ASSOCIATED PROGRAMME
ON FLOOD MANAGEMENT

INTEGRATED FLOOD MANAGEMENT TOOLS SERIES

COASTAL AND DELTA FLOOD MANAGEMENT

ISSUE 17
MAY 2013

Global Water Partnership

World Meteorological Organization
Weather • Climate • Water

The **Associated Programme on Flood Management** (APFM) is a joint initiative of the World Meteorological Organization (WMO) and the Global Water Partnership (GWP).

It promotes the concept of Integrated Flood Management (IFM) as a new approach to flood management. The programme is financially supported by the governments of Japan, Switzerland and Germany.

www.floodmanagement.info

The **World Meteorological Organization** is a Specialized Agency of the United Nations and represents the UN-System's authoritative voice on weather, climate and water.

It co-ordinates the meteorological and hydrological services of 189 countries and territories.

www.wmo.int

The **Global Water Partnership** is an international network open to all organizations involved in water resources management. It was created in 1996 to foster Integrated Water Resources Management (IWRM).

www.gwp.org

Integrated Flood Management Tools Series No.17

Cover photo: Westkapelle, Netherlands

Layout, design and iconography : www.lamenagerie.net

To the reader

This publication is part of the *"Flood Management Tools Series"* being compiled by the Associated Programme on Flood Management. The *"Coastal and Delta Flood Management"* Tool is based on available literature, and draws findings from relevant works wherever possible.

This Tool addresses the needs of practitioners and allows them to easily access relevant guidance materials. The Tool is considered as a resource guide/material for practitioners and not an academic paper. References used are mostly available on the Internet and hyperlinks are provided in the *References* section.

This Tool is a *"living document"* and will be updated based on sharing of experiences with its readers. The Associated Programme on Flood Management encourages disaster managers and related experts engaged in management of coastal floods around the globe to participate in the enrichment of the Tool. For this purpose, **comments and other inputs are cordially invited**. Authorship and contributions would be appropriately acknowledged. Please kindly submit your inputs to the following email address: apfm@wmo.int under Subject: *"Coastal and Delta Flood Management"*.

Acknowledgements

This tool has been developed jointly by the APFM technical Support Unit in close cooperation with DELTARES, NL. Special recognition is given to Messrs Marcel Marchand, Herman van der Most and Deepak Vatvani.

PREFACE

Coastal flood hazards are diverse (storm surges, tsunamis, tropical storms, seiches etc.) and are highly unpredictable. A profound understanding of these hazards, their mechanisms and potential impacts is therefore indispensable in order to derive an appropriate risk management response.

Such response should be selected from the widest range of measures and policies possible, taking due account of the inherent uncertainties both with respect to the probability of hazard and evolving socioeconomic developments.

This Tool paper aims at providing practical guidance to flood management practitioners and other stakeholders to formulate an appropriate (i.e. sustainable, minimum total cost and socially acceptable) coastal flood risk management policy.

Although coasts also experience types of ‘inland’ flooding, e.g. from rivers and local rainfall, this paper focuses on the hazards coming from the sea. Typical of these hazards is that they cannot be prevented, are often difficult to predict and are amongst the most forceful of floods.

CONTENTS

FIGURES, TABLES & BOXES

1 INTRODUCTION

1.1 Coastal disasters

1 Coastal disasters are increasing **(Figure 1)**. Nevertheless, there is no clear evidence of a significant worldwide increase in the frequency or intensity of storms. In fact there is still much scientific debate on this issue, especially due to the limited historic record and complex mechanisms that drive coastal storms (see for instance Knutson et al. 2008, Watts, 2012).

2 It is likely that there has been an anthropogenic influence on increasing extreme coastal high water due to an increase in mean sea level. But the uncertainties in the historical tropical cyclone records, the incomplete understanding of the physical mechanisms linking tropical cyclone metrics to climate change, and the degree of tropical cyclone variability provide only low confidence for the attribution of any detectable changes in tropical cyclone activity to anthropogenic influences (IPCC, 2012).

3 What we do know for sure is that the trend in damages is increasing, and that this can be explained by societal factors, such as an increase in coastal populations and associated higher economic investments. Such trends are observed in various countries, such as the USA and India (Pielke Jr., et al., 2008, Raghavan & Rajesh 2003).

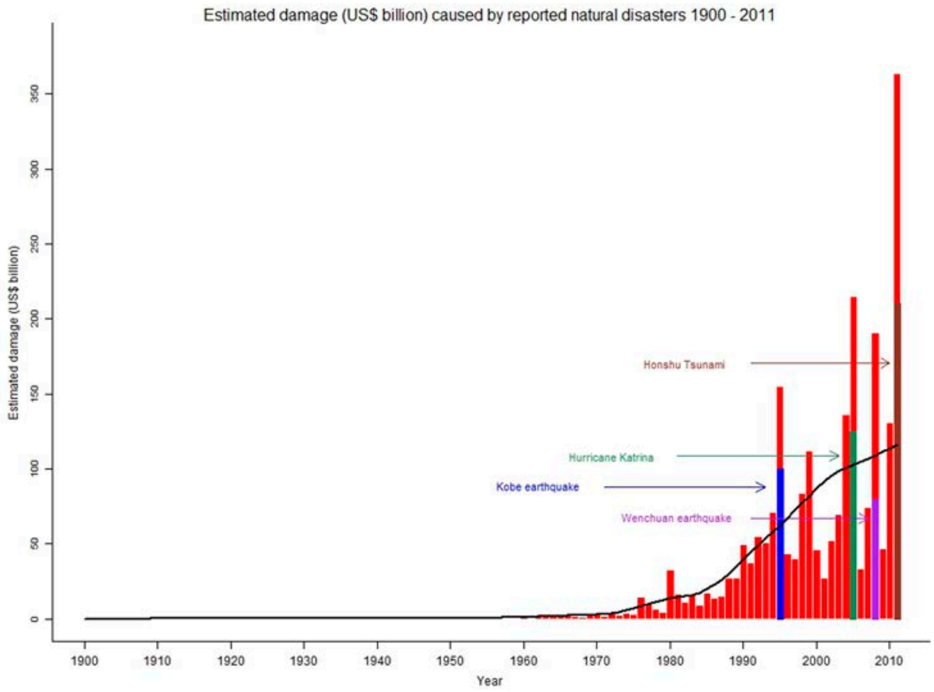


Figure 1 — Increase in natural disasters over the past century (Source: EM-DAT 2013).

1.2 Terminology

4 Risk, hazard and vulnerability are closely related terms and therefore should be used only with proper definition, thus avoiding overlapping meanings. In this Tool Paper we will use the definitions explained in the APFM Tool publication Risk sharing in Flood Management.

Figure 2 — New Orleans, August 30, 2005. US Coast Guard looks for survivors in the wake of Hurricane Katrina

5 Mathematically, risk can be expressed as the product of probability and consequence:

Risk = Probability x Consequence

6 Flood risks are defined as the expected losses from given flood events, in a given area over a specified period. Flood events can be described in terms of the nature and probability of the flood hazard. A hazard does not necessarily lead to harm (Gouldby & Samuels, 2005).

7 Consequences of exposure to flood hazard are determined by the degree of exposure of receptors (or elements at risk), their susceptibility and the value of the receptor.

8 The susceptibility of the receptor depends on its sensitivity – the damage caused by an event of a given magnitude, and adaptive capacity – the ability of a system to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. The value and susceptibility of the receptor is combined to represent vulnerability.

9 Often, the exposure is also included as a factor that determines the vulnerability (cf. Turner et al., 2003). In this publication, however, while defining flood risks, a clear distinction between the exposure and the vulnerability is maintained.

10 Flood risk can be expressed as the (annual) expected impact (e.g. an average annual damage). This implies that although a risk could be very small (due to the infrequent occurrence of the hazard event), in contrast, the vulnerability could be very high. Hence, it can make a difference if coastal managers use risk as their basis for planning or if they use vulnerability.

1.3 Reading guide

11 This Tool Paper provides an overview of coastal flood risk management. It has been logically structured along the steps which should be taken to formulate a management plan. In reality the procedure would of course differ according to the context of a country with its specific hazards, development phase, socio-cultural identity and institutional structure. The steps also require iterations and side-steps and should therefore be regarded as building blocks rather than a blueprint. The approach pictured in **Figure 3** provides the reader a quick overview of the structure of the Paper which leads him or her to the topics one is most interested in.

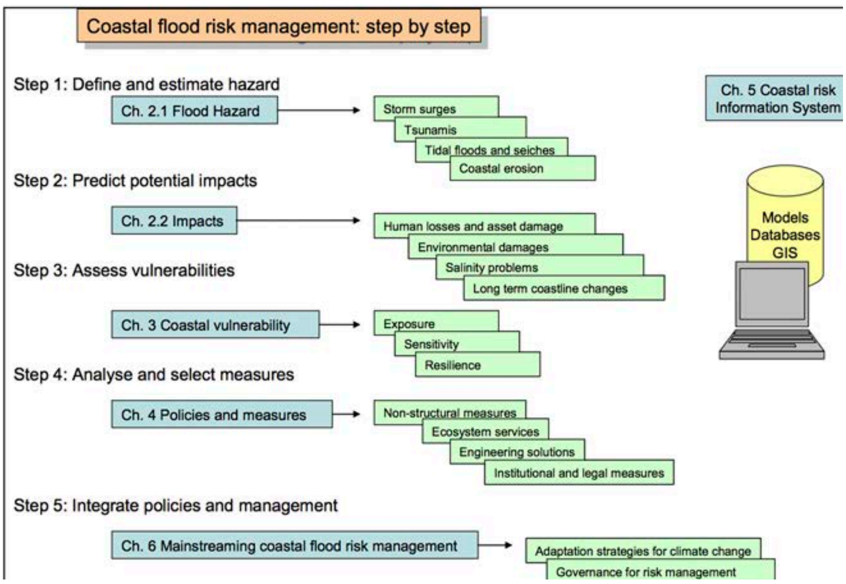


Figure 3 — Step by step guide to coastal flood risk management

2 COASTAL FLOOD HAZARDS: CAUSES AND IMPACTS

2.1 Types of hazards and their impacts

2.1.1 Storm surges

12 Coastal storms create storm surges or wave set-up along the coast. Its impact on coastal areas, depending on the coastal bathymetry, can be differentiated into surge dominated coastal areas (e.g. Bangladesh, Myanmar, Mississippi River Delta) and wave setup dominated coastal areas (e.g. Hawaii, Fiji, Dominican Republic) as shown in **Figure 4** below.

