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Storm Surge Reduction by Mangroves

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The Nature Conservancy's **Natural Coastal Protection** project is a collaborative work to review the growing body of evidence as to how, and under what conditions, natural ecosystems can and should be worked into strategies for coastal protection. This work falls within the Coastal Resilience Program, which includes a broad array of research and action bringing together science and policy to enable the development of resilient coasts, where nature forms part of the solution.

The **Mangrove Capital** project aims to bring the values of mangroves to the fore and to provide the knowledge and tools necessary for the improved management of mangrove forests. The project advances the improved management and restoration of mangrove forests as an effective strategy for ensuring resilience against natural hazards and as a basis for economic prosperity in coastal areas. The project is a partnership between Wetlands International, The Nature Conservancy, Deltares, Wageningen University and several Indonesian partner organisations.

About The Nature Conservancy

The mission of The Nature Conservancy is to conserve the lands and waters upon which all life depends. For general information, visit: www.nature.org. For more information about the Natural Coastal Protection project, visit: www.naturalcoastalprotection.org and www.coastalresilience.org.

About The Cambridge Coastal Research Unit

The Cambridge Coastal Research Unit is based in the Department of Geography in the University of Cambridge. It aims to provide the high quality scientific research to underpin sustainable coastal management. For more information, visit: http://www.ccru.geog.cam.ac.uk/ and http://www.geog.cam.ac.uk.

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The mission of Wetlands International is to sustain and restore wetlands, their resources and biodiversity. Wetlands International is the only global non-profit organisation dedicated to the conservation and restoration of wetlands. It works through a network of 18 offices and many partners and experts to achieve its goals. For more information, visit http://www.wetlands.org/.

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Executive Summary

Storm surges occur when high winds and low atmospheric pressure raise water levels at the coast, causing sea water to surge onto the land. They are a major threat to low-lying coastal areas and their inhabitants. The largest storm surges are caused by tropical cyclones (also called hurricanes and typhoons in different regions); peak water levels can exceed 7 m in height, and can result in extensive flooding, loss of life and damage to property. Global climate change may result in increased storm surge flooding in some areas, through intensification of the cyclones driving the storm surges and as a result of sea level rise.

Mangroves can reduce storm surge water levels by slowing the flow of water and reducing surface waves. Therefore mangroves can potentially play a role in coastal defence and disaster risk reduction, either alone or alongside other risk reduction measures such as early warning systems and engineered coastal defence structures (e.g. sea walls).

Measured rates of storm surge reduction through mangroves range from 5 to 50 centimetres water level reduction per kilometre of mangrove width. In addition, surface wind waves are expected to be reduced by more than 75% over one kilometre of mangroves.

Few data are available on surge reduction rates through mangroves because of the difficulties associated with measuring water levels during storm surges. All data currently available are from the south-eastern United States, where networks of recorders have been placed in wetland areas. Numerical models and simulations, validated using this data, provide the only means of exploring the importance of different factors in reducing storm surge heights.

The numerical model of Zhang *et al.* (2012; Estuarine, Coastal and Shelf Science 102: 11-23) suggests that mangroves are more effective at reducing the water levels of fast moving surges than those of slow moving surges. The model also indicates that water level reduction through mangroves is non-linear, with the greatest reduction in surge height occurring near the seaward edge of the mangroves. Seaward of mangroves, a bulge of water can form as the water piles up in front of the mangroves; this can increase storm surge levels in this area.

Several topics relating to storm surge reduction by mangroves are yet to be explored, such as the effect of mangrove density, species composition and vegetative morphology. Dense mangrove forests, including species with aerial roots, are expected to increase storm surge reduction rates.

By reducing water levels and wave energy, mangroves can save lives and reduce storm-surge related damage to infrastructure: during a typhoon in north-east India, mangroves reduced the number of lives lost, as well as reducing damage to houses, crops and possibly coastal defence structures. Mangroves can also help people recover after coastal disasters by providing firewood, building materials and food sources (e.g. fish and shellfish that live among mangrove aerial roots).

Cyclones and storm surges also impact mangroves themselves; some trees may be defoliated or uprooted. Extreme events with very high water levels and wind speeds may severely damage or destroy mangrove areas, rendering them less effective at reducing surge heights. Natural recovery can take many years to decades; restoration projects may speed up recovery.

Further data on storm surge reduction by mangroves and further refinements to numerical models and simulations will improve our ability to understand and quantify the coastal defence services provided by mangrove forests against storm surges. Such information is needed to ensure that the coastal defence functions of mangroves are utilised appropriately, either alone or in combination with other measures, to reduce risk to people and infrastructure from storm surges.

CONTENTS

Introduction to the Natural Coastal Protection Series

The world's coastal margins are among the most densely populated and intensively used places on Earth. Coastal populations are growing rapidly, as is associated infrastructure, industry and agriculture. These populations and coastal lands can be at risk from natural hazards such as waves, storms and tsunamis. The numbers of people at risk are increasing with the expansion of human populations, and the risks will likely be exacerbated by the effects of climate change and associated sea level rise. At the same time, coastal ecosystems are also impacted as populations expand, reducing ecosystem resilience and their ability to provide ecosystem services such as coastal defence.

In the face of growing risks and vulnerability, increasing attention is being given to adaptation and disaster risk reduction in the coastal zone. An array of measures can help reduce the vulnerability of coastal populations, including: changes to planning and development patterns in near-shore zones; development of early warning systems and hazard response strategies; and coastal defence measures that maintain, enhance or develop structures or features that reduce the risk of impacts on coastal populations and lands. Against this background there have been growing calls for the consideration of the role of natural coastal ecosystems in coastal defence. Claims have been made that some coastal ecosystems, including mangrove forests, coral reefs and salt marshes, can help to reduce the risk associated with some coastal hazards. Such ecosystems also provide a host of associated ecosystem services which may be lost if natural systems are degraded or converted to alternative land uses.

If a case is to be made that ecosystems form a realistic part of coastal adaptation, however, it will depend on having a solid science foundation, and on the ability to predict when, and under what conditions, the ecosystem may be able to function effectively as a defence against coastal hazards. The Natural Coastal Protection Series are a series of technical reports investigating the role of ecosystems in coastal defence. The reports aim to summarize current information relating to this topic in a way that is accessible to a broad spectrum of people, including scientists, coastal engineers, decision makers, site managers and conservation advocates. The reports also aim to introduce the topic such that non-experts are able to understand and assess the current state of knowledge.

1. Introduction

This report explores the capacity of mangroves to reduce storm surge water levels and inundation, and hence to reduce the impact of storm surges on coastal populations and infrastructure.

Storm surges are movements of sea water onto land, caused by high winds and low atmospheric pressure raising water levels at the coast, so that the sea literally "surges" onto the land. Storm surges can be highly destructive, sometimes causing the loss of thousands of lives and extensive damage to property (Table 1). An extreme example was the 7 m high storm surge that hit the south-west part of Bangladesh in 1991; the storm surge was caused by a cyclone with a maximum recorded wind speed of 225 km/hr, and 138,000 people lost their lives (Bern *et al*., 1993; Matsuda, 1993). Storm surges are a major risk in many low-lying coastal areas (Storch and Woth, 2008), and in terms of loss of life and property, they are probably the most destructive natural hazards of geophysical origin (Flather, 2001). Section 1.1 and Box 1 describe storm surges in more detail.

Global climate change may result in increased storm surge flooding in some areas, both through intensification of the cyclones driving the storm surges, and from underlying sea level rise (Mousavi *et al.,* 2011). The overall extent of regions susceptible to tropical cyclones and their associated storm surges may also increase geographically (Flather, 2001). In addition, the increasing numbers of people living in low-lying coastal regions result in greater risks from coastal flooding, as more people live in exposed areas and more infrastructure is built there to accommodate them (McGranahan *et al.*, 2007; Kron, 2008).

Table 1. Examples of some major storm surges over the past century. Data on these cyclones and associated storm surges sometimes vary between sources, and this is probably related to actual uncertainty e.g. in numbers of deaths or value of losses, and to different locations where wind speed and storm surge water levels were measured. *PWL: Peak water level (see Box 2); SSHWS: Saffir-Simpson Hurricane Wind Scale (see Box 3 below). Additional data from Blake (2011) and National Hurricane Center (2012a).

Name of cyclone	Year	Location	Surge PWL* (m)	Wind speeds (km/hr)	SSHWS* category	Deaths	Losses (US $)	Sources
Extratropical storms – southern North Sea								
North Sea Flood	1953	Southern North Sea	3.0	75		1,783		Garrison, 1999; Pugh, 1987
Tropical cyclones – Atlantic Ocean								
Hurricane Carol	1954	Rhode Island	5	185	3	60	41 million	Garrison, 1999
Hurricane Camille	1969	Mississippi coast	7	305	5	256	1.4 billion	Garrison, 1999; Pugh, 2004
Hurricane Andrew	1992	South Florida and Louisiana	5.1	280	5	26	30 billion	Garrison, 1999; Pugh, 2004; NHC 2012b
Hurricane Katrina	2004	Gulf coast	8.5	190	3	1200	125 billion	Kron, 2008, NHC; 2012b
Tropical cyclones – Indian Ocean								
Cyclone Bhola	1970	Bangladesh	10 - 12	222	3	300,000		Garrison, 1999
Cyclonic storm BOB 01	1991	Bangladesh	5 - 8	225	4	138,000		Matsuda, 1993; Bern *et al*., 1993
Cyclone 05B	1999	Orissa, India	7 to 8	250	4	10,000		Pugh, 2004
Cyclone Nargis	2008	Myanmar	5	210	4	138,000	10 billion	Fritz e*t al*. 2009

In areas that are particularly susceptible to storm surges, a variety of measures are usually in place to protect people and property. Structural measures include sea walls and levees, and these are used alongside early warning systems, evacuation plans and refuge. Recently, there has been increasing interest in the use of ecosystems as a cost effective form of coastal defence against hazards such as storm surges; for example, mangrove restoration projects often cite coastal protection as one of the benefits that the restored mangroves will provide (Tri *et al*., 1998; Jegillos *et al*., 2005; Primavera and Esteban, 2008; Erwin, 2009; Powell *et al*., 2011). While it is clear that the dense vegetation of a mangrove forest can significantly reduce wind and swell waves over a few hundred metres (McIvor *et al*., 2012), there is less evidence supporting the ability of mangroves to reduce storm surges. Such information is urgently needed for people to assess when and where mangrove forests can form part of a coastal defence strategy against surges.

