The role of mangroves in coastal protection

1. Introduction

Mangroves are an example of wetland ecosystems which fringe the coastline of countries in tropical/sub-tropical regions. They provide a variety of ecosystem services to local populations, including the provision of food and timber products. They also provide a key coastal defence service which has been shown to reduce the impact from coastal hazards.

As seen in the British Virgin Islands, areas of mangrove are rapidly becoming fragmented and destroyed, due to the pressures of new development along the coastline and the impact of increasingly frequent hurricanes. Given the damage caused by Hurricane Irma in 2017 and the vulnerability of small islands states to the impacts of climate change, it has never been more important to conserve and in some cases, restore, the natural protection that is offered by mangrove ecosystems in the BVI.

This information document aims to summarise the best available scientific evidence regarding the role of mangrove ecosystems in coastal protection from wind, swell waves, storm surges and tsunamis; to provide an overview of the key factors which effect the level of protection that is offered and to demonstrate the benefits of protecting mangroves in the British Virgin Islands.

Figure 1.1 Damaged mangrove forests at Paraquita Bay, BVI (2019).

2. How do mangroves protect the coast?

Hurricanes Katrina and Rita in 2005 and the Indian Ocean tsunami of 2004 have provided compelling evidence regarding the value of mangrove protection to scientific researchers, economists and policy-makers alike. The mounting evidence which exists to demonstrate their value as natural measures of disaster risk reduction has led to increased interest in their research, worldwide. The World Bank has highlighted the role of mangroves as a form of sustainable coastal defence, as discussed in the 2016 WAVES report[i]. As a result of their increasingly recognised protective value, there has been growing global interest in their restoration and conservation.[ii]

Figure 2.1 Aerial mangrove roots

For example, according to UNEP the conservation of mangrove forests is directly related to progression towards Aichi Target 14 which, by 2020, aims to "restore and safeguard ecosystems that provide essential services which contribute to health, livelihoods and well-being by taking into account the needs of women, indigenous and local communities." The UN's Aichi Biodiversity targets are part of a strategic plan for biodiversity (2011-2020) to address the underlying causes of biodiversity loss, by mainstreaming biodiversity across government and society

2.1 Wind and swell waves

There is a range of evidence comprising field measurements, numerical studies, laboratory experiments as well as local anecdotal evidence highlights the ability of mangrove forests to attenuate waves and buffer oncoming winds. Mangrove physiology, wave height and forest width are all factors which influence the level of risk reduction they provide.

Generally speaking, wind and swell waves originate from an area of surface water outside of the mangrove forest which has been agitated by the effects of wind. The WAVES report demonstrates that the ability of mangroves to buffer wind speed and reduce wave height relates to a number of forest characteristics, including species composition and the density of vegetation. Wave height, wave period and depth of incoming water column also have contributing effects and can also cause damage to the mangroves themselves.[iii] This is illustrated from the images of post-Irma mangroves at Paraquita Bay.

The way waves are buffered by mangroves is affected by differences in mangrove physiology between species. The WAVES report and McIvor *et al*. (2012) have summarized the current scientific evidence which highlights how physiology can influence wave attenuation. For example, common species of mangrove trees such as the red mangrove (known as Rhizophora) have aerial, claw-like roots which are intended to prop the trees up off the softer sediment in which they grow. However, the aerial roots also have the ability to act as an obstacle to oncoming wave and wind energy, resulting in wave heights reducing as they approach the mangrove area.[iv]

In contrast to the claw-like aerial roots of *Rhizophora*, other species of mangrove – such as *Sonneratia* and *Avicennia* develop what are known as pneumatophores – small, pointy structures that grow up and out of the water column. Their biological role is intended to facilitate root respiration - but also proves very effective at reducing wave height by acting as an obstacle to an oncoming body of water as it moves over.

Even mangrove species without aerial roots or pneumatophores can help protect the coast. For example, *Kandelia candel* species are less efficient at reducing wave heights at shallower depths because they lack these structures. However, their dense foliage higher up in the trees is effective under instances where oncoming waves are deeper – thus slowing and reducing waves as they pass through the thick vegetation.[v] A video clip of a scale model demonstrating the effects of a mangrove forest on waves can be seen here: https://www.youtube.com/watch?v=-WYJc-AtdrY.