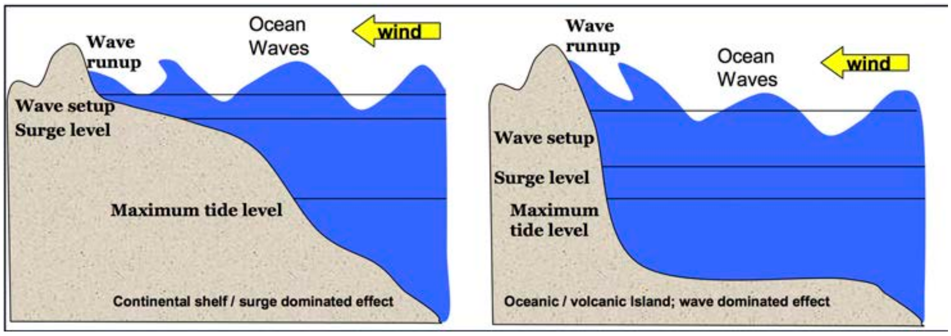


Figure 4 — Schematic representation of the effects of storm depending on coastal bathymetry.

13 Its driving force can be divided into two main categories: extra-tropical storms and tropical storms. Extra-tropical storms are atmospheric pressure disturbances and associated winds and result in intense energy transfer from the atmosphere to the ocean which increases water levels (a surge). Tropical storms extract energy from the warm ocean water to grow in strength. Tropical storms are known under different names: cyclones (Indian subcontinent), typhoons (Southeast Asia) or hurricanes (Americas), but their physical characteristics are essentially the same.

2.1.1.1 Extra-tropical Storms

14 Extra-tropical storms (also known as mid-latitude or baroclinic storms) are low pressure systems with associated cold fronts, warm fronts, and occluded fronts. An extra-tropical storm primarily gets its energy from the horizontal temperature contrasts that exist in the atmosphere. Tropical cyclones, in contrast, typically have little to no temperature differences across the storm at the surface and their winds are derived from the release of energy due to cloud/rain formation from the warm moist air of the tropics (NOAA, 2013).

15 As a typical example of extra-tropical storms, a European coastal storm is the result of a disturbance in the atmosphere over the Atlantic Ocean, leading to a local pressure low **(Figure 5)**. The horizontal pressure difference gives rise to air flow, or winds, in the direction of the depression. Deflection due to the rotation of the earth creates a storm with characteristic anti-clockwise rotating winds around the depression in the Northern hemisphere and clockwise rotating winds in the Southern hemisphere.

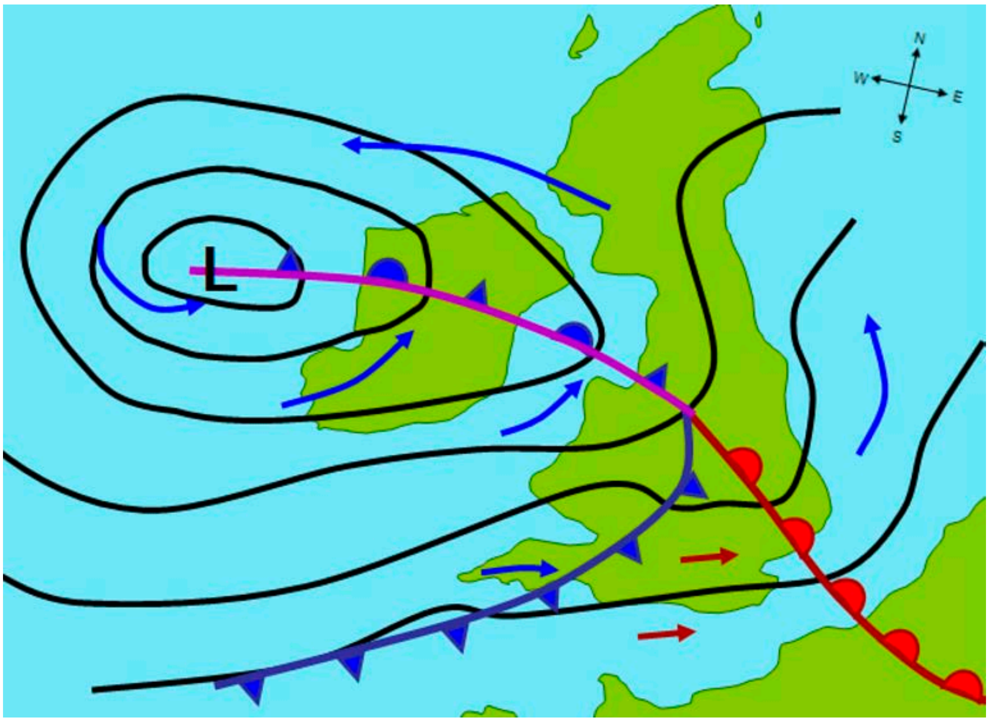


Figure 5 — A fictitious synoptic chart of an extra-tropical cyclone affecting Great Britain & Ireland
The blue and red arrows between isobars indicate the direction of the wind and its relative temperature, while the "L" symbol denotes the center of the "low". (Public domain)

16 Over deep oceanic waters, the pressure difference around the pressure low results in an immediate rise of the water level below. A 1 millibar pressure decrease represents 0.1% of standard atmospheric pressure and equals a 1 cm water level rise. When the storm reaches the continental shelf, air pressure differences no longer result in the immediate water level rise, mainly due to friction along the sea bed, which reduces and slows down the response.

17 For these more shallow waters, wind dominates, setting the water in motion through surface drag. For strong depressions, which are associated with high and sustained winds, the surface wind drag, counteracted by bottom friction, leads to a water level rise or surge. The surge

propagates in the direction of the wind, also with a deflection due to earth rotation. In decreasing water depths towards the coast, interactions with the sea bed and tide increase, resulting in a further enhanced wind-induced surge height along the coasts, as long as the wind maintains the effect. Depending on the presence of local sea bottom (bathymetric) characteristics, plus constrictions such as river inlets and estuaries, severe storms may easily lead to peak surge heights that exceed 5 meters. When the wind decreases, or changes direction, the surge height decreases as the water surface tends to regain its original state, such as normal tides.

18 Storm winds also generate and propagate surface waves referred to as "sea state". Waves that have been generated by winds elsewhere are called "swell". For a severe storm in open sea, significant wave heights may reach levels of 8-10 meters or more. In shallow water, moving to the coast, interactions with other water and land phenomena, breaking and further dissipation takes place, leading to a decrease of wave height. In coastal areas with steep bathymetry slope, the waves generated by a storm contribute to a large extent to the flooding caused by piling of water (wave set-up) and by wave overtopping.

19 Both the storm-induced surge and wind waves cause hazards for navigation and port operations along with potentially severe damage to coastal structures including flood barriers. Examples are dune erosion, along with dike collapses as a result of saturation due to sustained wave overtopping or pressure from surge and wave forces.

20 The 0-12 Beaufort Scale is used to indicate wind severity. Named after its originator Rear-Admiral Sir Francis Beaufort (1774-1857), the Beaufort Scale is based on a combination of visually recorded state of surface waters and damage caused by the winds (Hsu, 1988). Beaufort Scale 6 (38-49 km/h) corresponds to a strong breeze, while Beaufort Scale 10, 11, 12 correspond to winds of storm, severe storm and hurricane force (winds of 89-102; 103-117; >117 km/h) respectively.

2.1.1.2 Tropical Storms

21 Tropical storms are cyclones that originate over a tropical ocean. Their measured winds exceed 200 km/h and are accompanied by torrential rains (Riehl, 1979). They are generated in the band of the trade wind current of the tropics, just north and south of the equator, tending to move away from the equator initially, but then sometimes following complex pathways with multiple changes of direction.

22 Several conditions are needed for the formation of a tropical storm. Most importantly the sea surface temperature must be above 26°C, which is why such storms do not occur at high latitudes. The warm water heats the air moving from the surrounding water toward the central low **(Figure 6)**. The ocean feeds heat and moisture into the storm, providing energy that causes the warm air in the centre to rise faster. As long as the cyclonic centre remains over warm water, the supply of energy is almost limitless. As more and more moist air spirals inward into the low pressure centre to replace the heated and ascending air, more and more heat is released into the atmosphere and the wind circulation continues to increase (Hsu, 1988). When the wind speeds exceed 119 km/h, the storm has formally reached the level of a tropical cyclone.