Mangroves are coastal forests found in tropical and sub-tropical regions, many of them in areas subject to cyclones, hurricanes and typhoons and their associated storm surges. Local people often believe that mangroves can provide protection from storm surges (Walters, 2003 and 2004; Badola and Hussain, 2005; Walton *et al*., 2006; Walters *et al*., 2008; Warren-Rhodes *et al*., 2011). This report reviews available information about the capacity of mangroves to reduce storm surges, in order to inform decision makers, planners and coastal engineers about the potential role that mangroves can play in coastal defence against storm surges. Where mangroves can contribute important coastal defence functions, there may be considerable benefits to ensuring their inclusion in coastal planning and adaptation strategies. Such coastal defence functions are in addition to the multitude of other benefits provided by mangroves, such as firewood, materials for building, and food in the form of shellfish and fish that live among the mangrove roots (Barbier *et al*., 2011).

The first section of this report provides some basic information about storm surges and the factors affecting surge levels and surge reduction. Section 2 explores the evidence for mangroves reducing storm surge water levels, followed by Section 3, which focuses on the attributes of mangroves that affect the level of storm surge reduction. Section 4 reviews the effect of mangroves on surface wind speeds, which affect wave generation and hence surge water levels. Section 5 reviews the literature on the ability of mangroves to reduce loss and damage caused by storm surges. Section 6 then explores how mangroves are themselves affected by storm surges and cyclones.

1.1 Storm surges

Storm surges may be defined as abnormally high sea water levels in coastal areas caused by a short-lived atmospheric disturbance such as a hurricane or storm. Box 1 compares the characteristics of storm surges with tsunamis, tides and other sea waves.

Storm surges are created by tropical cyclones (also called hurricanes and typhoons in different geographical regions), extratropical storms (mid-latitude frontal storms or mid-latitude depressions) and other types of atmospheric disturbance such as polar lows (Storch and Woth, 2008); the different characteristics of tropical cyclones and extratropical storms are shown in Table 2. Tropical cyclones are usually more intense but of shorter duration and less extensive spatially. They typically originate in the tropics, but can travel to sub-tropical latitudes. The following descriptions and explanations relate primarily to tropical cyclones and the storm surges they produce, because tropical cyclones are the dominant atmospheric disturbance in areas where mangroves are found.

Box 1. Comparing storm surges, tsunamis, tides and other water waves

Table 1.1 compares the characteristics of storm surges with other types of sea waves. Storm surges differ from tides and tsunamis in that the increased water levels during a storm surge are caused by atmospheric disturbances, as opposed to astronomical forces, which cause lunar or solar tides, or crustal disturbances, i.e. earthquakes, volcanic eruptions or landslides, which can cause tsunamis (Groen and Groves, 1962). Storm surges interact with astronomical tides, and are at their most dangerous if they coincide with a high spring tide, when even a modest surge can create a significant flooding hazard (see Section 1.1.1).

Storm surges act like very high tides, except that the rise in water level is unpredictable and faster than during normal tidal changes in water level (Garrison, 1999; Krauss, 2009). Storm surges differ from tsunamis in that tsunamis may affect much larger areas of coasts, usually consist of several waves, come onto land much more rapidly than storm surges, and also flow off the land more rapidly. Storm surges and tsunamis can result in similar depths of flooding and inundation extents.

Table 1.1. Different types of waves, the physical mechanisms causing them and their wave periods (the time between two successive peaks passing a given point; see Fig. 1). *For storm surges, this time period refers to the duration of the change in water level experienced at the coast. (From Massel, 1996; Pugh, 1987; Groen and Groves, 1962).

Wave type	Physical mechanism	Wave period
Wind waves	Wind shear, gravity	< 15 s
Swell waves	Wind waves with a longer period and wavelength that were created far from the shore. Shorter period wind waves travel more slowly, are dissipated more quickly and some of their energy is subsumed by the longer waves, resulting in only the longer waves reaching distant shores.	< 30 s
Tsunami	Earthquakes, volcanic eruptions, landslides, submarine slumping	10 min – 2 hours
Tides	Gravitational action of the moon and sun, earth's rotation	12 – 24 hours
Storm surges	Wind stresses and atmospheric pressure variation in combination with local bathymetry and geomorphology (occur during storms, hurricanes, cyclones, typhoons)	1 hour to 4 days*

Storm surges can temporarily increase coastal sea levels by several metres (Table 1 and 2). Tropical surges are relatively short-lived phenomena, with raised water levels usually lasting for less than 12 hours (Groen and Groves, 1962); their interaction with tides is described in the next section. The raised water levels flood coastal areas, and this can cause loss of life and property and damage to infrastructure and agriculture (Table 1). Surges can be particularly destructive on micro-tidal, low wave energy coasts, where high water levels are extremely rare and the design of local infrastructure may not take such events into consideration.

Table 2. Comparison of storm surges caused by tropical cyclones and extratropical storms (adapted from Storch and Woth, 2008)

Parameter	Tropical cyclone	Extratropical storm
Spatial scale of storm	500 ± 200 km	1000 ± 500 km
Surge height	Larger; extreme surge heights between 5 and 12 m (Table 1)	Smaller: extreme surge heights between 2 and 4 m
Surge duration	Several hours, up to half a day	2-5 days
Length of coastline affected by the surge	Usually < 200 km	Several hundred kilometres

1.1.1 Timing of surges relative to astronomical tides

Storm surges are particularly dangerous when they coincide with high spring tides. In areas with large tidal ranges, the timing of the surge relative to the tidal level is critical, and can make the difference between a storm surge having little effect and causing major flooding (Flather, 2001). Figure 1 shows the changes in predicted tidal level, storm surge, and observed water level (storm tide) during a storm surge in Bangladesh in 1970. The highest surge height occurred slightly after the predicted high tide; if the two had occurred simultaneously, the peak water level (highest storm tide) would have been higher than observed.

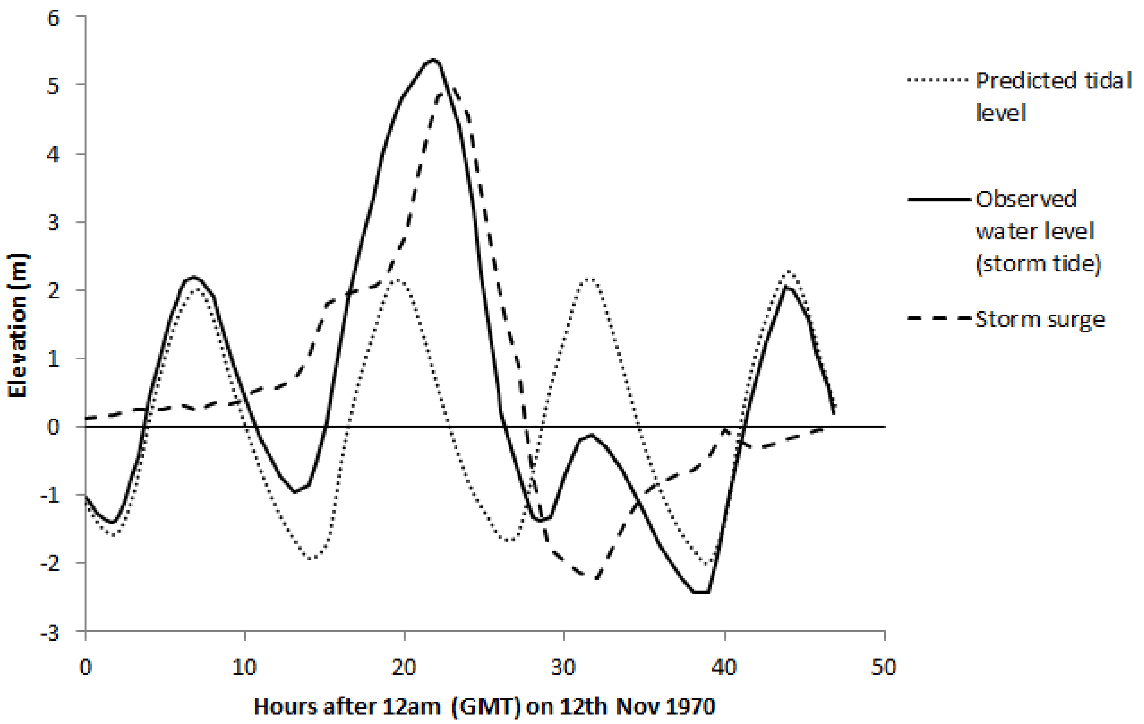

Figure 1. The observed water level, predicted tidal level and storm surge residual at Sandwip Island, Bangladesh, during the storm surge of 12-13 November 1970. The peak water level was 5.4 m at this location. Adapted from Flather (2001).

1.1.2 Where do tropical storm surges occur?

Figure 2 shows the storm tracks of tropical cyclones between 1985 and 2005, illustrating how tropical cyclones, and the storm surges they create, are most common on the eastern shores of North America, South East Asia and southern Africa, the west coast of Mexico and Central America, within the Bay of Bengal and along the northern coast of Australia. Very few cyclones or storm surges occur along the equator, around the coast of South America or on the west coast of Africa. Tropical cyclones only form where sea surface temperatures exceed 26.5 ºC (i.e. they do not form in the temperate zones); their formation is dependent on the local vertical component of the Earth's rotation (the Coriolis effect), and this explains why they do not form within 5º of the equator (Flather, 2001). Atmospheric disturbances that form over the warm tropical oceans are generally carried westward by the easterly trade winds (Ahrens, 2007), resulting in hurricanes occurring more frequently on the eastern margins of land masses.

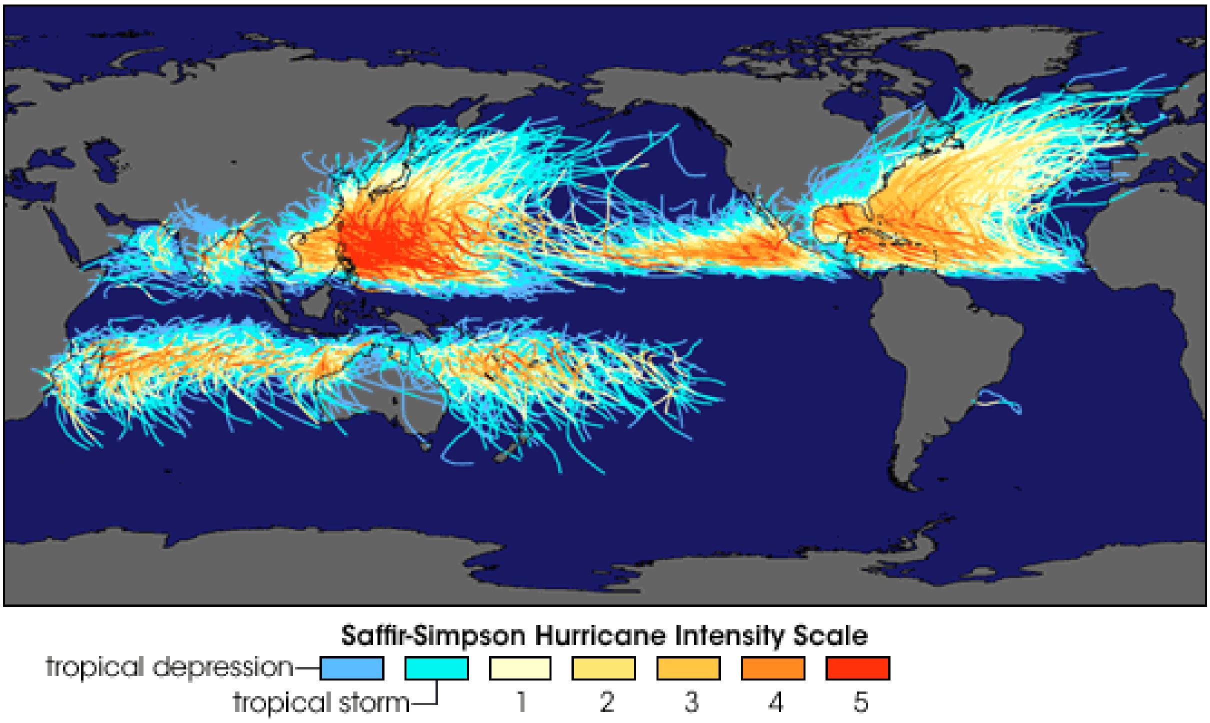

Figure 2. The tracks of tropical cyclones that formed between 1985 and 2005. The colours represent the strength of the cyclone according to the Saffir-Simpson Hurricane Wind Scale (see Box 3 for a description of this scale). (Image by Robert A. Rohde, Global Warming Art, NASA Earth Observatory; http://earthobservatory.nasa.gov/IOTD/view.php?id=7079.)