Mazda *et al.* (2006) showed in field experiments of typhoons off the coast of northern Vietnam, that in forests made up of *Sonneratia*, rates of wave reduction over 100m belts of mangrove forests were calculated at 45% when water depth was 0.2m, and 26% when water depth was increased to 0.6m. The study also found that the ability of the mangroves to reduce waves decreased with increasing wave depth as the effect of the pneumatophores taper off. However, when water levels then again reach branch height – wave reduction may increase again. Thicker forests provide higher levels of wave attenuation, due to the fact that a central factor effecting wave attenuation is the density or the obstacles encountered by the waves as they pass through.[vi] There are four different species present in the BVI – these include both *Rhizophora* and *Avicennia,* as well as white mangroves (*Laguncularia racemosa*) and buttonwood mangroves (*Conocarpus erectus*).[vii]

Forest thickness is a critical factor - mangroves can reduce the height of wind and swell waves over relatively short distances with attenuation. Over 100m width of mangrove forest, wave heights can be reduced by between 13-66%, while over a 500m width of mangrove forest wave heights reduction is 50-100%. The highest rate of wave height reduction per unit distance occurs near the mangrove edge.[viii,ix,x] During periods of storm surge, significantly thicker forests (>1km) are needed to offer protection. This is discussed under Section 2.3.

2.2 Tsunamis

Quantitative models and evidence from the Indian Ocean tsunami indicate mangroves can reduce the risk to coastal communities from tsunami. However, wave depth is a critical factor. It is estimated that a 500m wide forest can significantly dissipate force of tsunamis under 3m but beyond this – mangroves are likely to become damaged.

While a range of quantitative evidence exists regarding mangrove's ability to attenuate wind and swell waves, there is still some debate in the scientific literature regarding their ability to offer protection from tsunamis. A number of studies using hydraulic modelling and wave channel experiments exist, and in some cases, these models have been validated using data collected in the aftermath of the Indian Ocean Tsunami of 2004. It has been widely reported that extensive forests can reduce loss of life and property damage from tsunamis by absorbing the first brunt of impact, and as such, dissipating wave energy as it approaches the coastline. For example, in the Phang Nga province of Thailand large inland territories were only slightly damaged due to protection offered by surrounding mangrove belt.[xi] Furthermore, post-tsunami studies indicate that human deaths and loss of property was a function of the type and area of coastal vegetation [xii]

To investigate the effectiveness of coastal forests in mitigating tsunami waves, Kh'ng *et al* (2017) developed a 2-D model to quantify the reduction in wave heights and velocities due to the presence of coastal forests. The degree of reduction varies significantly depending on the forest's flow-resistant properties, including vegetation characteristics, forest density and forest width.[xiii] Furthermore, modelling results from Yaganisawa *et al.* 2010 indicate that a 500m wide belt of mangrove forest could potentially reduce the hydrodynamic force of a tsunami by 70% when oncoming waves remained under 3m. However, when wave depth was increased to 4m – the mangrove forest was destroyed. It is therefore important to note that wave depth and forest thickness are critical factor and studies which highlight protection from tsunamis generally consider mangrove belts between 100-500m wide. Hence, isolated mangrove patches may not provide the same level of protection from tsunamis. However, despite forests becoming damaged over a certain wave depth and not offering complete protection it is still likely that forest presence reduces more acute risks to the area behind the mangrove.

2.3 Storm surges

Storms and waves can severely damage mangroves, which is illustrated from the effects of Irma in BVI. However, field observations and quantitative models indicate mangrove forests play a role in reducing the risk of storm surges and coastal flooding. Forest thickness and storm intensity are critical factors in the level of protection provided – during more intense storm surges, mangrove forests need to be thicker to protect the area behind them.