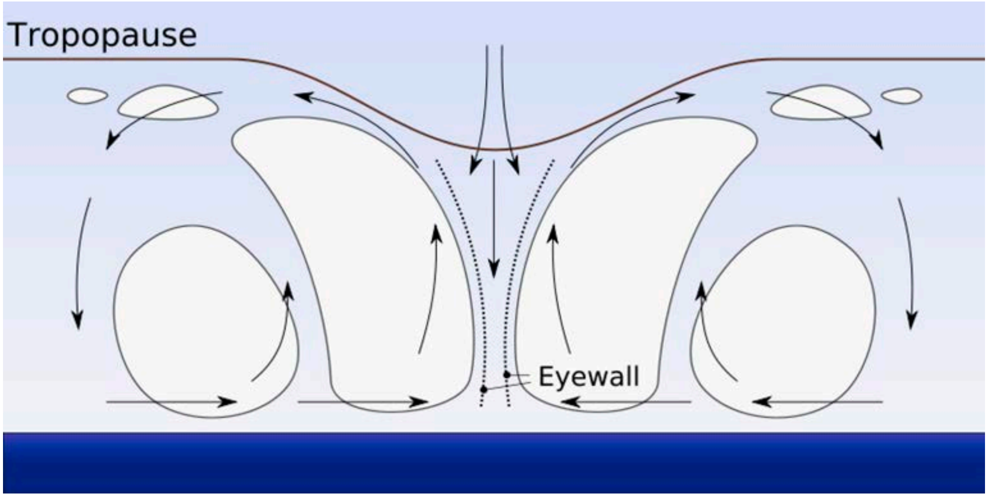


Figure 6 — Tropical cyclones form when the energy released by the condensation of moisture in rising air causes a positive feedback loop over warm ocean waters (Public domain)

The Saffir-Simpson Scale **(Table 1)** divides tropical storms into five categories, based on their damage potential from wind only—surge height is calculated and is included, but damage from flooding especially from rainfall is not factored into the Saffir-Simpson Scale. Although **Table 1** has limitations, it is an internationally used classification. For example, storm surge height at landfall also depends on local topography and bathymetry while the observed damage must always be influenced by vulnerability.

Moving into coastal shelf areas, the intense winds around the pressure low create large surges and or waves, which propagate with the storm towards the coast, where they sweep across the often low-lying coastal areas. The strong winds, surge waters and wave forces of even category I and II storms may cause significant loss of life and destroy infrastructure and vegetation.

Table 1 — Saffir-Simpson damage-potential scale for tropical storms (Hsu, 1988)

Scale number	Central barometric pressure (in hPa)	Wind speed (km/ hr)	Storm surge height (at landfall / along coast)	Commonly observed damage
I	> 980	119 – 153	1.2 – 1.5 meters	Minimal
II	965-979	154 – 177	1.8 – 2.4 meters	Moderate
III	945-964	178 – 209	2.7 – 3.6 meters	Extensive
IV	920-944	210 - 249	3.9 – 5.4 meters	Extreme
V	< 920	> 249	> 5.4 meters	Catastrophic

Figure 7 — Eastern Scheldt Storm Surge Barrier closed during storm

2.1.2 Tsunamis

23 A tsunami is a wave cause by a sudden rising or lowering of the ocean floor or by large masses of earth falling or sliding into the water and propagates as consecutive, very long period ocean waves over long distances. Tsunamis are mostly (around 90%) triggered by strong earthquakes below the ocean floor. A typical characteristic is that on high seas, even large tsunamis with amplitudes of mostly only a few decimetres are not registered due to the enormous wavelengths of several 100 km. They therefore cause no risk to ships on high seas. It is only in the shallow waters of the coastal areas that the dangerous water fronts build up to several 10 m (Bormann, 2006). In contrast to a storm surge, a tsunami runs over the land as a wall of water, destructing everything crossing its path **(Figure 8)**.

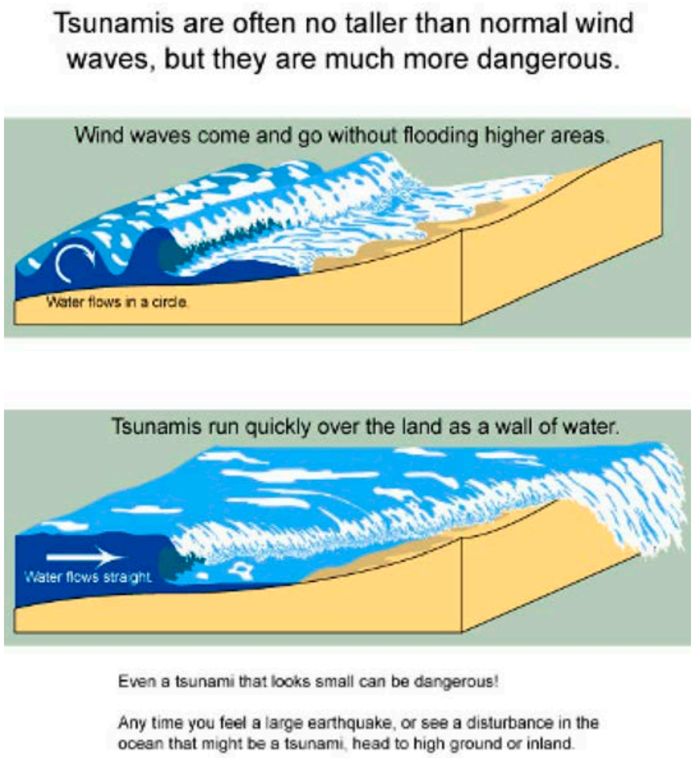


Figure 8 — The difference between a tsunami and wind waves.

24 In order to avoid confusion, terms such as water level and run-up need to be clearly defined. Standard parameters as described by the International Tsunami Information centre (ITIC) are widely applied (IOC-UNESCO, 2012) **(see Figure 9)**.

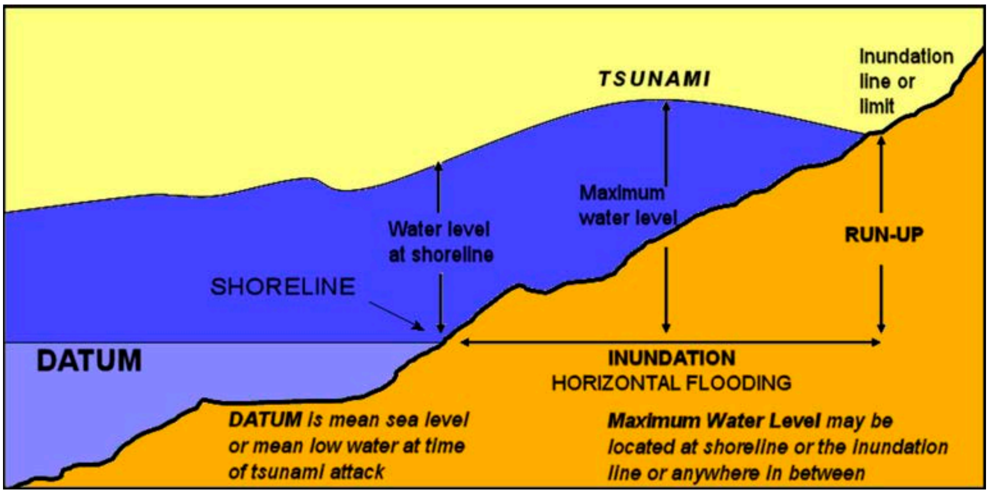


Figure 9 — Definition of run-up and other tsunami characteristics (IOC-UNESCO)

25 Off-shore a tsunami wave is in the order of a few centimetres to a metre or more, generated by the vertical movement of the ocean floor. When this wave, which can travel at a speed of many hundreds km per hour, reaches a coast, the shallow water depths cause the wave to rise. A convex coastal profile produces up to twice a higher water level and 40% higher run-up than a concave (hollow) profile (Van der Plas, 2007).

Box 1 — High water levels in Jakarta, Indonesia

Precise and timely predictions may contribute to the protection of large parts of Jakarta from flooding, as was demonstrated on Tuesday 3 June and Wednesday 4 June 2008. The government in Jakarta pulled out all the stops to get sandbags out in time and to start pumping operations. The timely high water warnings allowed provisional water defences to be built from sandbags and bamboo with all speed. The result was a dramatic limitation of the flood damage.

The flood predictions were based on an extensive analysis of the water levels near Jakarta. A number of phenomena had been identified that, in conjunction, resulted in exceptionally high water levels off the coast of Jakarta on 4 June. First of all, there is a intensification of spring-tides in a cycle of 18.6 years. This cycle is caused by the variations in inclination of the moon's orbit around the Earth, which result in variations in the distance between the moon and the earth. The cycle peaked that year, resulting in higher spring tides. Secondly, this peak in the 18.6-year cycle on 4 June coincided with a semi-annual peak in spring tide levels. The combination of these two phenomena ensured that the tide was exceptionally high on 4 June (and the days before and after).

A third phenomenon that plays a role in the water levels near Jakarta – the 'Sea Surface Anomaly' – is not, strictly speaking, tidal. These anomalies consist of variations in the water level of a seasonal nature. They are caused by large-scale seasonal variations in the (monsoonal) meteorological patterns above the Pacific and Indian Oceans. In Jakarta, on average, June is the month with the highest anomaly. Because the anomalies vary from year to year and depend on the weather (the presence of anticyclones, for example) the variations in water levels that they cause are difficult to predict.

2.1.3 Tidal floods and seiches

26 Tides are caused by the gravitational pull of the sun and moon. Some shorelines experience two almost equal high tides and two low tides each day, called a semi-diurnal tide. Some locations experience only one high and one low tide each day, called a diurnal tide. Some locations experience two uneven tides a day, or sometimes one high and one low each day; this is called a mixed tide. The times and amplitude of the tides at a locale are influenced by the alignment of the Sun and Moon, by the pattern of tides in the deep ocean, by the amphidromic[1] systems of

---

1 An amphidromic point is a point of zero amplitude of one harmonic constituent of the tide. The tidal range for that harmonic constituent increases with distance from this point. Amphidromic points occur because of the Coriolis effect and interference within oceanic basins, seas and bays creating a wave pattern — called an amphidromic system. At the amphidromic points of the dominant tidal constituent, there is almost no vertical movement from tidal action (Wikipedia).

the oceans, and by the shape of the coastline and near-shore bathymetry. Approximately twice a month, around new moon and full moon when the Sun, Moon and Earth form a line the tidal force due to the sun reinforces that due to the Moon. The tide's range is then at its maximum: this is called the spring tide. When the Moon is at first quarter or third quarter, the Sun and Moon are separated by 90° when viewed from the Earth, and the solar tidal force partially cancels the Moon's. At these points in the lunar cycle, the tide's range is at its minimum: this is called the neap tide. Spring tides result in high waters that are higher than average, low waters that are lower than average (Wikipedia). Spring tides, especially combined with strong winds can lead to excessive flooding.

