurers could be found, this seems unlikely. While future steps are inherently uncertain and too subject to assumption for detailed quantification, the basic characteristics of the existing situation are clearly visible in the BVI, in particular the concentration of economic activity near the coast, meaning that the costs of structural change will almost certainly be greater than $74.3m. The unresolved question is how much greater.

The calculation of the US$74.3m is not an estimate of a 'replacement cost', such as the amount of investment that would be required should reefs disappear, but it is an estimate of the stream of benefits that flows to BVI under current conditions. Assuming the reefs continue to exist, the greater the protection they provide to society and the economy, the greater their value. Population growth and increasingly frequent and intense weather are just two factors which increase this value.

The degradation of reefs is a first step towards reef erosion and arguably differs only in degree. The impact of degradation of reefs is much smaller at US$3.6m annually, reflecting a more minor physical change, though benefits will arise from a similar set of reasons, such as population growth. If reefs were degraded rather than destroyed, the additional cost is lower, at +US$3.6m annually. Degradation, is however a process which continues as once reefs erode

Table 6.5 Estimates of annualised welfare costs to the BVI categorised tropical storms

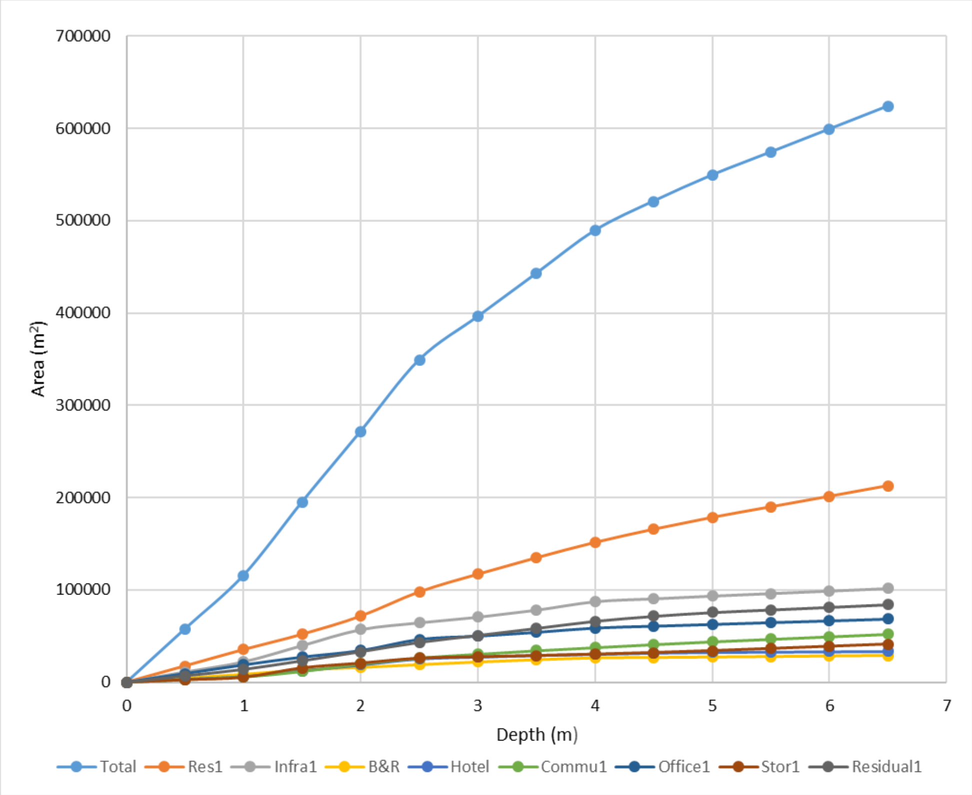
	Total	**Residential**	**Infrastructure**	**Bar/ Restaurant**	**Hotel/ Resort**	**Community**	**Offices**	**Storage**	**Other**
Expected annual losses (US$m)	**30.3**	7.3	10.2	4.3	1.6	0.9	2.5	1.2	2.3
Increase if reef degraded (US$m)	**+3.6**	+0.8	+1.4	+0.4	+0.3	+0.1	+0.2	+0.2	+0.2
Increase if reef destroyed (US$m)	**+74.3**	+13.5	+19.1	+10.2	+7.2	+5.1	+6.8	+9.8	+2.6

Source: Wood estimates

Economic land use and the impact of coastal flooding

Figure 6-4 shows the aggregate footprint area of buildings flooded at different depths. The total is shown in the upper (light blue) line. The other lines show the flooded area for a breakdown of the total into 8 building types reflecting land use and economic activity.