1.1.3 Characteristics of storm surges

Storm surges are measured in a number of different ways, and these ways are summarized in Box 2. The destructiveness of a storm surge depends on:

- the inundation extent, i.e. the area that is flooded;
- the depth of flooding and the peak water level, i.e. the maximum depth of the water;
- the duration of inundation (this may be a particular issue for agricultural areas, where crops may survive brief floods, as described in Badola and Hussain, 2005);
- the height of the waves riding on top of the storm surge, which may cause more severe damage to structures;

Box 2: Measures of storm surges

Various characteristics of storm surges are measured in order to describe the surge:

- **Storm surge** (also called **storm surge height** or **amplitude**) is the difference between observed water levels during the surge and predicted water levels caused by astronomical tides (Box 1 and Section 1.1.1). The precise technical term for this is the **non-tidal residual** or **surge residual** (Flather, 2001; Pugh, 2004); throughout this report we use the term “storm surge height”. Calculating the storm surge residual from the observed water level (storm tide; see below) and predicted tidal level is complicated by the fact that the two interact: for example, the timing of the astronomical high tide may shift because the tidal wave is travelling through deeper water (Groen and Groves, 1962). Therefore it is not possible to simply subtract the predicted tidal level from the observed water level to estimate the surge residual. However in many cases simple subtraction can provide an adequate estimate of the surge residual. **Skew surge** is also used to refer to the difference between the highest observed water level and the predicted water level of the nearest high tide (de Vries *et al*., 1995).
- **Storm tide** refers to the total water depth above a reference level, usually mean sea level. It includes both the storm surge and the tidal level. For example, a 2 m storm surge on top of a 0.6 m tide produces a 2.6 m storm tide (National Hurricane Center, 2012b; Figure 1.1).
- **Peak water level** is usually used to refer to the highest water level experienced during a storm surge in a particular area, i.e. the largest storm tide recorded during a particular storm surge in that area. It usually refers to the **still water level** i.e. the water level without the effect of waves. Still water levels can be difficult to measure; an example of a still water level would be the height that water reached within a building where waves did not enter.
- **Inundation extent** refers to the area of land flooded during the storm surge. This can often be estimated from lines of debris made up of grass, seeds, and rubbish (National Hurricane Centre, 2012b). The **flooded volume** is the volume of water that floods onto land. As flooded volume increases, so does inundation extent; the relationship between the two will depend on local topography.

For more information about how these are measured in the field, see the National Hurricane Centre (2012b) document “Introduction to Storm Surge”.

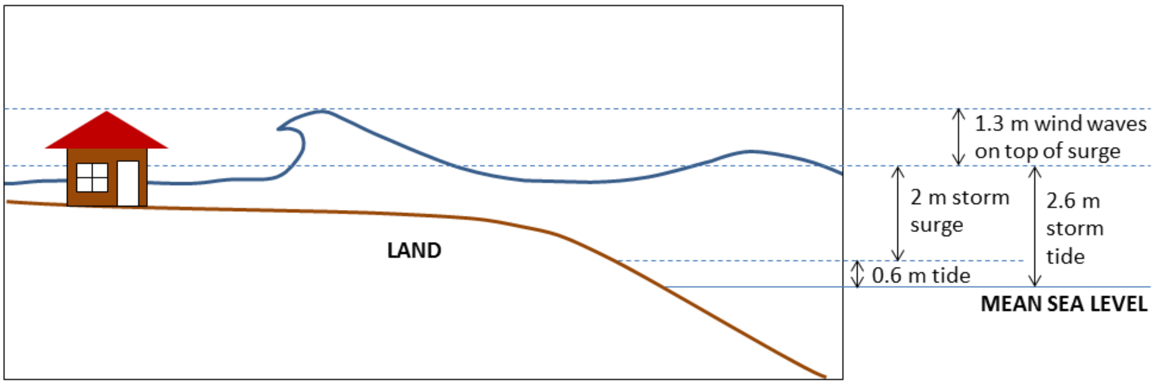

Figure 1.1. Schematic diagram of a storm surge, showing Mean Sea Level (MSL), the predicted high tide (0.6 m), the storm surge residual (2 m), the storm tide (2.6 m) and the wind waves on top of the surge (an additional 1.3 m). (Figure adapted from a diagram in National Hurricane Centre (2012b) document, “Introduction to Storm Surge”.)

- and the strength of currents that are generated within the water body, which can cause coastal erosion (Flather, 2001).

Tropical storm surges are usually accompanied by very high winds and heavy rainfall which may also cause extensive damage.

Other characteristics of storm surges include the speed of travel of the surge, which is measured as the velocity of travel of the peak water level, and the storm track, i.e. the location and direction of travel, which interact with the local bathymetry, topography and geomorphology to influence the peak water level and inundation extent (described in more detail in Section 1.3).

While tropical cyclones are routinely assigned a category based on their maximum sustained wind speeds (Box 3), storm surges are quantified using measures such as storm surge height, storm tide, peak water level, and inundation extent, as described in Box 2. Storm surge height is only partially related to the category of a cyclone, as many other factors also affect it, as described in Box 3 and Sections 1.2 and 1.3 below.

Box 3. The relationship between hurricane category and storm surge

Hurricanes in North America are routinely assigned a category according to the Saffir-Simpson Hurricane Wind Scale (Simpson, 1971; Table 3.1). Earlier versions of the scale included central atmospheric pressure and storm surge height as components of the categories (Simpson, 1971), but the scale has recently been revised such that the categories are based on maximum sustained wind speeds only (Schott *et al.*, 2012). This is because the inclusion of storm surge height within the categories can be misleading, as even a low category storm can produce a large surge (Table 3.1). This is because various factors other than wind speed affect the surge produced, notably hurricane areal extent (i.e. the geographical extent of hurricane-force winds), local bathymetry (i.e. the depth of near-shore areas), local topography, the hurricane’s forward speed, and the angle at which the hurricane approaches the coast (Schott *et al*., 2012). These factors are discussed in more detail in Section 1.3 below. Alternative classifications are often used for typhoons and cyclones in India, Japan, Australia and the Southwest Indian Ocean; these have different names for the categories, boundaries between categories, and different ways of measuring maximum wind speeds.

Table 3.1. The Saffir-Simpson Hurricane Wind Scale categories and wind speeds, with examples of hurricanes in each category, showing the peak water levels of the surges.

Saffir-Simpson Scale		Example	
Category	Sustained wind speed (km/hr)	Name of hurricane	Surge height (m)
1	119-153	Hurricane Irene (2011)	3.4
2	154-177	Hurricane Ike (2008)	6.1
3	178-208	Hurricane Katrina (2005)	8.5
4	209-251	Hurricane Charley (2004)	2.4
5	252+	Hurricane Camille (1969)	6.9

1.2 Forces creating tropical storm surges

Several forces contribute to creating a storm surge, as shown in Figures 3 and 4. For tropical storm surges, the largest forcing is created by the cyclonic winds. Wave set-up can also contribute a large part of the surge level. The rise in water level due to the low atmospheric pressure is relatively small by comparison. The different forcings are described in more detail below. (The following descriptions are simplified and omit much of the complexity of storm surge dynamics; for more detailed descriptions of storm surge forcings, see Flather (2001), Resio and Westerink (2008) and other references included in the text below.)

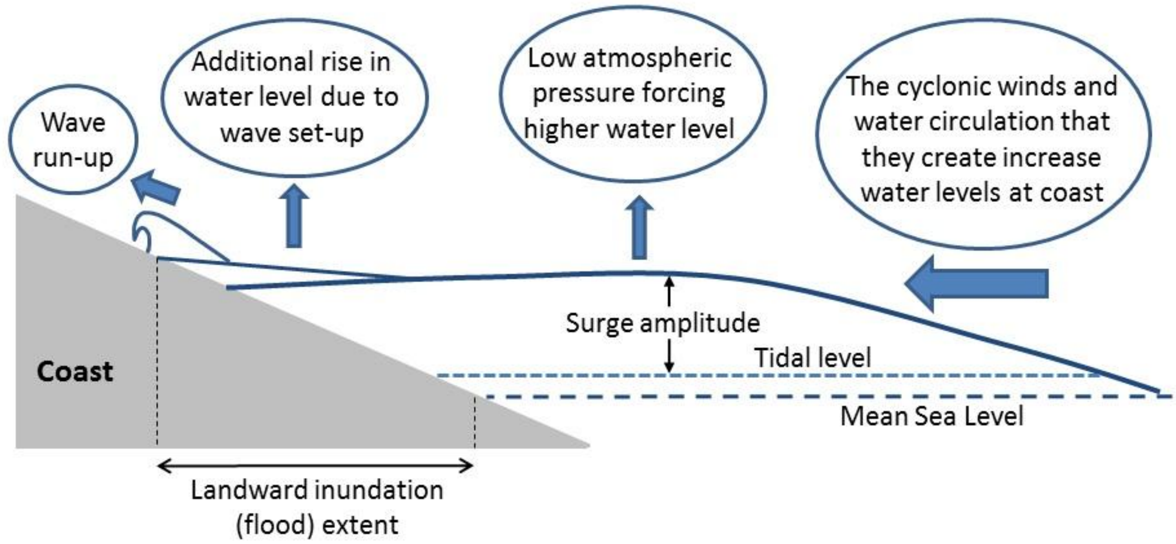

Figure 3. Schematic diagram showing how tropical storm surges are created, with the different forces involved.