27 A seiche is a standing wave in an enclosed or partially enclosed body of water. Seiches and seiche-related phenomena have been observed on lakes, reservoirs, swimming pools, bays, harbors and seas. The key requirement for formation of a seiche is that the body of water be at least partially bounded, allowing the formation of the standing wave (Wikipedia).

2.1.4 Coastal erosion

28 Coastal erosion is a significant hazard in many countries and a huge budget is spent for countermeasures. For instance, in France some €20 million is spent each year on mitigation measures and in The Netherlands the annual budget for sand nourishment amounts to some €41 million.

29 Coast erosion is the process of wearing away material from a coastal profile due to imbalance in the supply and export of material from a certain section. It takes place in the form of scouring in the foot of the cliffs or dunes or at the subtidal foreshore. Coastal erosion takes place mainly during strong winds, high waves and high tides and storm surge conditions, and results in coastline retreat and loss of land. The rate of erosion is correctly expressed in volume/length/time, e.g. in m^3/m/year, but erosion rate is often used synonymously with coastline retreat, and thus expressed in m/year (Mangor, 2004).

30 Understanding coastal erosion processes requires an insight into all the factors that interact along the shoreline and an awareness of different time scales. On a geological time scale, the balance between sediment demand and supply drives the evolution of the coast. If we look at what happens during a storm only a part of the long term processes is visible **(Figure 10)**. On a sandy coast, for example, a combination of high tide and strong winds pushes up the sea water level, exposing the beach and dunes to heavy attack by the incoming waves, usually resulting in erosion. Sand is dragged down the slope by the down rush causing erosion of the beach and dunes and undermining of the dune toe. Part of the dune face may collapse and this slumped sediment will slide downwards where it can be eroded further again by wave-induced processes. The sediment is then transported to the sea where it will settle at deeper water. During a subsequent calmer period some of the sediment may return to the coast through onshore directed wave-driven and wind-driven transport, usually resulting in accretion in the beach zone.

31 However, longshore currents may also remobilise the sediment, leading to further sediment movement away from the original location.

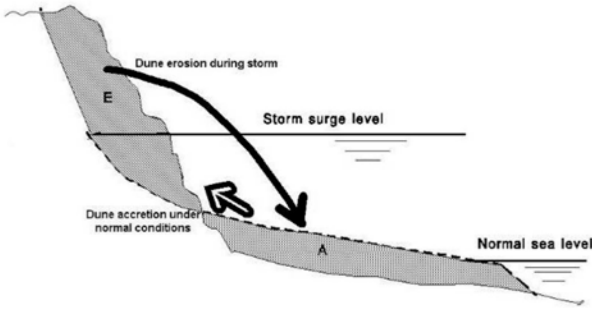


Figure 10 — Dune erosion during a storm

32 For a better understanding of the coastal erosion processes a coastal sediment cell can be used **(Figure 11)**. Such cell contains a complete cycle of sedimentation including sources, transport paths and sinks. Delineating the coast into several coastal cells is most easily achieved by using natural or artificial boundaries, such as headlands, capes or long groynes.

33 The net balance between losses from and inputs to a coastal cell determines, to a large extent, whether a coastline is eroding or accreting, especially in the longer term. It is clear that any human interference in these processes, such as the blocking of sediment transport by building a jetty or breakwater, or sediment starvation through reduced riverine input could have repercussions on the delicate natural balance and thus on erosion patterns. Transport rates for each of these processes are used to model the changes in the sediment budget, which makes it possible to predict future coastline fluctuations caused by such human interventions.

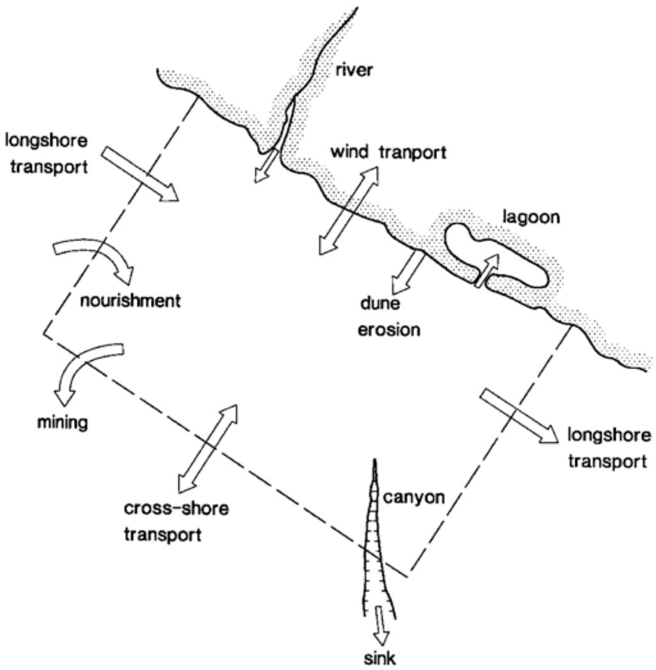


Figure 11 — The coastal cell and its sediment pathways (Marchand, 2010).

34 Since erosion, high velocity wave action, and flooding can be caused from several different natural hazards, it is important to collect and utilize inundation data from all potential disasters. This has been the trend in the United States and internationally, to implement a program for

hazard mitigation that protects inhabitants from all natural hazards, whether it is flooding from a tsunami, storm surge or other natural event (Hwang et al., 2005).

2.2 Impacts

35 The effects of coastal storms depend on the population's and community's characteristics, including demography, livelihoods, and planning along with coping capacities. An additional factor is infrastructure designed to provide protection in coastal areas along with its location and the elevation in relation to the nature of coastal hazards (wind, surge and waves). We will discuss coastal vulnerability in the next section. But first we will have a closer look at the physical effects of coastal floods.

2.2.1 Human losses and asset damage

36 Coastal storms will often combine the hazards of wind and flood effects, leading to casualties, societal disruption and infrastructure damage. Strong winds and low atmospheric pressure push water into the coast. Additionally, surface winds can generate large waves that can cause beach erosion and the destruction of properties in coastal areas. Some available coastal storm statistics from the twentieth century are summarized in **Table 2**.

37 In general, it is expected that flood effects will be the most significant causes of damage and loss of life. Although some fatalities may be associated with wind effects (and landslides in mountainous hinterland areas), most of the fatalities due to coastal storms are caused by the flood effects (Rappaport, 2000). The number of wind fatalities will often be limited as most people will be able to find shelter during the passage of the storm. Especially low-lying coastal areas are susceptible to flooding, such as areas built on marshland in eastern England; river deltas with examples being the Rhine (Europe) and Yangtze (China) rivers; and low-lying islands such as built up barrier islands on the east coast of the USA and coastal areas of the Cook Islands in the Pacific.

38 Coastal floods are capable of causing large numbers of fatalities, as they are often characterised by severe flood effects (large depths, high flow velocities and powerful waves). In addition, coastal storms have sometimes occurred unexpectedly, i.e. without substantial warning. This allowed little or no time for warning and preventive evacuation and resulted in large exposed populations. Bangladesh in particular has been often severely affected by coastal floods **(see also Table 2)**.

39 The enormous energy of a tsunami wave explains the colossal damage and havoc it may bring onshore. Besides the direct impact to structures and people, considerable damage is caused by the resultant floating debris, including boats and cars that become dangerous projectiles that may crash into buildings, break power lines, and may start fires (Kohl et al., 2005; IOC-UNESCO 2012). The high water velocities and the debris make it for people difficult to escape if not warned in time and swimming often impossible. The major causes of death and injury are therefore usually drowning and blunt trauma (Schwartz et al., 2006).

40 In most flood risk exercises water depth is used as the determining parameter for damage. This holds true for floods originating from rivers and also for storm surges. For a tsunami

however, it is expected that this parameter cannot describe its devastating power. The wave length of a tsunami is much larger that that of a storm surge, which means that the energy of the wave is also much greater. A tsunami wave in deep waters can have wave lengths of hundreds of km while storm surge waves in deep water have a wave length that is one or two order of magnitude(s) lower. So a tsunami of the same wave height as a storm surge can have 100 to 1,0000 times more energy. Also the wave height plays a major role. Therefore a more appropriate parameter to describe the destructive power is wave length times wave height to the power of two. This means that a double wave height increases the energy available for destruction four times.

Table 2 — Overview of coastal floods since 1950 (sources: EM-DAT, 2000, others) [2]

Date	Location	Hazardous phenomena	Fatalities[2]	People exposed
1-2-1953	Netherlands, Southwest	Storm surge	1836	250,000
1-2-1953	United Kingdom, East coast	Storm surge	approximately 307 on land	32,000
26-9-1959	Japan, Ise Bay	Typhoon	5101	430,000
12-11-1970	Bangladesh	Tropical cyclone	500,000	
18-9-1974	Honduras	Tropical cyclone	8,000	
12-11-1977	India, southern	Tropical cyclone	14,000	9,000,000
25-5-1985	Bangladesh	Tropical cyclone	10,000	1,800,000
30-4-1991	Bangladesh	Tropical cyclone	139,000	4,500,000
End of October 1998	Central America	Tropical cyclone	19,000	
29-10-1999	India, Orissa	Tropical cyclone	9800	12,600,000
29-8-2005	United States: Louisiana and Mississippi	Hurricane (Katrina)	1100#	100,000
25-12-2004	Indian Ocean	Tsunami	250,000	
15-11-2007	Bangladesh	Tropical cyclone (Sidr)	More than 3000^	
2008	Myanmar	Tropical cyclone (Nargis)	138,000	
11-03-2011	Japan	Tsunami	16,000	

#: number of fatalities in Louisiana – most of these were due to flooding. ^ - estimate based on press sources, November 2007.