Figure 6-4 Aggregate areas of flooded buildings by building type



Source: Wood estimates

At all flood depths, the type of property which experiences the greatest area of flooding is residential, which is shown in the second [orange] line on the graph. Next in terms of flooded area are infrastructure assets (which includes retail premises and utilities), followed by (in order): offices, community buildings (including agricultural premises), storage, hotels, and bars and restaurants. A final category (in dark grey) covers poorly identified and abandoned buildings.

The aggregate area of buildings exposed to floods of depths of 2 and 4 metres is shown in Table 6.6. Overall, 14% of the total property area is exposed to a 2 metre flood but the proportion differs substantially between types of building. The greatest effect is on bars and restaurants where 44% of their aggregate total floor area is affected while the minimum effect, of 6%, is shown for residential buildings. In a 4 metre flood the total exposed rises to 27%, while bars and restaurants rise to 72%, still the maximum across all types of building, and residential rises to 13%, still the lowest across all types of building.

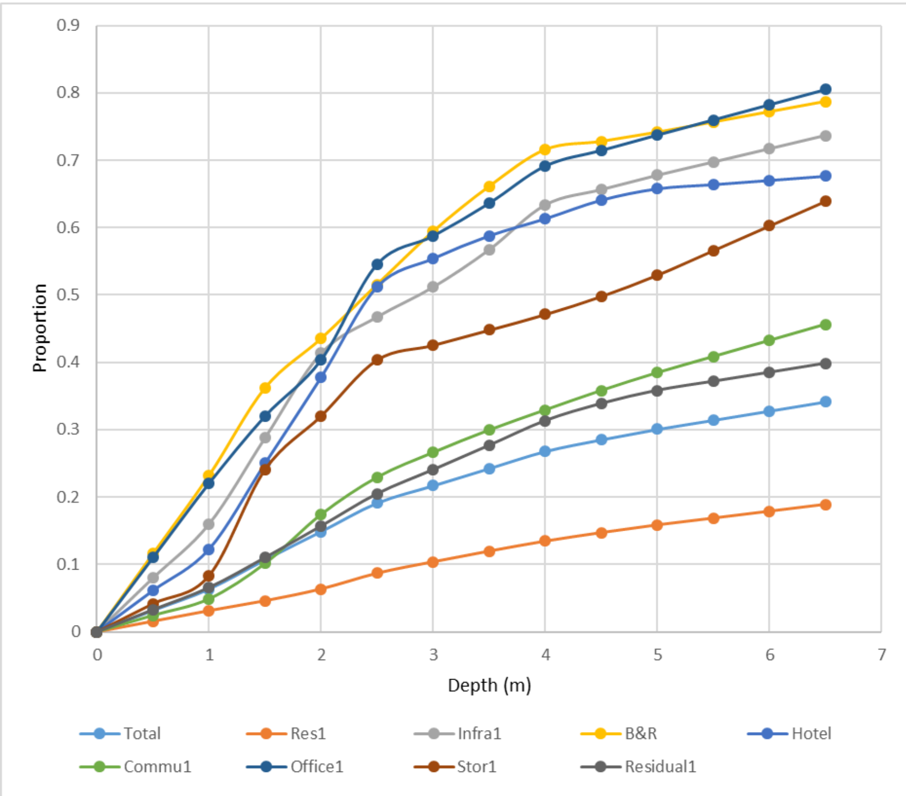
Table 6.6 The aggregate area of buildings exposed to floods of depths of 2 and 4 metres

	Total	Residential	Infrastructure	Bar/ Restaurant	Hotel/ Resort	Community	Offices	Storage	Other
Total area of property in BVI (m^2)	1,826,138 (100%)	1,125,565	137,974	36,909	49,872	114,622	85,447	64,587	211,162
Area exposed to a 2m flood (m^2, %)	271,894 (100%)	6%	41%	44%	38%	17%	40%	32%	16%
Area exposed to a 4m flood (m^2, %)	489,294 (100%)	13%	63%	72%	61%	33%	69%	47%	31%

Source: Wood estimates

The proportion of each type of building exposed for flood depth up to 6 metres is shown in Figure 6-5. This indicates that building types fall into approximately three groups. The most affected are the commercial building types which include bars, restaurants, hotels, and offices but also include infrastructure (including retail premises) such as power plant and desalination works, and storage (which may indicate vulnerability of apparent reserves). The least affected, as a proportion of the total stock, are residential buildings. The main building type in the middle group is community facilities. Also shown as part of the middle group are the total (light blue) and residual building types (dark grey). Community facilities include both those forming part of residential communities and so affected in a similar way to the residences, and those making up other local services and so affected in a similar way to the commercial properties. The residual group also comprise a mix of residentially-related and commercially-related building types, as does the total.