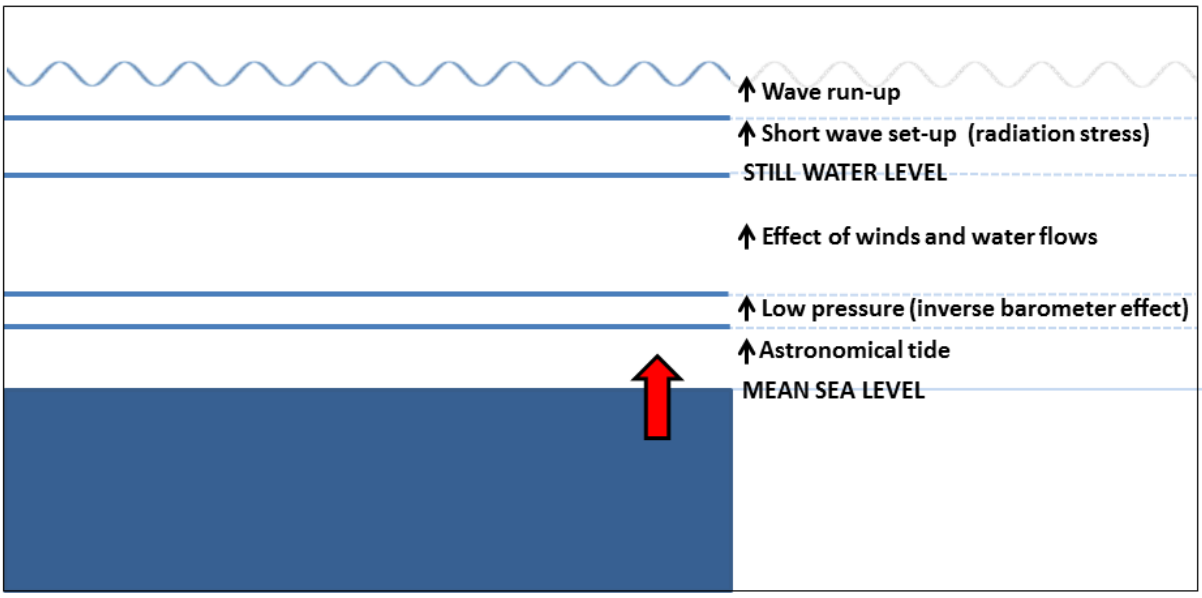

Figure 4. Schematic diagram of the relative contributions of the different forcings that produce a storm surge, approximately showing their relative magnitude, although this will vary greatly with each storm surge (for example, sometimes astronomical tide will be below mean sea level; the relative importance of short wave set-up is still under discussion, see text). (Adapted from Graber *et al*., 2006).

As described in Section 1.1.1, storm surges occur on top of **astronomical tides**, and the tidal level can have a large influence on peak water levels in areas with large tidal ranges. Astronomical tides are caused by the gravitational forces from the moon and sun, and tidal ranges can be greater than 6 m in some areas (Woodroffe, 2002).

The **low atmospheric pressure** present in the centre of tropical cyclones results in a dome of water forming, as the sea responds to atmospheric pressure variations by adjusting sea level, such that the water pressure at depth is uniform (Flather, 2001). This is called the inverse barometer effect, and a decrease in atmospheric pressure of 100 pascals (≡ 1 millibar) produces an increase in sea level of approximately 1 cm (Flather, 2001). The maximum water level increase caused by this effect is approximately 1 m. Before the cyclone reaches the shore, this effect is responsible for the majority of the storm surge height.

The **high winds** associated with cyclones are the strongest force increasing storm surge height when the cyclone nears the coast, as wind forcing is greatest in shallow water (Flather, 2001). The winds increase water levels in several ways. Winds blowing toward the shore create water flows in the same direction, creating a water surface elevation gradient and increasing water levels at the coast (Flather, 2001). Winds blowing parallel to the shore create a net transport of water to the right of the direction of the wind in the northern hemisphere, and to the left of the direction of the wind in the southern hemisphere, in a process called Ekman transport (Stull, 2000); this can also pile up water along a shoreline. Another mechanism results from the cyclonic winds setting up a circular motion within the water, with the water being forced either clockwise or counter-clockwise (in the southern and northern hemisphere respectively), and towards the centre; this forces water to flow downwards towards the sea floor in the centre. In shallow water, this downward flow of water is blocked, resulting in a dome of water forming at the surface (Simpson and Riehl, 1981; Masters, 2012).

The waves created by the high winds produce **wave set-up**, which also contributes to increased water levels. Wave set-up occurs when waves break onto the shore; the set-up produces a rise in the mean water level above the still water level of the sea (Komar, 1998). The set-up can be observed as an upward slope of the water towards the land (Komar, 1998; shown schematically in Figure 3). Wave set-up is caused by the transfer of wave momentum to the water column that occurs when waves break; this forces a change in the water level (Weaver, 2004) (this effect is also referred to as radiation stress). In Florida, Dean and Bender (2006) estimated that wave set-up could contribute 30 to 60% of the total 100-year return period storm surge peak water levels.

When the waves break, the water rushes up the shore until the energy in the flowing water is dissipated by friction and by its work against gravity. This final flow of water from breaking waves is called **wave run-up**, and the zone receiving only run-up is called the swash zone.

1.3 Factors affecting surge height and surge reduction

In addition to the forces described in Section 1.2, a number of other factors also affect surge height and extent, either increasing it (e.g. estuaries may funnel water, resulting in increased water levels and inundation extent) or decreasing it (e.g. surface friction can slow water flows, lowering surge height and inundation extent). These additional factors include:

- **hurricane size** (measured as the radius of maximum winds): hurricanes with large geographical extents generate higher peak water levels and greater flooded volumes (i.e. larger inundation extents, dependent on local topography) (Rego and Li, 2009);

- **hurricane forward speed**: surges created by hurricanes with faster forward speeds are expected to create higher surges, but lower flooded volumes (and therefore smaller areas of inundation). Surges with lower forward speeds produce more flooding but lower peak water levels (Rego and Li, 2009);
- **near-shore bathymetry**: coastal shelves with large shallow-water areas produce larger surges than steep off-shore slopes (Flather, 2001; Resio and Westerink, 2008; Rego and Li, 2009);
- **geometry of the coastline**: concave coasts concentrate the surge into a smaller area, resulting in higher water levels, while when the coast is more convex, the water is able to flow sideways and the surge height is reduced (Flather, 2001);
- **inland channels interconnecting water bodies**: these allow the surge to flow more easily and quickly through the landscape, and the surge can propagate further inland;
- the **storm track** has a major effect on the characteristics of a storm surge, through the interaction between the cyclone and landscape features (i.e. coastline geometry and coastal topography), which may affect the build-up of water. For example, Hurricanes Donna and Betsy occurred in the same area (the Florida Keys) and were of comparable size and intensity (they were category 4 and category 3 hurricanes respectively when they made landfall in Florida). However, the south to north track of Hurricane Donna produced a 4 m storm surge in the Middle Florida Keys, while the east to west track of Hurricane Betsy across Florida resulted in a smaller 3 m storm surge at Biscayne Bay (Perkins and Enos, 1968); and
- **frictional resistance,** usually referred to as **surface roughness**, of the land surface: surface roughness is affected by topographic features, ecosystems (e.g. mangroves and saltmarshes), and man-made structures. Increased surface roughness will slow the rate at which water flows inland, and also lead to a steepening of the surge front (i.e. water levels rise more quickly in any given location) (Resio and Westerink, 2008).

1.4 Storm surge reduction by mangroves

Of the factors known to affect surge height that are described above, mangroves directly affect surface roughness (discussed in Sections 2 and 3), height of surface wind waves (Section 3.2 and McIvor *et al*., 2012), and the speed of the wind directly over the water surface within areas where the vegetation reaches above the water level (Section 4).

Over the longer term (decades to centuries), mangroves can also alter the surface elevation of the shore (influencing the bathymetry and topography), the local geometry (e.g. through progradation, which is the expansion of wetland areas towards the sea) and the location of channels (Spencer and Möller, 2012; McIvor *et al*., in prep), all of which also influence the height of surges (Section 1.3 above).

In this report we focus on the ability of mangroves to reduce storm surge water levels through their immediate effect on surface roughness and wind waves. In separate reports, we describe the attenuation of wind and swell waves by mangroves in more detail (McIvor *et al*., 2012) and the change in surface elevation within mangroves (McIvor *et al*., in prep.).

2. Evidence for storm surge reduction by mangroves

Evidence for the ability of mangroves to reduce storm surges and associated damage comes from three sources: direct observations of water level heights (Section 2.1); the use of well-validated numerical models that simulate storm surge behaviour in the presence or absence of mangroves (Section 2.2); and observations of the damage caused and the number of lives lost from storm surges (Section 5).

2.1 Water level observations

Very few studies have measured storm surge water levels within mangrove areas. Here we describe the study by Krauss *et al*. (2009). Zhang *et al*. (2012) also have water level data, which they use to validate numerical models of storm surges, as described in Section 2.2 below. For comparison, estimated reductions in peak water levels through saltmarshes are given in Table 3; these range from 1.7 to 25.0 cm/km.

To investigate whether mangroves can reduce the height of peak water levels as storm surges pass through, Krauss *et al*. (2009) analysed water level measurements in wetland areas during Hurricanes Charley (2004) and Wilma (2005) in Florida (Table 4). They used a network of water level recorders that collected water level data at hourly intervals in two different wetland ecosystems containing mangroves and saltmarshes (Table 4), as described below.

As the storm surge from Hurricane Charley passed through the Ten Thousand Islands National Wildlife Refuge (NWR), the peak water level reduction was 9.4 cm/km through an area that included both mangroves and saltmarsh. The following calculations based on data given in Krauss *et al.* (2009: Figure 2 and p. 145) show how the reduction in peak water level through the mangrove area may have been higher. At the first recording point 2.3 km from Faka Union Bay, the peak water level was 78.6 cm above ground level and 43.6 cm above the expected high tide level; at the second recording point 3.2 km further inland, at the transition between the mangrove and the marsh, the peak water level was 40 cm above ground level and 29.6 cm higher than the water level prior to the arrival of the storm surge. This implies a decrease in peak water level of 14.0 cm (reduction in water level relative to high tide/antecedent water levels) over 0.9 km, equivalent to a reduction in peak water level through mangroves of 15.8 cm/km.

Table 3. Measured rates of storm surge reduction across coastal marshes in Louisiana. Most of the data (except the first two rows) are based on a data-set from Hurricane Rita collected by McGee *et al.* (2006).