41 A proper parameter that probably describes the damaging capacity of a tsunami wave is the momentum flux, which is a function of the water mass and its acceleration (Loomis, 2006, Guard et al., 2005).

42 Experience from Japan shows that local tsunami amplitudes below 1.5m do not usually pose any risk to people and structures. If wave heights are over 2m, most lightweight buildings made from wood, sheet metal, mud/clay, etc. are totally destroyed, if the waves are > 3m high, concrete block buildings are also destroyed. If the wave heights exceed 4m the number

2 The reported numbers of fatalities may include considerable uncertainty. For example, for the 1991 floods in Bangladesh, the estimated death toll ranges between 67,000 and 139,000 (Chowdhuryet al., 1993), resulting in a national mortality between 1.5% and 3.1%.

of deaths also rises drastically. Well-built reinforced concrete structures on the other hand can withstand tsunami waves at least 5m high. Therefore, the upper storeys of reinforced concrete high-rise buildings/hotels can also be used as refuges in case of very short early warning times and small chances of escaping outdoors (Bormann, 2005).

43 There is no limit to the height of a tsunami, especially those caused by landslides or volcano eruptions. The Great Meiwa Tsunami, which devastated the Yaeyama Archipelago, including Ishigaki and Miyako Islands in 1771, killing or leaving missing some 10,000 people, reached to a height of 85.4 m in Miyara Village (MLIT, 2011). Krakatau volcano eruption generated giant waves reaching heights of 40 m above sea level, devastating everything in their path and hurling ashore coral blocks weighing as much as 600 tons. Finally, the 1958 Lituya Bay mega-tsunami occurred on July 9, 1958, when an earthquake triggered a landslide that caused 30 million cubic metres of rock and ice to fall into the narrow inlet of Lituya Bay resulting in a wave hundreds of metres high, that washed over trees and was ultimately measured as washing 524 metres (1,720 feet) up the opposite slope of the inlet (Wikipedia).

2.2.2 Environmental damages

44 Relatively little attention has been given to the effect of coastal storms on the environment. Nevertheless, these impacts can be huge. Coral reefs are known to suffer from severe coastal storms and tsunamis. But also mangroves, dunes and sea grass beds can be destroyed by the force of surges and tsunamis. For instance, the Indian Ocean Tsunami damaged 20 percent loss of sea grass beds (around 600 ha) and 30 percent damage to the 97,000 ha of coral reef (UNEP, 2006). The most serious threat to the coastal environment from the tsunami currently stems from the massive amounts of natural and man-made materials that were dragged into the ocean by the receding waters. This waste ranges from vehicles and fuel tankers to silt and debris, including whole trees.

2.2.3 Salinity problems for drinking water and agriculture

45 Saltwater intrusion is the movement of saline water into freshwater aquifers and most often is caused by groundwater pumping from coastal wells (Barlow, 2003). Large areas of the Mediterranean coastline in Italy, Spain and Turkey are reported to be affected by saltwater intrusion (EEA, 2003), but this is probably mainly due to over-exploitation of groundwater rather than from coastal floods.

46 The immediate effect of saltwater flooding is often a shortage of fresh and safe drinking water. But flooding by salt-water can also lead to longer term damage and difficult recovery of agriculture and ecology. After the 1953 North Sea storm surge, flooded areas were still suffering from salt contamination for years afterwards.

47 Tides and storm surges can be local sources of increased groundwater salinity in low-lying areas. Flooding of agricultural land by hurricane storm surges can have both short-term and long-term effects on both crops and soil structure. While most of the "salt" in seawater is sodium chloride (table salt), it also contains appreciable amounts of magnesium sulfate (Epson's salts) and other elements. After heavy rains, sodium and chloride will be preferentially lost in runoff and leachate. Therefore, within the next two years, much of the agricultural land flooded by last season's storm surges should naturally recover and return to previous levels of productivity.

Recovery will occur more quickly in fields that received lower amounts of salt. A few areas that accumulated very high levels of salt are possibly at risk of becoming sodic, and may not recover without help. Preliminary estimates of the economic impact from hurricane Katrina to Louisiana agriculture were calculated as well over $1 billion dollars (Williams, 2010).

2.2.4 Long term coastal morphology changes

48 The forces from storm surges, waves and tsunamis reshape soft coasts, causing coastal erosion as described in **Section 2.1.4**. Although such coasts show considerable resilience leading often to a return to the pre-disaster coastline position, sometimes this does not happen because too much sediment is lost from the coastal sediment cell. In **Box 2** an example is given of the long term coastal morphological changes that occurred after the 2004 Indian Ocean Tsunami.

Box 2 — Morphological changes after Indian Ocean Tsunami (De Vroeg, pers.comm.)

For the coastal morphology the main effect of the tsunami wave is re-distribution of sand. The sand transport by tsunami waves is directly related to the movement of the water. No reliable descriptions of the water movement in the near-shore area and of the tsunami propagation on land are available. A reliable description of the 2DV propagation along a coastal profile (incl. inland) would be required to identify areas of potential erosion and deposition along a coastal profile. The lack of reliable water movement descriptions forms a considerable restriction for the description of the sediment transport.

During the tsunami event, with rising water levels erosion is expected to occur mainly of the beach and upper coastline. Part of the eroded sand is expected to be deposited inland. With retreating water levels erosion of the upper and middle shore is expected, and deposition at more offshore locations (as a bar).

The level contours of the hinterland may be relevant for the wave propagation and morphological consequences, as illustrated schematically in **Figure 12** below.

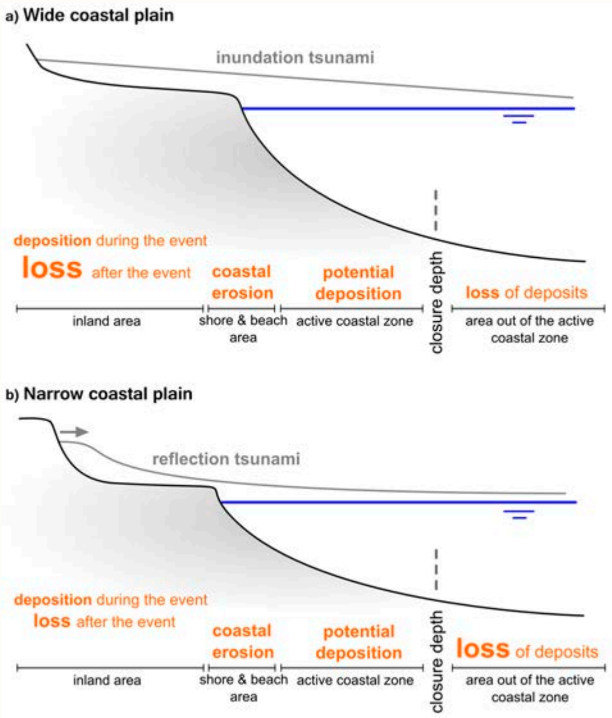


Figure 12 — Difference in tsunami propagation for wide and narrow near shore bathymetry profile

Box 2 — Morphological changes after Indian Ocean Tsunami *(cont'd)*

On wide coastal plains – such as the Banda Aceh area – wave energy gradually dissipates (friction, breaking) **(Figure 12a)**, resulting in a relatively large potential for partial sediment deposition inland. In that case significant volumes of sand may be transported from the shore and beach area to the inland area. Sand deposited inland is taken out of the active coastal zone and will not be available for coastal recovery. In other words, inland sand deposits can be expected to result in a permanent loss of sand from the coastal system, thus in a permanent post-tsunami coastline position landward of the pre-tsunami situation.

At some locations the tsunami wave reflected against mountains located close to the shoreline **(Figure 12b)**. In that case the above described potential for deposition inland is expected to be smaller, since sand will tend to remain in suspension in the turbulent movement of the incoming and reflected wave. In this case it is expected that most of the eroded sand will be deposited on the shore and possibly on the deeper foreshore. The water depth at which the sand is deposited may be considerable. Sand deposited above the closure depth (which is roughly estimated at MSL -10 m, to be confirmed in a later stage on the basis of wave data) will remain in the active coastal zone and can be expected to contribute to the recovery of the coast in the years to decades after the tsunami. Sand deposited below the closure depth (outside the active zone) should be considered as a permanent loss. Unfortunately no data seems to be readily available with which the percentage of deposition above and below the closure depth can be estimated.

2.3 Coastal hazards and Sea Level Rise

(Reference is made to the APFM Tool Paper *Flood Management in a changing climate*)

49 Of all potential climate change effects on coastal hazards, sea-level rise is probably the most important for deltas and coasts. Estimated current rates of sea-level rise are 2-6 mm per year, or 2-3 times higher than for the previous century (IPCC, 2007). Densely populated and heavily industrialized urban areas in, for instance, the Netherlands are already located below mean high water level, making them extremely vulnerable to future rise in sea level. But instead of looking at the absolute rise in sea level, it is more important to assess the rise relative to vertical movement of the land. While tectonic uplift exists in some coastal areas (e.g. in Scandinavia as a result of isostatic post-glacial processes), which partly offsets sea-level rise, other coasts experience subsidence. This often originates through a combination of geotechnical processes, such as compaction and chemical processes (e.g. oxidation of peat soils). Anthropogenic sources are also often involved, such as excessive groundwater exploitation. In coastal cities such as Bangkok and Jakarta this has resulted in extremely high subsidence rates of several cm up to locally 10 cm per year.

50 Combined with subsidence of the coast, sea-level rise can lead to a series of changes in coastal environments. The change of the land height with respect to the sea increases the flood risk during storm events because more land is exposed to lower storm heights. It also increases coastal erosion, thereby threatening human settlements and enlarging the area at risk from coastal flooding. Furthermore, sea-level rise and coastal subsidence lead to landward movement of the tidal influence and salt wedge in rivers, jeopardizing freshwater intakes for agricultural, industrial and domestic water supply systems.