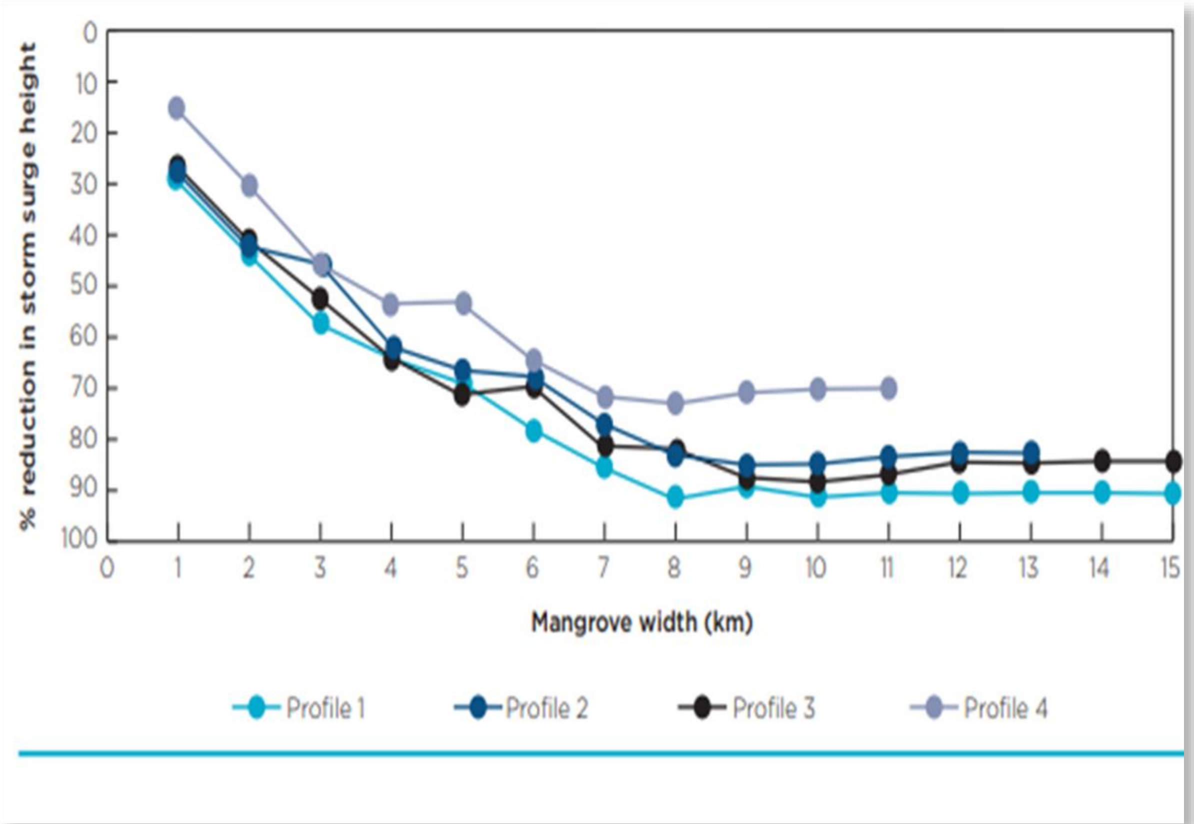
As illustrated by the effects of Hurricane Irma, the BVI is particularly vulnerable to the effects of cyclones, hurricanes and storm surges. These phenomena are caused when high winds and low atmospheric pressure are combined, causing a sharp increase in water levels approaching the coast line, resulting in intense coastal flooding.[xiv] Storm surge is caused by a temporary rise in sea level 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 the cause of much damage in the BVI and the intensity and frequency of tropical storms is important to overall effects on society. It should be noted that studies of mangrove wave attenuation have mostly been focused on smaller waves with less research on hurricane conditions and storm surges.

As explained under Section 2.1, the mitigating effects on wind and swell waves are increased with mangrove forest density and forest thickness. Mangroves can reduce the height of wind and swell waves over relatively short distances with attenuation, but thicker forests are required to protect against storm surge.

In order to reduce storm surge peak water levels – mangroves forests are generally required to be greater than 1km. Field observations and modelled simulations indicate that larger, thicker mangrove forests of 6-30km have a significant role to play in mitigating storm surge damage. This has been illustrated from the results of Zhang *et al.* (2012) off the coast of Florida. The results presented in Figure 2.2 show how mangroves attenuated storm surges through a reduction in both the amplitude and extent of coastal flooding. Freshwater marshes which were located behind the mangrove forests were also protected from saltwater inundation. However, the results also indicate that larger waves can have a damaging effect on the mangrove forest - the Florida mangroves could protect the area behind them against flooding from a Category 5 hurricane with a rapid forward speed of 11.2 meters/second, but not from a Category 5 hurricane with a slower forward speed of 2.2 meters/second.[xv]

As illustrated from the picture of devastated mangroves at Paraquita Bay in the introduction, Hurricane Irma caused extensive damage to the mangroves in BVI – particularly to red mangrove species. Mangroves in Tortola and Anegada also showed signs of damage, with mangroves being the hardest hit type of vegetation from the storms. However, field work assessment indicates that the good quality of native forest (specifically regarding stem diameter and wood density) in Tortola point towards higher levels of forest resilience, and that it is likely that the damaged forests will able to bounce back from the Hurricane impacts. According to field work undertaken by Kew UK & Islands programme, the mangroves show signs of recovering.[xvi]