Hurricane (year, category)	Location	Vegetation type	Surge reduction (cm/km)	Reference
Multiple (1907-1957)	Louisiana	coastal wetlands	6.9 (range 1.7 to 20)	US Army Corps of Engineers (1963) in Engle (2011) (also referred to in Wamsley *et al*. (2010) and Krauss *et al.* (2009))
Andrew (1992; cat. 5)	Louisiana	marsh and open water	4.4 to 4.9	Wamsley *et al*. (2010) and Engle (2011) using data from Lovelace (1994)
Rita (2005; cat. 3)	Cameron Prairie, Louisiana	marsh	10.0	Wamsley *et al*. (2010), calculated with data from McGee *et al*. (2006)
Rita (2005; cat. 3)	Sabine, Louisiana	marsh	25.0	Wamsley *et al*. (2010), calculated with data from McGee *et al*. (2006)
Rita (2005; cat. 3)	Vermillion, Louisiana	marsh	4.0	Wamsley *et al*. (2010), calculated with data from McGee *et al*. (2006)
Rita (2005; cat. 3)	Vermillion, Louisiana	marsh	7.7	Wamsley *et al*. (2010), calculated with data from McGee *et al*. (2006)
Rita (2005; cat. 3)	Louisiana	marsh	13.5 (range 3.3 to 23.3)	Kemp (2008), based on data from McGee *et al*. (2006)

As the storm surge from Hurricane Wilma passed through the mangrove forest along the Shark River in the Everglades National Park, peak water levels were reduced by 4.2 cm/km; this was measured across 3 recording stations set back from the river by 50 to 80 m. The highest water level reduction was between the 2 inland stations that were located 9.9 and 18.2 km from the mouth of the river: peak water level fell from 104.0 cm to 46.2 cm, equivalent to a peak water level reduction of 6.9 cm/km. Between the seaward recording stations located 4.1 and 9.9 km from the river mouth, there was a slight increase in water level, presumably because of river water backing up behind the surge (Krauss *et al*., 2009).

Krauss *et al.* (2009, p. 147-8) conclude by pointing out that “while our observations indicate that water levels were reduced as storm surge moved though coastal mangrove ecosystems, uncertainty remains over the relative contribution of mangroves over other wetland types, open water or microtopographic relief along the Gulf Coast over similar distances”; i.e. it is unclear what the contribution of mangroves was to the reduction in peak water level, as it is impossible to control for these other factors that may also affect water level changes. Because of this, numerical models that include this greater range of factors have an essential role to play in helping us understand the relative contribution of mangroves to storm surge reduction; such models are described in the following section.

Table 4 Peak water level reduction during storm surges passing through mangrove wetlands in Florida (data from Krauss *et al.*, 2009). Hurricane categories refer to the Saffir-Simpson Hurricane Wind Scale (Schott *et al*., 2012; Box 3). *These statistics have been calculated from data in Figure 2 of Krauss *et al.* (2009), as described in the text above.

Location	Associated hurricane	Wetland type	Water level recording points	Peak water level height reduction (cm/km)
Ten Thousand Islands National Wildlife Refuge, Florida, USA	Hurricane Charley, a category 4 hurricane, 13 August 2004, with maximum sustained winds of 240 km/hr at landfall; the location of peak water level travelled at 0.4 km/hr	mangrove/ interior marsh community; in mangrove area, dominant species was *Rhizophora mangle*	4 points approx. 1 km apart and in line with each other, laid out in a landwards direction; area between 1st two points was mangrove, other areas were salt marsh	9.4 across all 4 recording points, which included salt marshes and mangroves; 15.8 in mangrove area*
Along the Shark River (Everglades national Park) in south western Florida, USA	Hurricane Wilma, a category 3 hurricane, 24 October 2005, with maximum sustained winds of 195 km/hr and a very wide eye 89 – 105 km in diameter (Smith *et al*., 2009); location of peak water level travelled at 1.4 km/hr up river; peak water level 5 m in some locations; the hurricane crossed the Florida peninsula in 4.5 hours	riverine mangrove swamp, dominant species is *Rhizophora mangle* (Chen and Twilley, 1999)	recorders placed 50-80m from the river's edge at river-km 4.1, 9.9 and 18.2	4.2 across all 3 recording points; -0.2 between lower pair of recorders due to river water backing up, 6.9 between upper recorders

2.2 Numerical modelling studies

Numerical simulations of storm surges that are well-validated against field observations offer a complementary approach to understanding the factors affecting storm surge water levels. When such simulations can be shown to accurately represent storm surge behaviour in the presence of mangroves, then they may be used to look at the effect of varying parameters such as storm surge height, forward travel speed and the width of the mangrove forest, as described below. Such models might also be applied to predicting storm surge reductions due to existing mangroves or planned mangrove restorations.

Four studies that have used numerical modelling approaches to better understand the factors affecting storm surge inundation in mangroves are summarised below. The first two studies relate specifically to mangroves; the second two studies are based on models that include vegetation which is relatively similar to mangroves.

2.2.1 The ELCIRC model

Xu *et al*. (2010) used an unstructured Eulerian-Lagrangian Circulation (ELCIRC) model (Zhang *et al*., 2004) to model the surge from Hurricane Andrew (1992; category 5; Table 1) at Biscayne Bay on the east coast of Florida. They found that their model overestimated peak water levels and flooding extent in the southern part of the bay, an area containing mangrove zones with widths of 1 to 4 km and tree heights of 1 to 20 m. This suggested that land cover types, in particular the large areas of mangroves, were having significant effects on flood levels and extent. To improve the accuracy of the storm surge simulation, they incorporated the effect of land cover into the model by varying Manning's coefficient, a measure of surface roughness (described in more detail in Box 4). They tested three different values of Manning's coefficient (0.05, 0.1, and 0.15) for areas with mangroves, and found that surge inundation extents most closely matched the observed debris line when a coefficient of 0.15 was used (a Manning's roughness coefficient of 0.15 is relatively high, and is typical of dense woodlands; Box 4). They concluded that changes in roughness coefficients due to vegetation can significantly influence the local inundation patterns during storm surges.

2.2.2 The CEST model

Zhang *et al*. (2012) used a different model, the Coastal and Estuarine Storm Tide (CEST) model, to simulate the passage of Hurricane Wilma (category 3; more storm characteristics given in Table 4) as it passed over the Gulf Coast of South Florida in 2005. This is a 200 km length of coastline, with a mangrove belt varying between 6 and 30 km in width. The mangrove trees are 4 to 18 m high, with stem diameters of 5 to 60 cm, and scrub mangrove is found further inland; the dominant species are *Rhizophora mangle, Laguncularia racemosa* and *Avicennia germinans*. Hurricane Wilma resulted in extensive coastal flooding with a maximum storm surge of 5 m (Smith *et al*., 2009). Zhang *et al*. (2012) were able to compare the model's outputs with abundant field data describing water levels, collected by various agencies including NOAA, USGS, FEMA and academic researchers.

In particular, Zhang *et al*. (2012) focused on whether the model's predictions were improved by including mangroves in the model. The geographical extent of mangroves was taken from the National Land Cover Dataset created by the US Geological Survey in 2001. Following Xu *et al*. (2010), the drag force from mangroves was included in the model by adjusting Manning's roughness coefficient. While Xu *et al*. (2010) used a Manning coefficient of 0.15, Zhang *et al*. (2012) reduced it to 0.14 because of the large number of lakes, rivers and creeks inside the mangrove zone in this area.

Box 4. Manning's Roughness Coefficient *n*

Manning's roughness coefficient (also called Manning's friction factor, denoted by the symbol *n*) is one of the most important parameters for describing water flow over surfaces (Li and Zhang, 2001). It is used to quantify the resistance to flow in channels, floodplains and areas affected by storm surges (Chow *et al*. 1988). It includes the shear stress caused by the boundary roughness (i.e. friction between the fluid and the surface), and, when vegetation is present, it also includes a drag force caused by the vegetation (Jin *et al*., 2000). It is usually considered to be dimensionless (Chow, 1959; see p. 98-99 for a discussion of this issue).

Manning's *n* has been empirically measured for a variety of surfaces that may occur in river channels and floodplains; Table 4.1 gives some values for various surfaces. On floodplains, *n* usually varies with the water depth, and is highest when the water is shallow (Chow, 1959). In vegetated areas, *n* can also vary with season and is highest in the growing season (Chow, 1959).

Table 4.1 Manning's roughness coefficient (Chow,1959; Mattocks and Forbes, 2008).

Land use type	Manning's coefficient
Open water/sand	0.02
Scattered brush/shrub/scrub	0.05 (0.035 to 0.07)
Forest/estuarine forested wetland	0.10 (0.08 to 0.12)
Dense woods (e.g. dense willows)	0.15 (0.11 to 0.20)

Zhang *et al*. (2012) ran simulations using: i) a constant Manning coefficient of 0.02 for all spatial cells (a Manning coefficient of 0.02 is typical of the seabed, and so in this simulation, mangroves were not included) and ii) with varying Manning coefficients that reflected the presence of mangroves in some cells. The best match between the simulation and the observed data was seen when mangroves were included in this way; the root mean square error of computed peak surge heights versus observed ones decreased from 0.60 m (mangroves not included) to 0.39 m (with mangroves included). The inundation areas predicted by the model were 4,220 km^2 without mangroves and 2,450 km^2 with mangroves, suggesting that mangroves had a large effect on the inundation extent. Flooding was restricted within the mangrove zone when mangroves were included in the model, and this matches well with the measured inundation extent taken from surge-induced sediment deposits, which were limited to a zone less than 14 km from the Gulf of Mexico.

Storm surge reduction rates were between 20 and 50 cm/km through the mangrove areas (Zhang *et al.,* 2012). The simulations indicated that without the mangrove zone, surge amplitudes would decrease by 6 to 10 cm/km. The simulations suggested that storm surge reduction was non-linear across the mangrove width, and this is discussed further in Section 3.1 below.

While the peak water level height was reduced as the storm surge passed through the mangroves, Zhang *et al*.'s (2012) simulations showed a 10-30% increase in water levels in front of the mangrove zone, compared to simulations without mangroves. This is because the mangroves act as an obstruction to the flow of water, causing water to build up in front of them. Increased friction within mangroves may also lead to a steeper surge front as the surge moves inland (Resio and Westerink, 2008).

2.2.3 A model exploring wave set-up

In addition to the long period wave that makes up the storm surge, short period wind waves are often present on top of the storm surge. These wind waves increase the damage caused by the storm surge, and can increase the area that is flooded through wave set-up. However, such wind waves may be reduced by mangroves over relatively short distances: small wind waves can be reduced in height by more than 75 to 100 % over 1 km of mangroves (Mazda *et al*., 2006; Quartel *et al*. 2007; these values are calculated from the wave reduction rates per metre given in these original studies, using equation 2 from Mazda *et al*., 2006; note that these wave reduction rates were not measured during storm surge conditions). Wave reduction is expected to be dependent on the surge water level and the density of vegetation (i.e. aerial roots or branches); the largest rates of wave reduction occur when the waves encounter the densest vegetation (Quartel *et al*., 2007). Therefore mangroves may be able to significantly reduce wave set-up and run-up during storm surges, thereby reducing impacts on local infrastructure.