3 COASTAL VULNERABILITIES AND RISKS

3.1 What makes people want to live at the edge of land and sea?

51 Formed by the interplay between rivers and sea, deltas and coastal plains have flat, highly fertile soils that are easy to till. They can be travelled across on its waters, full of fish. But as the sea gives, it can also take. Their low lying topography makes coasts vulnerable to storm surges and river flooding. If not through surface flooding, the seawater enters from below: seepage of saline groundwater poses a constant threat to crops.

52 Hence, people choose to dig, drain and develop. Land reclamation, irrigation, soil drainage and embankments have made many deltas hospitable, in assuming that a place to live safely has been built while living off the fruits of the land and sea. Several deltas have developed into the major granary or rice bowls of an entire country, such as the Red River Delta in Vietnam and the Godavari and Krishna deltas in India.

53 Besides agriculture, transport and industrial development, tourism also generates an increasing economic profit along the coast. For instance, the Mediterranean coast is the world's most important tourist's resort. Around 250 million travellers came to this region in 2001 (Sarda et al., 2004). The value of beaches in Spain can be as high as 700€/m²/year (Azira et al., 2008). Coastal storms have not diminished that.

3.2 Components of vulnerability

54 There are many definitions of flood vulnerability and vulnerability indices, both in verbal descriptions and mathematical formulations. However, there is a rather general agreement

that vulnerability (V) consists of three main components (Chavoshian et al., 2009, Turner et al., 2003, Marchand 2009, Birkman, 2006):

- Exposure *E*
- Sensitivity (also named as susceptibility or basic vulnerability) *S*
- Coping Capacity *C*

We can translate that into:

$$V = f(E*S)/C$$

55 Exposure relies heavily on the physical conditions where people live: in areas liable to flooding. Sensitivity relates mostly to the socioeconomic situation (livelihood) of the society. Coping capacity relates to the wide array of structural and non-structural countermeasures and mechanisms through which the people reduce their vulnerability. Hence, importantly: vulnerability has both a physical and socioeconomic dimension.

3.3 Differential vulnerability and resilience

56 A key aspect which has gained increasing attention is the difference in vulnerability between individuals, households or communities being exposed to the same risk. Social vulnerability assessments, household resilience and recovery studies as well as individual vulnerability based on age, race and health all focus on differential vulnerability (Winchester, 1992; Clark et al., 1998; Rygel et al., 2005: Cutter & Emrich, 2006; Amendola, 2004; Marchand, 2009). Therefore, one can say that natural disasters highlight the inequalities of societies. Hurricane Katrina has shown that this phenomenon is not restricted to underdeveloped or developing nations.

57 Although poverty is often seen as a root cause of vulnerability, the two are not identical. Income levels are only part of the story that explains vulnerability. Socio-cultural conditions are equally important. For instance, poor people living for generations in a hazardous environment are usually better prepared for natural vagaries than those that have migrated recently to a place unfamiliar to them. Economic growth can help reducing vulnerability by raising the living standard of the population. But social cohesion and equality are probably even more important, as they can tackle the root causes of vulnerability, which reflect the distribution of power in a society (Blaikie et al., 1994).

4 POLICIES AND MEASURES

4.1 Need for active coastal flood risk management

58 Of all potential impacts of a rising global temperature, sea level rise is probably the most important for coastal zones. Combined with soil subsidence, sea level rise can lead to a series of changes in the coastal environment. It increases coastal erosion, thereby threatening human settlements and enlarging the risk of coastal flooding. But sea level rise also leads to landward movement of the tidal influence and salt wedge in rivers, which jeopardizes freshwater intakes for agricultural, industrial and domestic water supply systems.

4.2 Protect, retreat or adapt?

59 A complicated factor to protect from coastal hazards arises from the fundamental reason of living in this area: the connection to the sea is an essential livelihood asset, as exemplified by the harbour and related industrial activities as well as the recreational value of the shoreline. This always makes structural measures a compromise. Traditional waterfronts are already a balance between tourists and livelihoods in many areas, such as the Mekong Delta and London. Storm surge barriers constructed across estuary mouths can be closed to prevent surges from entering the river, but need to be open under normal conditions to provide easy access for shipping and discharge of river water. Examples are the Thames Barrier near London and the Maeslantkering near Rotterdam. These apply mobile gates which can close or open the river mouth within hours. A similar barrier is currently being constructed for New Orleans (Jonkman et al., 2010).

60 The previous tsunami measures assumed such levels of tsunami that have occurred repeatedly in the past and are highly likely to happen in the near future. The massive tsunami caused by the March 11 earthquake far exceeded such assumptions, causing enormous damage. It was recognized anew that with breakwaters alone, it is difficult to protect towns behind them from tsunami that rarely occurs but is colossal in scale, and that there is a limit to depending on the

disaster-prevention functions of such structures though they are effective to a certain extent in lowering the height of the tsunami, delaying it from reaching towns, and maintaining the coastline as observed in the tsunami this time (MLIT, 2011).

61 Traditional protection measures (**Section 4.5**), such as dikes and storm surge barriers will remain a crucial element in any coastal flood risk management plan. However, there is an increasing attention towards using a broader range of measures, especially by actively using the services of coastal ecosystems (**Section 4.4**). Besides these measures, there is a whole gamut of non-structural measures, such as land use planning and adaptation mechanisms that can be used to make life in coastal zones less risky (**Section 4.3**).

4.3 Non-structural measures

62 The list of non-structural measures is long and includes coastal zone planning and land-management, early warning and evacuation procedures, protection of critical infrastructure, coping and insurance of (residual) risk, community preparedness, poverty reduction and self help. A selection of the main topics will be briefly described hereafter. Early warning systems will be discussed in the next Chapter on Coastal Risk Information Systems. Note that the term 'non-structural' refers to those measures that do not reduce the exposure to coastal floods but that aim at reducing the vulnerability and susceptibility of people and their goods living in the coastal zone.

4.3.1 Spatial planning

63 Historically environmental conditions played a major role in the spatial 'planning' of land and water use. The available natural resources as well as the transportation potential were major reasons to occupy coasts. Infrastructure development was necessary to take full advantage of the benefits coasts had to offer. Due to the debate on climate change as well as the occurrence of some major floods in the past few years there is a trend to take better account of the limitations and risks posed by the natural system.

64 One specific spatial planning measure for the coast is the set-back line. A setback line is normally defined as the landward limit of a buffer zone along the coastline where building restrictions or prohibitions are applied. The width of this buffer will depend on the associated physical, environmental and socioeconomic criteria.

65 The use of setback lines is basically a trade off between coastal development on the one hand and prevention of an unacceptable risk due to coastal erosion or flooding on the other. Many investors are either unaware of the risk, or do not think they are liable for any possible damage. Often only the commercial potential is included in the investment decision to build close to the sea while the risk is entirely disregarded (Winckel et al., 2007). Regional and national governments should however maintain a broader perspective of the issue, including the long term risks and the need for coastal resilience. This requires an assessment of the risk from coastal erosion as well as a procedure how to incorporate this risk into an economic cost-benefit analysis. An example of risk lines for coastal erosion is given in **Figure 13**. Furthermore, also ecological values and social motives, such as public access to the beach, can be included in the rationale for defining set-back lines.

Figure 13 — Example of risk lines for coastal erosion

4.3.2 Insurance

66 Insuring natural catastrophes (or **CatNat** as the insurance world calls it, according to the French language) has become more relevant over the past decades, but also more difficult, as these kind of insurances are not standard procedures and state involvement is necessary when large damages occur. For instance, in a densely populated and rich country such as the Netherlands the capital at risk is considerable and has increased significantly over the past decades. It is therefore a legitimate question if these investments can be insured against flooding. Since the big flood of 1953 the Dutch insurance industry has decided that the Dutch delta is so unusual that insurance is not a suitable option and CatNat was completely excluded from all insurance policies since 1956. Hence, when it comes to big floods it is generally the government that is held responsible and where damage relief funds are asked for (Schut, 2003).

67 Nevertheless especially the re-insurance industry is playing an increasing role in the CatNat field. For instance, Munich Re, one of the largest re-insurers, is working in many countries closely with governments and specialist insurance providers to set up catastrophe funds for insuring the agricultural sector against extreme weather events such as windstorm, drought, flood, and late frost (Munich Re, 2010).

68 Many developed countries, including Japan, France, the USA, Norway and New Zealand, have legislated formal public-private hazard insurance programmes. The US National Flood Insurance Program **(NFIP)** is unique in that the federal government serves as the primary insurer, and persons living in exposed areas should eventually bear their own risks. Catastrophe insurance instruments area also emerging in low-income countries in the form of (usually pilot) micro-insurance programmes (Linnerooth-Bayer, 2012).

4.3.3 Building codes and adaptations

69 The strength and condition of buildings are an important factor in the damage from floods and tsunamis. For instance, the vulnerability of buildings to tsunami loads will depend on several factors including number of floods, the presence of open ground floods with movable objects, building materials, age and design and building surroundings such as the presence of barriers. Modern building codes aiming for unified building codes such as the International Building Code (IBC, 2009) include design requirements and standards for fire, wind, floods and earthquakes, but they do not contain requirements for tsunami-resistant design (Cruz, 2012). It must be noted that it is generally not feasible or practical to design normal structures to withstand loads of big tsunamis.

4.4 Ecosystem services

70 Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food and water; regulation services such as regulation of floods, drought, land degradation, and disease; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious and other nonmaterial benefits (Millennium Ecosystem Assessment, 2005). Ecosystems play an important role in modifying and regulating hydrological and meteorological processes, and thereby affect the positive as well as the negative consequences of floods and storms. The functions of ecosystems range from the regulation of surface and sub-surface flow to the modification of wave dynamics in coastal and near-shore areas. Normal as well as flood flow regimes are affected by vegetation and its characteristics; hence, one important ecosystem service is to control floods and storms (Mirza et al., 2005).