Figure 2.2 Mangrove width effects on wave height reduction

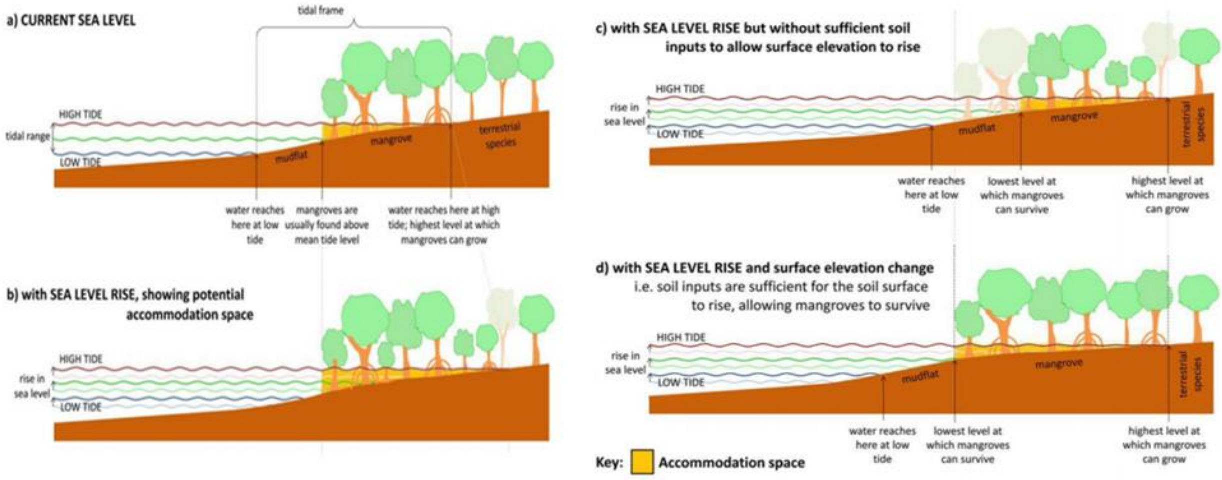


Source: Results of Zhang et al. (2012) presented in WAVES (2016)

3. Factors influencing the level of protection offered by mangroves

As demonstrated in the previous section of this document, the scientific evidence suggests that the quality and spatial extent of mangrove forests, as well as the physiology of mangrove species, can influence the level of protection that is being offered. However, there are other factors which play a role. Historically, mangroves have been shown to adapt well to changes in sea level, due to the ability of these dynamic ecosystems to migrate landward and seaward in response to sea level rise and regression. However, their ability to adapt can be influenced by human related activity. This section will discuss the human-related factors which can have an impact on mangrove health, their ability to adapt to climatic changes and thus the protection they offer to the coastline.

Figure 3.1 Schematic highlighting SLR effects on mangrove forests



Source: WAVES (2016)

3.1 Sea-level rise

Historically, mangroves have demonstrated an ability to migrate landward and seaward with sea level rise and fall. However, it is possible that more rapid rates of SLR and coastal development adjacent to mangroves may hinder their ability to keep pace with rising water.

The relationship between sea-level rise (SLR) and mangrove forests is not yet fully understood. Research has indicated that mangroves can keep pace with rates of SLR due to the ability of their root systems to accrue sediment, allowing them to gradually migrate landward during times of sea level rise, and seaward during times of sea level regression. This phenomenon is widely known, revealed by historical evidence from mangrove soil which can show historical patterns of mangroves over thousands of years.[xvii] Studies indicate that mangroves can generally build up sediment at a rate of 1-10mm/year – thus keeping pace with gradual increases in SLR.[xviii]

However, it is possible that SLR may negatively impact those mangroves where sediment levels can't keep pace with rates of rising water levels – especially in those areas where the mangroves ability to migrate landward is disturbed by coastal development or fixed terrestrial forest. This scenario is illustrated in Part C of the schematic diagram shown in Figure 3.1[xix]. If sediment can't accumulate and sea level rise occurs too rapidly for mangroves to keep pace – forests can die off rather than moving inland.