Dean and Bender (2006) used a numerical modelling approach to explore the effect of vegetation (modelled as an array of cylinders) on wave set-up. They found that when waves are modelled based on the Airy wave theory (linear wave theory), which assumes that wave height is small compared to water depth and wave length (Komar, 1998), vegetation in shallow water should reduce the set-up to one-third of the amount that would have been present without vegetation. Vegetation in deeper water may result in a set-down (i.e. a reduction in water level), and the water depth at which this change from a set-up to a set-down occurs is kh, where k is the wave number ($= 2\pi$ / wavelength) and h is the still water depth (i.e. depth without waves). For waves modelled using non-linear wave equations (based on third-order equations, which no longer assume that wave height is small relative to water depth; Stive and Wind, 1982), vegetation also resulted in a set-down (Dean and Bender, 2006). Dean and Bender's results are as yet unvalidated, but they suggest that vegetation such as mangroves could have a very large effect on storm surge water levels in those areas where wave set-up makes a large contribution to the raised water levels.

2.2.4 A model of the storm surge and wind waves from Cyclone Sidr

Tanaka (2008) developed a different approach to numerically model the storm surge from Cyclone Sidr, which made landfall in Bangladesh in 2007. He modelled the passage of short period wind waves (wave period 1 or 2 minutes) and a longer period storm surge (wave period 1 or 2 hours) through trees; both types of waves were modelled separately and in combination. The modelled vegetation characteristics were based on the non-mangrove tree species *Casuarina equisetifolia*; trees were modelled as cylinders, 10 m high and 16 cm in diameter, with 0.35 trees/m^2 in a triangular arrangement. He used a one-dimensional non-linear long wave differential equation to explore different short wave and long wave storm surge conditions and wind conditions, in the presence or absence of a 150 m wide band of vegetation. The underlying topography and vegetation measurements matched those seen in transects in Mathbaria, Bangladesh, and the model results were compared with observations of how this area was affected by Cyclone Sidr.

Using his model, Tanaka (2008) found that a 150m band of vegetation had a small effect on the wind's ability to raise water levels (assuming wind speeds of 60 m/s, but not including wind waves); the water level was 4 cm lower behind the vegetation than would be expected with no vegetation present. Vegetation had no effect on the water depth caused by the long wave component (i.e. the storm surge) although the vegetation slightly decreased the velocity of water inside the vegetation zone and the arrival time of the peak of the storm surge. When wind waves were included on top of the storm surge as short waves with a period of 1 or 2 minutes, the water depth behind the vegetation was reduced by 12 or 28 cm respectively (compared to no vegetation being present). This supports the idea that the largest effect of vegetation on storm surge water levels may be through their effect on the short-period wind waves on top of the surge.

Additionally Tanaka (2008) explored the effect of changing the ground slope. He found that when the gradient of the land was 1 in 500 (as opposed to 1 in 100, as used in the previous model runs), and with a long wave with a period of 2 hours and short waves with a period of 2 minutes, water depth behind the vegetation was 80 cm lower than it would have been without the vegetation. Tanaka concluded that the vegetation had a larger effect on reducing water depths (i.e. storm surge water levels) when the storm surge was passing over a lower angle slope (i.e. closer to horizontal).

The results from Tanaka's model broadly match observations: Tanaka (2008) reported that during cyclone Sidr in Bangladesh in November 2007, a 150 m band of river-side vegetation near Mathbaria may have caused a 0.5 to 1.0 m difference in water level (including the effects of wind and swell waves) behind the trees. The observed reduction in water level was based on interviews with local people about where the water reached.

Tanaka's model demonstrates that a relatively narrow band of trees (150 m) may result in a fairly large reduction in water levels (0.8 m), when the effect of vegetation on wind waves is also taken into account. Further research is needed to verify this result for mangroves.

3. Factors affecting storm surge reduction in mangroves

Storm surge reduction through mangroves is expected to depend on a number of factors including: mangrove characteristics, such as forest width, tree density and structural complexity (roots, stems, branches and foliage) of the dominant species; physical characteristics, such as the presence of channels and pools, and the topography of the area (both are influenced by mangroves); and storm characteristics, such as the size and forward speed of the cyclone (which may interact with mangroves to influence storm surge reduction). In this section we review what is known about how these different factors affect storm surge reduction. Few quantitative data are available; where data exist, they are generally derived from numerical models rather than observations.

3.1 Mangrove width

Measurements of storm surge reduction rates through coastal wetlands are often quoted as a certain number of centimetres of water level reduction per metre of inland distance, usually measured in the direction of travel of the surge (e.g. Tables 3 and 4). However such constant attenuation rates imply a linear reduction in water level with distance into the mangroves (i.e. mangrove width). This is rarely true, both because the landscape is usually heterogeneous (i.e. it is usually a mixture of channels, pools and vegetation with a varied topography), and also because the underlying rate of reduction might not be linear even if the environment were homogeneous, as described below. Consequently, such attenuation rates should be regarded with caution. At best they may serve as rules of thumb around which there is usually a high degree of scatter (Resio and Westerink, 2008; Wamsley *et al.*, 2010). Taking this into account and based on the studies described in Section 2, the rate of reduction of surges through mangroves appears to range between 5 and 15 cm/km (observed reduction rates; Krauss *et al*., 2009) up to 50 cm/km (well-validated numerical models; Zhang *et al*., 2012).

Zhang *et al*. (2012) used the simulations described in Section 2.2.2 to explore the effects of different widths of mangroves being present, and they found that surge attenuation through mangroves was non-linear: the largest reduction in peak water levels occurred at the seaward edge of the mangroves, while further inland the water level changed more slowly (Figure 5). They suggest that this might explain the relatively low rates of peak water level reductions measured by Krauss *et al*. (2009; described in Section 2.1), whose measurements start some distance into the mangroves; the water level reduction in the most seaward mangroves might have been higher.

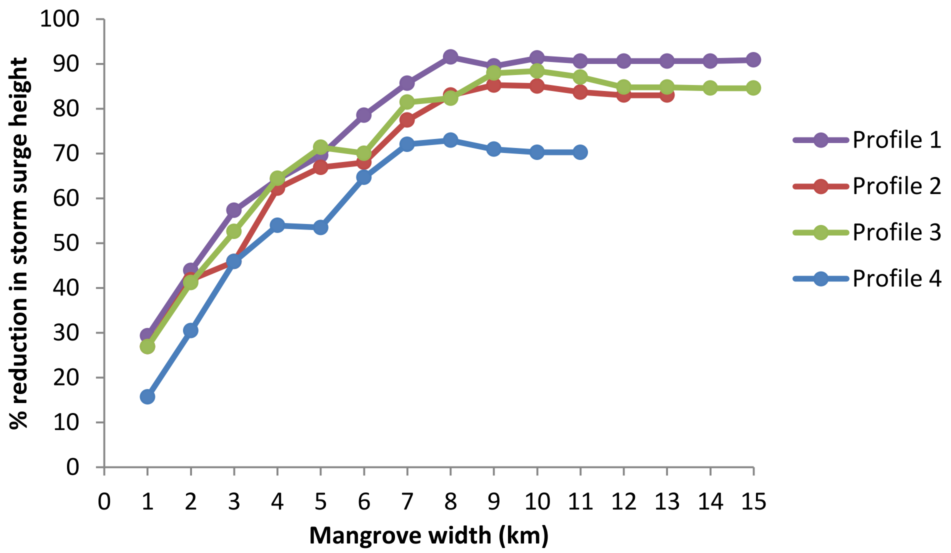

Figure 5. The reduction in storm surge height as the mangrove belt width increases for four different shore profiles (adapted from Zhang *et al*., 2012).

3.2 Mangrove vegetation characteristics

The density of mangrove vegetation and the diameter of aerial roots and stems are expected to affect the ability of mangroves to reduce storm surge water levels (Krauss *et al*., 2009; Alongi, 2008). However, few data are yet available to support this assumption.

Mazda *et al*. (1997a) studied tidal flows, which are relatively similar to storm surge flows, in an area with young *Kandelia candel* trees (less than 7 years old). They found that the tides rose faster at the early stage of the flood tide and fell more slowly at the latter stage of the ebb tide than in a nearby location without mangroves. They attribute this difference to the flow resistance from the mangrove vegetation and the bottom mud. They note that the changes in flow speed were considerably smaller than those seen in mangrove swamps dominated by *Rhizophora* spp. or *Bruguiera* spp., as measured by Wolanski *et al*. (1992) and their own unpublished data. Unlike *Kandelia candel,* these other species have prop roots or pneumatophores, which are likely to slow water flows more than the trunks of *Kandelia* (Mazda *et al*., 1997a).

Mazda *et al*. (1997b) created an "effective vegetation length scale" to quantify the effect of mangrove vegetation on tidal flows. The effective vegetation length scale is calculated from the projected area (i.e. silhouette) of the vegetation and the volume of the vegetation, and varies with tidal depth. Mazda *et al*. (1997b) conclude that mangrove species, density and tidal level strongly affect the hydrodynamics in mangrove forests.

The characteristics of mangroves known to reduce wave height are also likely to reduce wave set-up and wave run-up. The most important mangrove characteristic for reducing wave height is the projected area of vegetation (i.e. the silhouette of the vegetation, as seen from the direction of on-coming waves) (Quartel *et al.*, 2007). Dense forests containing species with aerial roots and dense canopies are therefore expected to reduce waves and wave set-up more efficiently. However most studies of wave attenuation in mangroves have focused on much smaller waves than those usually seen during storm surges (wave heights studied have mostly been less than 70 cm. (See McIvor *et al*. (2012) for a detailed review of this topic.)

3.2.1 Including vegetation characteristics within numerical models

Improved representation of vegetation (i.e. mangroves or saltmarshes) in numerical surge models could increase the accuracy of estimates of inundation extent and duration (Medeiros *et al.,* 2012). In order to include variation in mangrove density or morphology in numerical models such as the CEST model used by Zhang *et al*. (2012; Section 2.2.2), Manning's roughness coefficient would need to vary in a way that realistically reflected the geographical variation in mangrove characteristics. Currently, roughness is estimated from the National Land Cover Dataset (NLCD); land cover types such as grassland, woody wetland, open water and commercial uses are distinguished, and each of these is associated with a range of Manning's coefficient values.