71 In this respect we distinguish between the following services:

- Wave energy dissipation (through coral reefs, vegetation and geomorphology);
- Barrier to flooding (through natural terrain elevation, dunes etc.);
- Coastal stabilization / erosion control / sediment retention.

4.4.1 Wave energy dissipation

72 Reduction of high waves is especially important along coastal environments, where storm surges and tsunamis are among the most destructive forces of nature. Also in inland lakes and riverine environments wave reduction can be important, but to a lesser extent. Coastal ecosystems such as mangroves, coral reefs, seagrass beds and saltmarshes constitute elements that can physically exert an effect on waves. They cause a hydraulic resistance that can break the waves and reduce their velocity, thereby reducing the energy of the waves. Especially mangroves are able to significantly reduce the energy of huge waves such as storm surges that accompany cyclonic depressions. It is one of the main reasons for substantial mangrove rehabilitation efforts all over the world. Over the years these efforts show mixed results. It is therefore crucial to learn from these experiences in order to increase the success rate of mangrove restoration.

73 The role of coral reefs as submerged breakwaters is extensively studied (Kench and Brander 2006; Möller et al. 1999). This research shows that reefs constrain ocean swells, thereby transforming wave characteristics and consequently attenuating wave energy. Data from Grand Cayman demonstrated that wave attenuation was reduced by 20% and tidal current speed was reduced by 30% by the reef (Harborne et al. 2006).

74 In temperate areas similar services to coral reefs are provided by reef building shellfish species, such as mussels or oysters. These species are also clear examples of ecosystem engineers, in that they modify their local hydrodynamic and sedimentary surrounding (e.g. Folkard and Gascoigne 2009) and of foundation species, as they are able to construct hard substrate reefs in soft sediment areas. Reefs are soon colonized by anemones, sponges and algae that depend on hard substrate for settlement. Additionally, reefs offer refuge space for crabs, lobsters, shrimp and several fish species. Thus, shellfish reefs, similar to coral reefs, are an important source of marine food production by offering nesting and refuge area for mobile organisms. However, oysters and mussels themselves are of large importance for local food production as well. In many coastal areas communities have been building their livelihoods on mussel or oyster farming for decades.

75 Another property that shellfish reefs have in common with coral reefs is their ability to reduce local hydrodynamics (Borsje et al. 2011). However, in general shellfish reefs are considerably lower in height than a full grown coral reef. As a result, effects on reducing current velocities and wave dampening are more modest. In an example of reduction of wave heights over small oyster and mussel beds in a flume study, oysters were shown to reduce wave heights with 50% with low water levels (25 cm) and small waves (3.34 cm) (Borsje et al. 2011).

4.4.2 Barrier to flooding and elevated areas

76 Geomorphological features such as dunes and river levees are natural flood protection systems by providing barriers to flooding and higher areas to keep dry feet. Typically, dunes are formed at the interface between the coastline and the sea and can have an elevation which is significantly higher than that of the land behind it. In some places this land can even be below sea level, especially in delta areas (for instance in the Netherlands). Although the naturally formed dunes are usually characterized by small inlets and wash-overs, man often has closed these sea intrusions and thus formed a continuous high dune area that effectively protects the hinterland from flooding.

77 Historically, man has started settling first of all on the higher, sandier natural levees along the rivers and old beach ridges along the coast. An often encountered pattern of development is that towns and cities expand along these natural features, but later also settled in newly reclaimed land, that previously consisted of marsh or peat. Extreme flood events are likely to cause greatest damage and casualties in these low lying parts of the city (e.g. New Orleans).

4.4.3 Coastal stabilization, erosion control and sediment retention for deltas

78 Coastal vegetation plays a significant role in mitigating coastal erosion and promoting sediment deposition. Especially mangroves and saltmarshes are typical examples of 'ecosystem engineers', in that they modify their local hydrodynamic and sedimentary surrounding. This

make these ecosystems capable to adapting to rising sea levels provided the tidal movement is not restricted by human interference.

79 Natural sediment dynamics play an important role in delta formation and sustainability. Evidently, deltas are relatively young landforms shaped by the interplay of coastal and riverine processes. For example, the entire Yellow River Delta was formed in a period of slightly more than a century. Since 1855, when the Yellow River shifted its course from debouching in the Yellow Sea towards flowing into the Bohai Sea, each year up to several thousands of hectares of new land was formed (Liu & Drost, 1996). This rapid expansion of the delta is thanks to the enormous quantities of sediment transported by the Yellow River from the extensive Loss plateaux and from which the river has received its name. Although the Yellow River is quite exceptional in its sediment load, all other deltas have formed by the sediments brought in by their respective river and shaped by the interplay of tides, waves and currents.

80 Many of the deltas presently suffer from a sediment deficit, as has been evidenced by the research of Syvitsky and colleagues (Syvitski et al., 2005; Milliman & Syvitski, 1992; Syvitski & Milliman, 2007; Overeem & Syvitski, 2009; Syvitski et al., 2009). Partly this is the result of sediment starvation due to upstream developments (e.g. storage dams), but partly this is also the result of flood control measures. By preventing regular flooding of the delta, the river is not able to deposit sediments any longer. By protecting people from floods, also the benefits of flooding are lost, which, in combination with ongoing delta subsidence, leads to the problems many deltas now face.

81 Besides and in addition to these sand nourishments, also ecological engineering is being practiced. From the notion that mangroves can provide effective storm protection **(Box 4)**, there is increased attention to restore these coastal forests. Great potential exist to reverse the loss of mangrove forests worldwide through the application of basic principles of ecological restoration using ecological engineering approaches. Mangrove restoration can be successful, provided that the hydrological requirements be taken into account, which means that the best results are often gained at locations where mangroves previously existed, such as abandoned) aquaculture ponds (Lewis III, 2005; Stevenson et al., 1999;Samson & Rollon, 2008).

Figure 14 — Mangrove seedlings waiting for transplantation (Banda Aceh, Indonesia)

Box 3 — Example of storm protection by mangroves

Observations have revealed that Sunderban mangrove of Bengal suffer less from wind and surges (Ali and Chowdhury, 1997). The defensive role of mangroves during cyclones has been demonstrated at Bhitarkanika (Badola and Hussain, 2005), and by post-cyclone imageries of Orissa coast (Nayak et al., 2001). Casuarina trees often erode during storms but survive wind speeds of 100 km/h (Mascarenhas, 2004). This evidence supports bio-shields as efficient energy dissipaters during powerful oceanographic events (Mascarenhas & Jayakumar, 2008).

Since 1822, a total of 69 extreme cyclones landed on the Bangladesh coast of which 10 hit the Sundarbans mangrove forest. However, a cyclone that lands on the Sundarbans causes less damage compared to the likely damage caused the cyclone of equal magnitude lands on the central and eastern part of the coast. Most of the cyclone damage is caused by the surge. For example, a cyclone that landed on the Cox's Bazar coast generated 4.3 m surge caused deaths of 11,069 people in 1985. On the other hand, when a similar cyclone landed on the Sundarbans in 1988, the number of fatalities was just half of the 1985 cyclone (MEA, 2005).

4.4.4 From building against nature to 'Building with Nature'

82 Environmental considerations play a major role in the sustainable development of coastal zones. Concerns on environmental degradation have been institutionalized into environmental regulation. Almost no infrastructural development takes place without a proper environmental impact assessment. It is, however, not always easy to specify the environmental requirements to be met. These requirements are often subject of debate, and are sometimes hard, if not impossible to meet. That is why a different approach is being advocated. Not to try to minimize the negative environmental impacts, but in stead to make better use of the forces, interactions and materials present in nature. This approach reflects a shift in paradigm from building against nature to 'Building with Nature'.

83 The emphasis of the concept of Building with Nature is on sustainable development in densely populated coastal and delta areas. In implementing the method a new flexible dynamic equilibrium coastline is created using sand from the sea. The coastline may consist of a new primary range of dunes with a new beach in front. Solid sea-wall elements such as dams and dikes are kept to a minimum. The emphasis is on flexible soft structures in harmony with the sea, such as dunes and beaches. In the new coastline accretion and erosion are more or less balancing each other, only needing a limited maintenance through periodic beach nourishment.

84 The flexible integration of land-in-water and of water-in-land, in harmony with the natural environment, offers inherent flexibility and adaptability. Building with Nature has shown to be an environmentally friendly and economically advantageous concept. The concept is applicable in many settings and supports long-term sustainable solutions for the restoration of coastlines and habitats and in new approaches for land reclamation. The concept of is gaining acceptance worldwide.

Box 4 — Enhancing coastal safety by use of natural ecosystem engineers

Climate change involves rising sea levels and increased frequency and intensity of storms. Therefore, sustainable and cost-effective coastal protection is vital to low-lying coastal areas. Dikes and other civil-engineering structures are built for safety to flooding, but maintenance costs are high.

Salt-marsh vegetation is a good example of an ecosystem engineer: by reducing hydrodynamic forces, the vegetation traps and stabilizes sediments, leading to accretion, and reducing wave impact and flooding levels. Nowadays it is commonly known that dikes which are bordered by salt marshes require less height and enforcement. In the Netherlands, salt-marsh restoration is now combined with dike design in order to provide solutions that offer nature value, sustainable safety and a flexible basis for future dike adaptations, with sufficient space for additional uses such as recreation. Basic to this integrated concept is the understanding of functioning of salt marsh systems on a larger scale and in the context of the whole ecosystem. Ecosystem engineers may be present in different zones, facilitating each other. Species in the higher zones of the salt marsh are facilitated by species in lower zones, that absorb the energy of incoming waves. The tidal flat in front of the salt marsh, in turn, influences the intensity of incoming waves and supply of sediments.