The term "adaptive" capacity" is used to describe the ability of a species or ecosystem to accommodate or cope to the impacts of climate change with minimal disruption. The adaptive capacity can be bolstered through natural response, or by human actions that can help to reduce the vulnerability of ecosystems to environmental changes.[xx] Hence, sustainable management of existing mangroves by local stakeholders can influence the resilience of mangroves to the potential threat of SLR. As an example, limiting the coastal development of hard structures immediately adjacent to mangrove forests which may affect sediment load and potentially obstruct their inland migration. This could maximise their chances to adapt to SLR threats. – something that is particularly relevant to small islands states in the Caribbean.

3.2 Mangrove management

Given the effects of forest thickness and species physiology on reducing wind and wave height, and the affect that human activity can have on their adaptive capacity – mangrove management is an integral component of maximising the level of protection and maintaining their function as sustainable risk reduction measures. In order for mangroves to contribute optimally to risk reduction – conservation needs to be incorporated into broader coastal and marine management policy, especially regarding the inclusions of currently intact forests into protected areas.[xxi] Furthermore, early restoration or damaged mangroves can bolster the provision of their protective service in the future.

Restoration and replanting

Mangrove replanting schemes increased following the Andaman tsunami of 2004. The success of replanting and restoration schemes has been variable, particularly due to the sensitive nature of young mangrove saplings to sedimentation and water inundation. Within a restoration area in Malaysia, seedling mortality 90 and 120 days after replanting was 75 and 93%, respectively. Furthermore, the restoration process requires careful planning regarding choice of appropriate species, identification of viable restoration zones. It also requires technical inputs from a multi-disciplinary team e.g., engineers, hydrologists and ecologists to identify the site-specific needs of each restoration scheme.[xxii] Common mistakes of restoration projects include[xxiii]:

- Neglecting to choose the correct species for the site in question: single species replanting schemes host less biodiversity and are more likely to collapse all at once. Diverse forests are more resilient.
- Choosing sights which are too exposed for saplings that are very sensitive to soil erosion and wave action. Pre-existing mangrove sites can offer protection for saplings, rather than trying to plant on new sites that have been cleared of mangroves.[xxiv] Hence, even damaged mangrove sites could serve the purpose of a nursery area for restoration scheme, due to shelter offered by remaining vegetation.
- Neglecting to involve the local community: Communicating economic and social benefits of restoring mangroves to the community and local infrastructure is an important part of successful restoration schemes.

Useful guides have been developed by organisations with practical experience of restoration schemes, including:

- The Mangrove Action Project (MAP) have published their experience and offer training in mangrove restoration using a community-based approach.[xxv]
- Wetlands International have published guidance on *"To plant or not to plant"* – which offers high-level assessment for policy makers on the feasibility of restoration success at a site.[xxvi]

Mangrove conservation

Given the sensitivity of mangrove saplings during restoration, and the breadth of considerations to be made for successful regrowth – it is very likely that conserving intact mangrove forests is the most meaningful way of maximising the optimal level of protection they offer. This is reiterated by the fact that wind and wave attenuation is most effective when thick, healthy forests are considered. The economic value of mangrove ecosystem services is well-established in the literature, as summarized in the WAVES report, because of the protection they can offer to coastlines, yet missing markets (which do not consider the value of ecosystem services or natural capital) and pressure from development have contributed to rates of mangrove deforestation being greater than what is socially optimal.

The degradation of mangrove systems is an expensive example of natural capital depreciation. Pressure from development, and the intense impacts of hurricane Irma has taken its toll on BVIs mangrove forests – but mature, healthy trees have been maintained.[xxvii] As illustrated in the recently developed guide for natural capital accounting in the UK Overseas Territories published by the JNCC, the OTs face many challenges as they develop policies for economic development and enhanced environmental management, while trying to build resilience to the impacts of climate change. However, understanding the value of natural capital assets – such as mangroves – and the benefits they offer can help incentivise their conservation and protection.[xxviii] Modelling the level of protection offered by mangroves in the BVI and understanding their economic value could be considered as a first step to incorporating their value into fiscal planning, and thus allow for meaningful conservation.