Medeiros *et al.* (2012) tested the validity of using the NLCD to estimate roughness. They directly estimated Manning's roughness coefficient at 24 sites affected by storm surges in Florida, based on a visual assessment of vegetation density, microtopography and obstructions (e.g. tree stumps) using descriptions and images in Arcement and Schneider (1989). They then compared these observed values with the values of Manning's roughness coefficient estimated from the NLCD classification of the site. At some of the sites, their estimate of Manning's coefficient was quite dissimilar from the roughness coefficient based on the NCLD. This could be because of variability of surface roughness within land-cover types, original misclassification of the land cover type, or a lack of information about the roughness coefficient for some land cover types. They suggest that LiDAR (Light Detection and Ranging) data could be used instead of land cover data derived from aerial photographs to estimate Manning's roughness coefficient for use in numerical storm surge models. Methods are being developed to estimate surface roughness from LiDAR data (Straatsma, 2008; Forziera *et al*., 2010); this approach would allow local variation in mangrove vegetation to be included in storm surge models as variation in the surface roughness coefficient.

An alternative approach to including variation in vegetation in numerical storm surge models has been proposed by Sheng *et al*. (2012). They propose a three-dimensional numerical model of storm surges based on the coupled CH3D-SWAN (Curvilinear-Hydrodyamics 3D – Simulating Waves Nearshore) model (more information about the SWAN model is given in Booij *et al*.,1999, and Suzuki *et al*., 2011). Sheng *et al*. (2012) demonstrate the model by simulating the flow of a surge through vegetation similar to that found in marshes. The model allows them to vary the height, density and width of the vegetation, and they find that increases in height, density and/or width result in a reduction in inundation volume. Their model is yet to be applied to mangrove vegetation.

3.3 The presence of channels and pools within mangrove areas

Both Krauss *et al*. (2009) and Zhang *et al*. (2012) consider the presence of channels and pools as likely to decrease the ability of mangroves to reduce peak water levels, because the water is able to pass more easily along the rivers and penetrate further inland.

Krauss *et al*. (2009) recorded higher rates of reduction of peak water levels in intact, relatively unchannelized expanses of mangroves in the Ten Thousand Islands NWR than through riverine areas along the Shark River (9.4 cm/km versus 4.2 cm/km respectively). However they point out that such differences may have been due to differences in the storm characteristics or other factors. The peak water level also travelled more quickly up the Shark River mangrove area (1.4 km/hr in the Shark River area, compared to 0.4 km/hr in the Ten Thousand Islands NWR).

Zhang *et al*. (2012) found that surge height decreased at a rate of 23 cm/km through an area with a mixture of mangrove islands and open water, while in areas with less open water, surge height reduction rates ranged from 40 to 48 cm/km.

3.4 Topography

Topography is the most important local factor affecting inundation from storm surges, interacting with the peak water level to influence the extent of inundation. In addition to the potential interaction between topography and mangrove vegetation in reducing storm surge water levels (Tanaka, 2008, as described in Section 2.2.4), mangroves also affect local topography over the longer term through their effect on tidal creeks. The channels that usually drain wetland areas and the levees that form around these channels increase topographic roughness, thereby increasing drag on water flows, and potentially reducing storm surge water levels. Mangroves play a role in maintaining such features, both influencing creek depth and strengthening the banks of creeks (Spencer and Möller, 2012).

Mangroves influence creek depth as follows: once submerged during tidal inundation, the surface roughness induced by the trees holds back the water on the ebb part of the tidal cycle (during the falling tide), while water levels in the creeks themselves fall rapidly. This causes water surface slopes as high as 1 m per 1000 m; the high water surface gradients result in large tidal ebb flow velocities within the creeks once the water levels fall below their bank height (Wolanski *et al*., 1992). These high flows within the creeks help to maintain the network of creeks (Wolanski *et al.,* 1992). Mangrove species composition and morphology may influence ebb flow velocities (and hence possibly creek networks): species with dense prop roots and pneumatophores, e.g. *Rhizophora* and *Bruguiera*, may hold the water back more effectively than species without, resulting in higher flow velocities within creeks as the tide lowers (Mazda *et al*., 1997b).

The roots of mangrove trees also hold the soil together, reducing bank erosion, and trap sediments, causing the formation of levees near creek margins (Thom, 1967; Augustinus, 1995; Spencer and Möller, 2012). Some species of mangroves may reduce bank erosion more effectively than others; for example, Teas (1980) suggests that black and white mangroves (*Avicennia germinans* and *Laguncularia racemosa*) form denser mats of roots than red mangroves (*Rhizophora mangle*), and are therefore more able to stabilize shorelines. Likewise, species composition can influence accretion of sediment, with higher rates of accretion observed under the prop roots of *Rhizophora* than the pneumatophores of *Sonneratia* in Micronesia (Krauss *et al*., 2003).

3.5 The size and speed of the cyclone and storm surge

Storm surges associated with hurricanes with a fast forward speed may be reduced more by mangroves than surges created by hurricanes with a slower forward speed: Zhang *et al.* (2012) used numerical simulations to show that south Florida mangroves may be expected to protect the area behind them against flooding from a Category 5 hurricane with a fast forward speed of 11.2 m/s, but not from a Category 5 hurricane with a slow forward speed of 2.2 m/s. They estimate that a mangrove forest with a width of tens of kilometres would be needed to attenuate a 2 to 3 metre storm surge from a slow-moving Category 5 hurricane, as the mangroves have little effect on the slow flows seen in surges created by such hurricanes.

Storm surge reduction by mangroves also depends on initial surge height and surface wind speeds as a result of the damage that very large surges and very high wind speeds can do to mangroves. Extreme storm events with very high winds and very large surges may severely damage or destroy mangroves, resulting in smaller surge reduction levels either during that storm or in subsequent storms (see Section 6).

4. Reduction of surface winds by mangroves

Mangroves buffer the water surface from the effects of wind, thereby reducing the generation of wind-waves, wave set-up and run-up, which make a substantial contribution to storm surge flood levels and damage. However, it should be noted that the wind waves riding on top of a storm surge mostly originate from the effect of wind on the water surface outside the mangrove area; by reducing wind speeds over the water surface within the mangrove area, wind waves do not increase in size in this area (and they are usually reduced due to the presence of the mangrove obstacles). This section presents a brief overview of what is known about the ability of mangroves to reduce surface wind speeds and the likely effects of surface wind speed reduction on storm surge heights.

4.1 Measurements of wind speeds behind mangroves

It is well-known that forest canopies modify surface wind speeds (e.g. Raupach and Thom, 1981). Chen *et al*. (2012) measured wind speed and direction close to mangrove plantations (*Sonneratia apetala* and *Kandelia obovata*) in Sanjiang Bay in Haitian Province, South China. They took measurements 2 m above the ground, 50 m from the mangrove forest. They found that mean wind speeds up to 5 m/s were reduced by more than 85% by the mangrove forests, and greater reductions were seen near the *Kandelia* forest. When the mean wind speed was greater than 15 m/s, wind speed was reduced by between 58.9% and 63.6%. This reduction rate remained stable at higher wind speeds such as those seen during typhoons, when mean wind speed and extreme wind speed were reduced by 59.4% and 53.2% respectively (these latter wind speed reductions were measured for the *Sonneratia* forest). The authors note that the *Sonneratia* plantation reduced wind speeds more effectively during the warm season; presumably this resulted from denser foliage on the trees.

4.2 Estimating how reductions in wind speed caused by vegetation affect storm surges

It is not possible to directly measure the effect of vegetation-reduced wind speeds on storm surge heights, because the effects of reduced wind speeds would never occur independently of other effects such as increased drag on the water flow from the vegetation.

Using the Advanced Circulation numerical model, Westerink *et al*. (2008) explored how peak water levels varied in hindcasts of Hurricanes Betsy and Andrew when surface wind speeds were modified to reflect the differences in land cover (e.g. dense forested canopies, marshland, or buildings). Using two sources of information on atmospheric forcing, they then modified surface wind speeds to account for the higher surface roughness over land, as well as the level of local inundation (once a land feature was underwater it no longer affected wind speeds). They also took wind direction into account. They found that in the hindcasts of Hurricanes Betsy and Andrew, peak water levels were more than one metre lower in some areas when the modified wind speeds were included, as opposed to wind speeds assuming open-ocean marine conditions. (See Westerink *et al.* (2008) for a detailed explanation of their procedures for reducing wind speeds based on local surface roughness.) This implies that the effects of vegetation on wind speeds could significantly influence storm surge water levels.

5. Reduced damage and loss of life behind mangroves

A small number of studies have investigated whether mangroves help to reduce damage and loss of life during storm surges.

Badola and Hussain (2005) conducted a study based on local people’s perceptions of the protective services provided by mangroves against storm surges caused by cyclones. They worked in three villages in Orissa, India, following a cyclone with a 9 m storm surge in October 1999. The three villages were Bankual, located within the Bhitarkanika mangrove ecosystem wildlife sanctuary (145 km^2); Bandhamal, surrounded by embankments that were breached by the storm surge; and Singdi, which was not surrounded by either mangroves or embankments. The villages were within 15 km of each other and chosen to be otherwise similar in terms of their distance from the coast and the damage attributable due to wind (village elevation above sea level is not given, but the authors state that “water logging” was similar, i.e. flood water levels were similar).

Badola and Hussain (2005) found that in the mangrove-protected village, damage to houses and other adverse effects were lowest, while crop yields and other positive factors were least impacted. The loss incurred per household was highest in the village that was protected by an embankment (US$153.74), followed by the village with no protection (US$44.02), with the lowest losses in the village protected by mangroves (US$33.31). The reason losses were so high in the embankment-surrounded village was that the embankments were breached. This allowed sea water in, but subsequently the sea water took time to drain out of the breaches, so that crops were damaged more than in the village with no protection, whose fields suffered the highest level of inundation but the sea water quickly drained away, resulting in less crop damage. Badola and Hussain (2005) note that embankments near the mangrove forest were not breached while those further away were breached in a number of places, implying that mangroves may have helped to protect these embankments.

A larger scale study using data from several hundred villages was conducted by Das and Vincent (2009) after the same cyclone and in the same region as the study by Badola and Hussain (2005). Nearly 10,000 people died in the 1999 super cyclone, and more than 70% of these drowned. Das and Vincent (2009) used data from the Kedrapada District in Orissa, a district just north of the cyclone’s landfall, to explore whether the presence of mangroves in front of villages reduced the number of villagers who lost their lives. They included 409 villages in their study; all villages were known to have had mangroves between them and the coast in 1944, and this ensured that where villages were not fronted by mangroves in 1999, this was due to loss of vegetation and not a lack of suitable habitat. They used a regression analysis to test whether the number of deaths was related to the mangrove width in front of villages, and included a large number of other factors in their statistical model, such as distance from the coast and height of storm surge; the result was robust to the inclusion of these other variables[1].