Figure 6-5 Proportion of each type of building exposed for flood depths up to 6 metres



Source: Wood estimates

This distinction between groups of buildings of different types indicates overall land use and is consistent with residential properties, which are less affected, being situated on higher ground than commercial properties, which are more affected. As a result, for building types in the commercial group, every 1 metre of flood rise leads initially to an additional 20% of area being exposed. Subsequently, after the depth has reached 2 metres, there is a noticeable change, a kink in the graph, and each 1 metre rise leads to 10% being exposed. This is consistent with approximately half the commercial building stock being on the lowest lying land and a large proportion of the remainder, while less vulnerable, still at a significantly low elevation. In contrast, for residential properties, the increase in exposed area for a 1 metre rise is never greater than 5% and can be as low as 2%.

The proportion of property area exposed to flood by building type is shown in Table 6.7. The top line shows the proportions for the BVI in total. Amongst others, residential buildings make up 62% of the total, offices 6%, bars and restaurants 2% and hotels 3%. A 2 metre flood leads to 271,894m^2 becoming exposed, 15% of the total area. The proportions of this 271,894m^2 made up by each building type are shown in the table to the right. Residential properties make up 26% bars; hotels and restaurants and offices collectively also make up 26%; infrastructure accounts for 21%; and the remainder another 27%. A 4 metre flood has a similar split with areas equally split between these four types of building.

Table 6.7 Proportion of property area exposed to flood by building type

Area affected			Breakdown								
	Total (m^2)	% of Total Exposed	Residential	Infrastructure	Bar/ Restaurant	Hotel/ Resort	Community	Offices	Storage	Other	Total
Total area of property in BVI (m^2)	1,826,139	100%	62%	8%	2%	3%	6%	5%	4%	12%	100%
Area exposed to a 2m flood	271,894	15%	26%	21%	6%	7%	7%	13%	8%	12%	100%
Area exposed to a 4m flood (m^2, %)	489,294	27%	31%	18%	5%	6%	8%	12%	6%	14%	100%

Source: Wood estimates

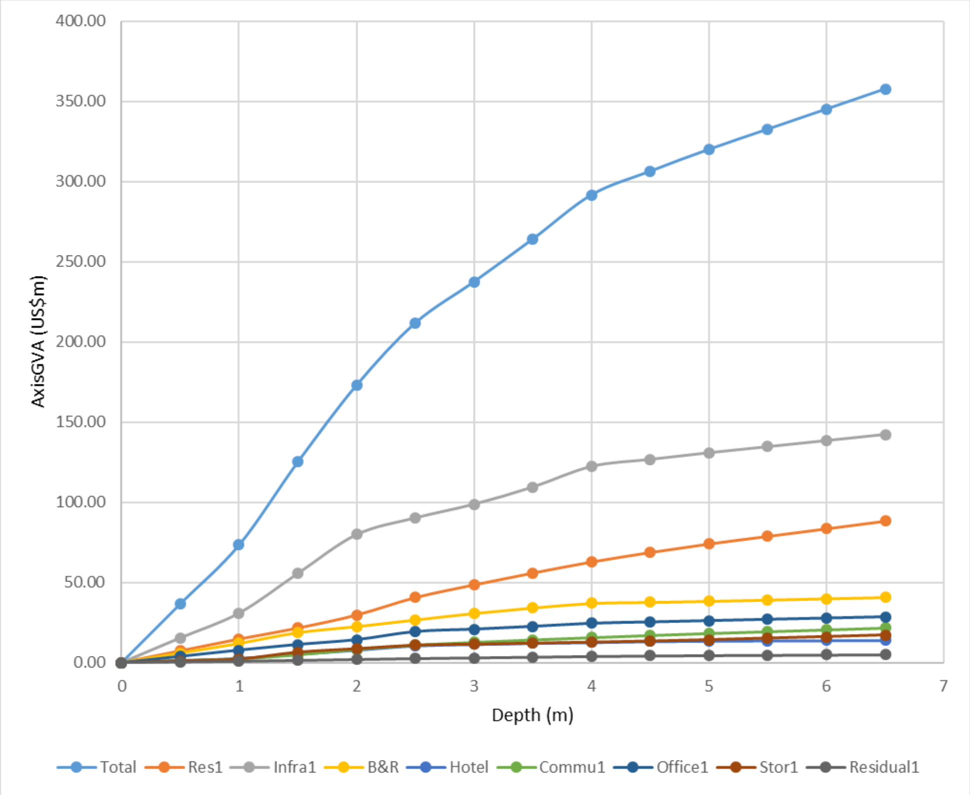
These areas and proportions reflect the unique characteristics of the geography and land use in the BVI, and are fundamental to the assessment of the economic impacts and for the calculation of monetary values. In particular, as regards areas exposed, at any flood depth:

- The area of residential properties exposed is greater than the area of any other single building type and accounts for a quarter of the total area affected by flood.
- Hotels, bars, restaurants and offices collectively make up another quarter of the total area, while infrastructure (retail and utilities) is next at one fifth of the total.

Although the flooded commercial area is similar in size to the flooded residential area (for a range of depths), it makes up a far greater proportion of the total commercial area. In comparison, the flooded part of the residential area is a much smaller proportion of the total.

Figure 6-6 presents the property exposure in terms of the value of economic activities rather than area, and clearly shows the vulnerability types.

Figure 6-6 Total property value affected by coastal flood at different depths



Source: Wood estimates

Sensitivities

The headline results provide a detailed modelling of a specific event (the R3i Category 4 storm), but the demonstration above of the vulnerability of the economy expressed in terms of building types provides a general tool for consideration of the sensitivity of the BVI to floods of different depths, and hence to potential structural effects on the economy.

The dominant features are shown in Figure 6-5, which identifies 3 main groups of building types, and the increase in the proportion which are flooded for a 1m increase in depth. There is high sensitivity of the commercial sector (bars, hotels, offices, infrastructure including retail and storage) to floods of even small depths. As mentioned, every 1 metre of rise leads to an additional 20% of area being exposed amounting to over 50% flooded with a 2.5m rise.

While high category storms produce the greatest newspaper coverage, these storms are in fact those where reefs have less of an effect on the economy, largely because flooding would occur anyway as the natural processes are so extreme. Lower category storms have less newspaper coverage, not least because the existing reefs are providing a protective function and so mitigating natural effects. However, without reefs, the floods from lower but more frequent category storms would significantly affect a large proportion of the commercial sector and on a more regular basis.

In the residential sector, less than 10% of properties are below 2.5m and the sector is inherently already better protected and less dependent on reefs to avoid flooding. Overall, although residents rely on businesses for their general needs, the benefit of reefs falls more directly on business than on residents and structural effects of reef loss and degradation would be related to responses in the commercial sector rather than the wishes of residents. Being flexible and price sensitive, the commercial sector would seek to reduce any vulnerability from reef degradation and loss, possibly by relocation, but more immediately and directly by ensuring that existing reefs continue to play their existing mitigating role.

The uncertainties in this analysis can be addressed in overall terms using the Figure 6-6. The use of the very detailed GIS datasets for building use means that there is very little uncertainty in the location of economic activity and its inherent vulnerability is very well mapped. The remaining uncertainty is related to meteorological effects and the physical effects of reefs. These combine to affect the response of society overall including the economy and business in a final overarching uncertainty. The value of reefs, in this analysis, results from society continuing to function as it currently does.

The uncertainty related to the physical processes of meteorology and reefs results in higher or lower flooding at various frequencies. The impact of flood depths on the economy is illustrated by the proportions in Figure 6-6. A view of how much and how regular events would need to be for structural change to occur can almost certainly only be obtained through opinion survey as the factors for individual businesses *not* to respond will be unique to them. Some may be resilient and aim to adapt to increased and more frequent flooding, while some may terminate their activities. The overall ability of the BVI to continue to operate, given possible changes in the mix of businesses that result together with any knock-on impacts, such as on reputation may also be important. Speculation on these aspects is outside the scope of the work for this study but is informed by its results.

In contrast, increased economic development will in general increase the natural capital value of the reefs which will then be protecting a greater amount of economic activity. Although speculation on this is outside the scope of this work, it is clear that development at lower elevations will lead to greater benefits from existing reefs.

The headline estimates of natural capital value are inherently and directly sensitive to the degree of economic development at lower elevations. The estimates are also sensitive to the modelling of meteorological and the physical processes. Recent experience of extreme events will affect the decisions of existing businesses even while protected by the existing reefs, and models based on historical patterns may not capture increased impacts, such as those resulting from global warming. Reefs can only protect against a proportion of these effects and if business decides that other factors are the main determinants of their actions, the reefs will play a less important role in their decision and will inherently be of less value to them. For example, reefs provide good protection against lower category storms but if it is the number of higher category storms (which are proportionally less effectively mitigated by reefs) that determine business decisions, reefs will have an inherently lower value. Similarly, sea level rise may reduce the effectiveness of reefs (depending on coral growth/death rates), even for lower category storms, and so will also reduce their value for coastal protection.