Figure 3.2 Mangrove forests in Paraquita Bay, BVI, 2019

4. Mangroves as carbon stores

More recently, research into the potential of mangrove forests for climate change mitigation has also been investigated.[xxix] Such research has been bolstered by recent policy initiatives such as REDD+ and The International Blue Carbon Initiative which aim to offer financial incentives for preserving the carbon storage potential of forests and coastal ecosystems – both ecosystem classifications which mangroves fall under.[xxx]

Mangroves have also been recognised as one of the most globally important stores of carbon, holding up to four times more carbon than other tropical forests, a characteristic likely to be an important future regulating service given expected global warming.[xxxi] This is particularly relevant for those small island states in the Caribbean, including the BVI, where the reality of climate change poses threats which include intensified natural disasters and sea-level rise.[xxxii]

Standard environmental economic theory shows that climate change mitigation is a public good, while adaptation is a private good. This is due to the fact that the benefits of reducing national carbon emissions effect everyone, while the abatement costs accrue solely to the country investing in the mitigation measures. This contrasts with adaptation, as the benefits of investing in adaptation measures to the effects of climate change accrue privately - only to that country.

Adaptation and mitigation are both vitally important in protecting against climate change, particularly in the context of the Caribbean. In the coastal zone, adaptation seeks to reduce the adverse effects and costs of storm surges and sea level rise when they occur (i.e. via the construction of breakwaters) while mitigation seeks to reduce the risks of climate change externalities in the future, through the reduction of national CO_2 emissions. This highlights that even for those patches of mangrove forest which appear to be badly damaged from the impacts of natural disasters or human activity and as such, may not offer much coastal protection when considered in isolation – there remains an incentive to engage in conversation or restoration programmes. Such action would not only potentially replenish the damaged forests but contribute to an overall national reduction in CO_2 emissions.

5. Key messages for policy makers

Overview

- Conservation of healthy mangrove forests can be viewed as an adaptive measure, reducing the risk of wind and waves to coastal communities as a form of sustainable coastal defence. It is important to note that forest quality influences the amount of protection that is offered. Hence, the conservation of currently healthy forests is integral to ensuring the future provision of this protective service. Mangrove protection may also be bolstered by restoration schemes – which need to be planned carefully to ensure success. Investing in mangrove management can be framed as a strategic national investment in private coastal adaptation.
- Damaged mangrove forests can also serve the purpose of a mangrove nursery – providing natural shelter to sensitive saplings in restoration programmes. This may encourage the survival rate of saplings during replanting schemes and thus contribute towards securing healthy mangrove forests in the future – and the future provision of their protective service.
- In addition to their protective value, due to the amount of carbon stored in mangrove forests, their conservation can also be framed as investing in climate mitigation, as reducing their deforestation for development contributes to overall CO_2 emissions reduction. Even those mangrove areas which have been damaged by natural disasters and human activity serve the purpose of carbon mitigation – as the deforestation of mangroves may release four times more carbon than clearing other kinds of vegetation

Lessons from the UK Caribbean Overseas Territory of the British Virgin Islands

- The hurricanes of 2017 had a major impact on the Caribbean Overseas Territories of Anguilla, British Virgin Islands and the Turks and Caicos Islands. The United Nations Economic Commission for Latin America and the Caribbean estimates total damage caused across all three OTs as over US$3 billion xxxiii with approximately two thirds of this attributable to damage ('societal, infrastructure and productive') in the BVI.
- UK Government supported work in the Caribbean British Virgin Islands has demonstrated the role of the natural environment in mitigating storm surge impacts on property and infrastructure in the coastal zone

with coastal mangrove and reefs playing a key role. The functional significance of these environments in absorbing storm surge energy has significant monetary value in terms of 'avoided costs.'xxxiv,xxxv

- Approximately 40% of the BVI infrastructure that supports the tourist sector (restaurants, hotels etc) falls within 2 metres of sea-level. The average storm surge for a Category 2 hurricane (the most commonly occurring hurricane event in the region) is 2.1 metres and the high concentration of economically important assets in the coastal zone of the BVI, and other islands, means significant economic assets are at risk from coastal zone flooding.xxxvi
- The role of mangroves in reducing storm surge wave height, in combination with reef and other coastal systems (Figure 2.2), is therefore crucial to protecting life and property in low lying coastal zones. Work undertaken by Wood and the UK's Joint Nature Conservation committee (JNCC) in the Caribbean Overseas Territories of Anguilla and the BVI suggests that 'avoided costs' associated with the storm surge mitigation provided by coastal zone environments in the region is equivalent to at least 10% of the GDP of these two islands.

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Issued by

Ellen Cunningham

Approved by

Chris Fawcett

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