Das and Vincent (2009) found that villages with wider mangroves between them and the coast had significantly fewer deaths than villages with narrower mangrove belts or no mangroves. They predicted that there would have been 1.72 additional deaths per village within 10 km of the coast if mangroves had not been present. They point out that mangroves saved fewer lives than an early warning issued by the government, which saved 5.84 lives per village. However, for those people who stayed behind despite the warning, the mangroves reduced the number of deaths (Vincent and Das, 2009). This example also illustrates how a combination of different risk reduction measures (in this case, early warning systems and mangrove forests) can provide an increased level of protection in comparison to single measures alone.

6. The effect of tropical cyclones and storm surges on mangroves

While mangroves can reduce storm surge peak water levels, they can also be affected by cyclones and their accompanying storm surges. The impacts of storms on mangrove ecosystems will depend on the mangrove ecology and local geomorphology.

Smaller cyclones and storm surges may result in some tree mortality and defoliation, but in most cases the structural complexity of the forest is maintained, and the forest is able to recover. During rare extreme events, tree mortality can be more extensive, caused by the breaking of trunks, uprooting of trees, the loosening or shredding of bark, and severe defoliation (Jimenez *et al.*, 1985; McCoy *et al*., 1996; Lacambra *et al.*, 2008; Figure 6). The flooding and siltation that may accompany cyclones can cause further tree mortality (Jimenez *et al*., 1985; Lacambra *et al*., 2008). If mass tree mortality occurs, it may result in the subsequent collapse of sediment and loss of surface elevation, as dead roots decay (Cahoon, 2006). The resulting elevation of the mangrove soil surface may be below mean sea level, making the areas unsuitable for colonisation by mangroves until such a time as the surface has risen in elevation to mean sea level (mangroves cannot live below mean sea level because the increased frequency and duration of tidal inundation create soil conditions that are harmful to the mangrove roots).

Tanaka (2008) examined trees that had been damaged by Cyclone Sidr in Bangladesh (2007) and found that the patterns of damage were similar to those seen after tsunamis or river floods. Trees were bent or their trunks were broken; some trees were overturned or uprooted;

[1] In response to Das and Vincent's (2009) study, Baird *et al*. (2009) questioned whether other important factors such as distance from the coast were taken into account and whether formal methods of model selection were used in the statistical analysis; they also suggested that the correlation coefficient between mangrove widths and village deaths was very low. In their reply, Vincent and Das (2009) pointed out that distance from the coast was included in the model, along with several other potentially relevant factors; that formal methods were used to progressively add in groups of related variables into their model, with no effect on the significance of their results; and that Baird *et al*. (2009) had wrongly interpreted the correlation coefficient because the discrete nature of the data for number of deaths required that count-data models were used: in fact, the data show that for villages within 10km of the coast, mangroves reduced the average number of deaths by 69%. Vincent and Das (2009) agree with Baird *et al*.'s (2009) point that mangroves saved fewer lives than the early warning system, but point out that many people did not evacuate despite the early warning system, and therefore mangroves played an important role in reducing the death toll amongst those that stayed behind.

the substrate had been eroded away from under some of the trees and there was local scour around the trees. Tree damage can be caused both by the force of the water in the storm surge and by the high winds. Larger trees are more likely to be damaged, and some species of mangroves may fare better than others: for example, after Hurricane Andrew passed across Florida in 1992, *Rhizophora mangle* fared better than *Avicennia germinans*, and both fared better than *Laguncularia racemosa* (McCoy *et al*., 1996).

Regeneration after a storm can take different pathways depending on the severity of the damage caused, which may determine whether recolonisation occurs primarily via sprouting from surviving trees (more likely from *Avicennia* or *Laguncularia* species) or via new seedling establishment (for *Rhizophora* species) (Baldwin *et al.*, 2001). In some cases, an understorey of mangrove seedlings can facilitate rapid regeneration after storms (Figure 6).

While cyclones can alter the structure of mangrove vegetation, in many areas such cyclones are infrequent and mangrove forests are usually able to recover their structural integrity over a number of decades, before another cyclone hits the same area (Krauss *et al*., 2009).

The speed of recovery after events is likely to be determined by the magnitude of the event and local conditions. This makes it difficult to predict the long-term effects of cyclones and storm surges on mangroves in any particular location. Lacambra *et al*. (2008) and Spencer and Möller (2012) review the effects of cyclones and storm surges on mangroves in more detail.

Figure 6. Left: A mangrove forest on the southwest coast of Everglades National Park in October 2005 after the passage of Hurricane Wilma, showing how trees have been defoliated and some trees have been knocked over. Photo: T.J. Smith III, US Geological Survey. Right: Large numbers of seedlings can be a common feature of the mangrove understorey, and can play a critical role in recovery from extreme storm events. Photo: Mark Spalding.

7. Future research needs and directions

Several areas of future research are needed in order to better understand the role of mangroves in storm surge reduction. Most importantly, further measurements of water levels and inundation extents in mangrove areas during storm surges would help to validate numerical storm surge models. All currently available data are from Florida; mangrove forests in other parts of the world include different species, with different vegetative structures, which may affect storm surge reduction rates.

An understanding of how surface roughness varies with mangrove forest characteristics might help to refine numerical storm surge models. Data on the geographical variation in mangrove characteristics would be required to include such variation within models.

The effect of mangroves on wave set-up and run-up under storm surge conditions is potentially large, but current understanding of this is entirely from numerical models. Measurements during storm surges are needed in order to validate these models.

Currently our understanding of the reduction of wind and swell waves through mangroves comes from measurements of small waves only (less than 70 cm in height); measurements of the reduction of larger waves during storm surges are also needed to better understand the capacity of mangroves to reduce wave-related damage during storm surges.

8. Conclusions

Both empirical data and numerical models suggest that mangroves can play a role in reducing storm surge peak water levels when the mangroves are present over sufficiently large areas. Mangroves slow the flow of water as the surge moves inland and reduce the waves riding on top of the surge, lowering water levels and reducing damage behind the mangroves.

Our current understanding of the effect of mangroves on storm surges comes from relatively few studies. These studies measured reductions in peak water levels of 5 to 50 cm per kilometre of mangrove. This implies that a mangrove belt several kilometres wide is needed to significantly reduce storm surge water levels. Such large areas of mangroves are still present in many parts of the tropics that are affected by cyclones and storm surges, including Mexico, the Caribbean, Florida, Bangladesh, India, Indonesia and Australia. In these locations, the conservation and restoration of mangroves can contribute to a risk reduction strategy against storm surge inundation and damage.

While mangroves can only reduce storm surges when they are present over large areas, the wind and swell waves on top of the storm surge may be reduced over much shorter distances (wave height reduction is expected to be greater than 75% over 1 km of mangrove; this is based on studies of smaller waves). By reducing wave height, mangroves are expected to reduce wave set-up and run-up, which contribute to the raised water levels, inundation and damage caused by storm surges. Mangroves also buffer the water surface from winds that would otherwise cause larger wind waves to form on the surge water surface.

There is considerable variability in the recorded levels of storm surge reduction by mangroves. Storm surge reduction is influenced by the characteristics of individual storm surge events, the local physical setting, and the characteristics of the mangrove communities. The relationship between storm surge reduction, bathymetry, topography, distance from shore and width of mangrove vegetation is highly complex; numerical models based on the underlying physics of wind forcing and water movement are best able to represent the behaviour of storm surges (Resio and Westerink, 2008). Such models are needed to explore the effects of mangrove characteristics on storm surge reduction: for example, Zhang *et al*. (2012) used numerical models to explore the effect of changing the width of the mangrove belt. They showed that peak water levels are expected to decline non-linearly with distance, with the greatest reduction in peak water level per unit distance occurring at the seaward margin. Therefore an increase in the width of the mangrove belt may not provide a proportional increase in water level reduction.

The ability of mangroves to reduce storm surges also depends on the storm surge forward speed, the height of the storm surge and the cyclone intensity. Numerical models suggest that mangroves will be more efficient at reducing surge height for fast-moving surges. Extreme events, with very strong winds or surges many metres high, may damage or destroy mangroves, reducing their ability to reduce surge height. The threshold at which such damage occurs is likely to depend on mangrove species and height (Lacambra et al., 2008). Such damage is usually localised to areas that are relatively close to the storm track.

One limitation of the current numerical models is their inability to include spatial variation in mangrove characteristics, such as mangrove density. It is very likely that the ability of mangroves to reduce peak water levels depends on mangrove characteristics, with sparse, fragmented or channelized areas reducing storm surge water levels less effectively than dense mangrove vegetation. Currently, mangroves are represented in numerical models as an increase in surface roughness, and a single value for the roughness coefficient is used for all mangroves areas (Xu *et al*., 2010; Zhang *et al*., 2012). Including mangrove variation would probably improve the prediction of storm surge heights, and would therefore aid in planning the use of mangroves in coastal defence.

Where extensive areas of mangroves currently exist, reducing the threats they face from development, sea level rise and other anthropogenic factors will help to maintain the coastal defence functions that they currently provide against storm surges. In other areas, large-scale restoration or afforestation of mangroves may provide increased levels of protection from storm surges. In such settings, numerical storm surge models will generally be required to calculate the potential benefits of mangroves, based on the known frequency and magnitude of surges in the region, and the physical characteristics of the mangroves (species composition and morphology) and the coast (topography, bathymetry, geomorphology, and the presence of other ecosystems that may provide coastal defence functions). Where mangrove planting is proposed as a means of reducing risk from storm surges, many other considerations should also be taken into account, including the chances of successful mangrove planting, which is dependent both on the methods employed (Lewis, 2005; Lewis and Perillo, 2009; Twilley and Rivera-Monroy, 2005) and on the social and legal frameworks, which may greatly influence future use and stability of tenure (Primavera and Esteban, 2008).

The most appropriate use of mangroves in coastal defence is likely to be in combination with other risk reduction measures. For example, sea walls and levees placed on the landward side of mangrove forests are likely to experience reduced water levels and wave energy during storm surges, greatly reducing the likelihood of the wall being overtoppped or damaged during a storm surge; this could significantly reduce the design specifications and therefore the cost of the sea wall (such combinations are sometimes referred to as ‘hybrid engineering’). Another example discussed by Das and Vincent (2009) demonstrated how early warning systems and evacuation centres had the greatest effect on reducing the death toll during a cyclone in India, but mangroves further reduced the death toll among those people who did not evacuate.

As Williams *et al*. (2007) point out, it is not just the presence of mangroves which is required to provide coastal defence services, but good coastal planning. This can ensure that evacuation plans and procedures are in place, that people are informed about these plans and procedures, and that they are willing to comply. When Cyclone Larry hit Australia in 2006, commercial, recreational and naval vessels in the port of Cairns sheltered in deep mangrove creeks. The protection given to the mangrove forests, and the careful planning that ensured that all vessel operators knew where and when to go, resulted in all vessels riding out the storm safely with no loss of life (Williams *et al*., 2007).

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