In summary, the dollar value of the headline estimates above are sensitive to projections of increased economic development at lower elevations, to modelling of physical processes, and to opinion of business as to their vulnerability and consequential responses. These factors are difficult to quantify, particularly as they require views on potential structural change. A judgement might be made that the headline estimates above, already considered a lower bound, might be a factor of 2 or 4 higher in the worst case.

Previous estimates of coastal protective value

Although very dependent on the unique geography of each Caribbean island, previous estimates of coastal protective value (CPV) are aligned in broad terms with the estimates here for the BVI.

Compared to the estimate for the BVI of $74.3m for CPV, Burke *et al.* (2008) quote $18-33m in Tobago and $28-50m in St. Lucia. Sarkis et al. 2010 quote $266m for Bermuda. The recent estimate by Van Zanten *et al.* (2014) quotes $8.9m in US Virgin Islands, but this cannot be compared directly as it is for a single 100 year event, whereas the BVI estimate is based on the typical pattern of hurricanes, including many more frequent lower magnitude storms.

The value of reefs is made up of more than just the value they provide for coastal protection. Van Zanten *et al.* (2014) state that CPV makes up less than a twentieth (4.3%) of their total economic value (TEV).

7. Conclusions and recommendations

Conclusions and recommendations for future work are highlighted in this Section.

7.1 Conclusions

The topography of the BVI in the coastal zone, both onshore and offshore, is the feature dominating this natural capital assessment. In particular:

- The rugged interior means that the main areas of economic activity are particularly vulnerable as it is concentrated low-lying coastal areas primarily for ease of access and construction. In contrast, residents typically live, perhaps from long experience, further up in the hills;
- Maximum water level heights do not have to be great to cover the coastal flats, but then the increasing steepness of the slopes means that relatively few additional properties are flooded for even substantial increases in flood depth. Hence the mitigating impact of reefs is relatively greater for lower category storms.
- Rainfall on steep slopes with limited soil depths leads to fast run-off with velocity dependent on the inclination of slopes which does not affect flooding depths but contributes to degradation through mechanisms such as sediment movement.

There is very little uncertainty in the assessment of the vulnerability of individual buildings and associated economic activity to flooding because of the use of very detailed GIS mapping. The main uncertainty is in the projections of meteorological effects and the physical effects of reefs and these, combined with the knowledge of vulnerability, are the basis of predictions of society's response. The degree to which a need for a response is avoided and society can continue to function as it currently does is the basis of the value of reefs.

Overall, reefs and mangroves are clearly of great value to the BVI and the assessment made here of their marginal value, excluding the structural changes that would follow their loss, shows them to have a value approaching 10% of GDP, which is assessed as a lower bound. While based on broad considerations only, a judgement made here of their potential value which also includes structural effects is that their value could be considered a factor of 2 to 4 times higher.

7.2 Recommendations

In order to improve, confirm and advance estimates of natural capital in the BVI

- To better value the natural capital of vegetation and other natural features involved in providing the ecosystem service function of soil retention and stabilisation:
  - Assess the effects of extreme weather events on existing and potential inland habitats including reinstatement of particular habitat types and further construction and development taking into account associated effects such as interception and infiltration and on the marine environment (such as effects of sediments on reef degradation).
- To better understand the impacts of coastal flooding on individual parts of the coastline of the BVI:
  - Seek better hydrodynamic information for events in addition to the Category 4 storm from a single direction that was used as the main scenario here (the 'R3i' scenario), in particular for lower category storms.
  - Extend analysis of the protective function of mangroves for the whole BVI coastline.

- To extend the analysis to value the related protective function of coral reefs on coastal erosion.
- To confirm the valuation of natural capital provided by reefs and mangroves, better understand the costs to business and their responses to increased impacts from flooding:
  - Seek information on the determinants of the possible reactions of business in particular any thresholds. For example, though questions such as "How frequent would flooding need to occur for you to consider relocation?"

In order to maintain the unique habitats and economic advantages that the BVI currently enjoys

- Recognise the value of reefs to the economy and manage them appropriately to avoid their inadvertent degradation and loss.
- Recognise in general the role of government and government action to fulfil the requirements of business and residents as identified above to ensure flooding does not increase or could be reduced.