Intertidal flats can be inhabited by oyster reefs. The reef-building oyster beds could function as stabilising or protecting agents, because they reduce wave intensity and current velocity, and provide an extra sediment flux to higher tidal elevations. After initiation or transplantation of reefs, natural processes may stimulate their maintenance and expansion. The newly formed ecotope will generate a diverse habitat, supporting a biodiverse community.

4.5 Engineering solutions

85 Generally, coastal structures such as groynes, detached breakwaters and artificial reefs are built to significantly reduce coastal beach erosion and to maintain a minimum beach for recreation. These structures are, however, no remedy for structural sediment deficiencies due to sea level rise, nor for dune erosion during conditions with relatively high surge levels (above the dune toe level). Seawalls and revetments are usually built in regions (along boulevards of beach resorts) where natural dunes are absent or have been removed for recreational purposes.

4.5.1 Costs of measures

86 It is difficult to make generalised cost estimations for measures, since this largely depends on local conditions, such as the design of the measure, the type of material used, local prices for labour and material etc. The costs can range from a few thousand Euros for localised protection measures to several millions of Euros for a complete restructuring of the coast. Hard structures (groynes, detached breakwaters) require relatively high capital investment plus the cost of maintenance works (storm damage, subsidence, scour problems, redesign, etc.) and costs of supplementary beach nourishment to deal with local erosion problems (opposite gaps and along the downdrift side). The use of soft shoreface nourishment requires less initial investments, but the cost of regular maintenance of the feeder berm (every 3 to 5 years) has to be added. Beach nourishment is twice as expensive as shoreface nourishments **(Table 3)**. In conclusion one could say that in general the differences in costs between hard and soft engineering solutions are relatively small. Other considerations, such as secondary effects, flexibility, amenity value etc. will often play a much larger role in the choice of the type of intervention (Marchand, 2010).

Table 3 — Unit costs for different kinds of shoreline protection (Marchand, 2010)

Type of structure	Construction + maintenance costs over 50 years (in Euro per m coastline per year)
Straight rock groynes	**50 to 150**
Rock revetments	**100 to 200**
Shoreface nourishments (every 5 years)	**100 to 200 (if sand is easily available)**
Sea walls	**150 to 300**
Beach fills (every 3 years)	**200 to 300 (if sand is easily available)**
Submerged breakwaters	**200 to 400**
Emerged breakwaters	**250 to 500**

87 There is ample evidence that coastal protection can greatly benefit from a resilience based approach. Many of the world's coastlines are highly dynamic by nature through the forces of winds, waves and currents. Hard engineering structures have more often than not led to increased erosion, either on the location itself, or at nearby, unprotected beaches. Instead, coastal practitioners are increasingly applying soft engineering measures, such as beach and foreshore sand nourishments. Modern modelling and surveying techniques are used to optimise these nourishments, whereby the question is how to best make use of the prevailing local physical conditions. A new approach of 'super-nourishments' is currently being under study in the Netherlands **(see Box 5)**.

Box 5 — Sand nourishment through Sand engine pilot

Sand nourishment is the mechanical placement of sand in the nearshore zone to advance the shoreline or to maintain the volume of sand in the littoral system. It is a soft protective and remedial measure that leaves the coast in a more natural state than hard structures and preserves its recreational value. The method is relatively cheap if the borrow area is not too far away (<10 km) and the sediment is placed at the seaward flank of the outer bar where the navigational depth is sufficient for hopper dredgers. Three types of nourishments are distinguished: beach-, shoreface- and dune nourishments (Van Rijn, 2008).

It should be noted that these kinds of measures need to be repeated every few years, because due to wave and current forces, these nourishments will be gradually spread out to the onshore and offshore direction. Typical lifetime of a normal shoreface nourishment is in the order of 5 years (Van Rijn, 2005). Therefore, also other alternative techniques of nourishments are being studied.

At this moment the potentials and risks of a 'super-nourishment' called 'The Sand Engine' in front of the Dutch coast (shoreface) are being investigated. Although the current beach nourishments are successful and effective for local coastline maintenance, such a super-nourishment could turn out to be more efficient in serving more functions than safety alone. The idea is to apply an extra amount of sand that would be redistributed by nature itself, thus stimulating natural dynamics of the coast, increasing a bufferzone for future sea level rise and enlarging the coastal intertidal zone which is beneficial for natural and recreational values alike.

4.5.2 Multifunctional use of infrastructure.

88 A promising way to respond to the increasing pressure on space is through multifunctional use of infrastructure. Revitalization of infrastructure opens new opportunities for multifunctional

use. Examples to be discussed later in this chapter include the transition of conventional embankments into super levees in Japan and the rehabilitation of the Closure dam of Lake in The Netherlands.

89 Multifunctional use of infrastructure may be especially promising for flood protection works. Linking flood protection to other development issues such as urban (re)development or nature development may be an attractive way to combine more immediate benefits of e.g. urban development with the long term benefits of flood protection. As such it may contribute to secure the necessary funds for improvement or maintenance of flood protection works.

4.6 Institutional and legal measures

90 Legislative measures for coastal flood management are on a cross-road between disaster risk reduction (DRR) instruments and coastal zone planning policies and strategies. In fact, many governments find themselves in the midst of a paradigm shift from traditional disaster management towards DRR as part of development planning (Lavell et al., 2012). New laws aimed at reducing disaster risks often follow the principles set out by the Hyogo Framework for Action (UNISDR, 2005). In **Chapter 6** more details are given on the relation between disaster risk reduction and governance and economic development, especially in view of a changing climate.

91 The legal framework in each country differs, but in general it consists of two main components, international and national law. The justification of international law derives from the consensus by states, which is technically expressed by conventions, treaties and agreements of various kinds. An example of international law is the European Flood Risk Directive. This Directive obligates each Member state to prepare flood risk maps for their territory and to develop management plans to deal with these risks. An example of a national law is the Dutch Water Law (Waterwet). Included in this law is a regulation to monitor the actual condition of the flood control system, such as dikes and dunes, and ensure its safety levels.

92 Also the institutional framework for coastal protection and planning differs considerably from each country. Sometimes it is highly decentralised, such as the waterboards in the Netherlands, but often (parts of) responsibility for the coastal management is given to national agencies, such as the Corps of Engineers in the USA and the Water Development Board in Bangladesh (BWDB).

93 It is good to note that modern flood risk management cannot be dealt with by laws alone. It also implies another distribution of responsibilities. Whereas flood prevention is basically a government responsibility, reduction of impacts is a joint responsibility of government and citizens. This is illustrated by the approach to flood risk management in coastal Louisiana **(see Box 6)**.

Box 6 — Flood risk management in coastal Louisiana

Louisiana's *Comprehensive Master Plan for a Sustainable Coast* (2007) indicates that levees are not the answer for every south Louisiana community. Since there are not enough federal dollars or available land to build levees everywhere flooding occurs, the Master Plan highlights ways in which citizens themselves can reduce their risks. The plan recommends that citizens take advantage of the Community Rating System, which can help homeowners reduce their insurance premiums if they raise or retrofit their homes. Making sure their communities curtail development in wetlands and flood prone regions is another measure that can lower flood risks as well as premiums. The plan's emphasis on non-structural solutions highlights the role citizens of the coast can play in making south Louisiana a safe place to live and work.

5 COASTAL RISK INFORMATION SYSTEMS

5.1 How can we determine coastal hazard and risk?

94 For the calculation of a risk it is crucial to have knowledge about the probability that an extreme event will happen. This could be a high river discharge caused by heavy rainfall in the catchment, a deadly storm surge generated by a combination of spring tide and strong winds, or a tsunami triggered by an earthquake. Essentially, many of these phenomena are stochastic, which means that their occurrence is difficult to predict. Luckily we have historical records of past events, and therefore we can use (extreme value) statistics to identify the threat. Models that simulate the extreme event, such as high rainfall in a river catchment or a storm at sea are used to calculate the hydraulic load, such as the water level. Probability methods are also used in assessing the chance of a failure **(Figure 15)**.

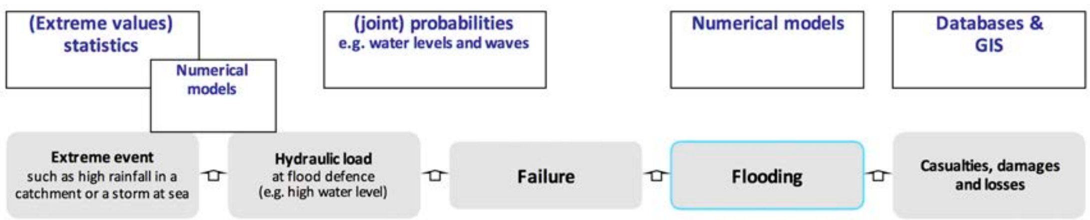


Figure 15 — Estimation of extreme events and their consequences

5.2 Flood hazard modelling

95 Being the driving force of the coastal hazard, weather (un)predictability also determines the (un) predictability of the Sea Surface Height **(SSH)** and waves associated with it. Therefore, forecast of flood hazard using models is being done in many countries using different approaches, depending on the predictability of weather conditions, the lead time required and the availability of computing power. In essence, at present, there are three common approaches of forecasting the probable occurrences of flood hazard:

- Empirical and/or Look-up table method;
- Deterministic method;
- Probabilistic method.

5.2.1 Empirical and/or Look-up table method

96 This forecast method is based on analysis of data on past events that has been collected, leading to a kind of empirical (or analytical) relation between SSH measured at a limited number of tide gauge stations that is available in (near) real time mode to other coastal locations where a forecast is needed. The method is applicable when a reasonably consistent relation can be derived, taking into account the travel time of tides and surge along the coast.

97 For waves, a similar but slightly different method may be applied, by relating the wave at a number of offshore wave gauges to wave heights at coastal locations for different prevailing wind conditions. The relation is determined by analysing the data from the past or by running wave models for past and hypothetical events. The outcomes of such analysis are stored in a table. Hence the name: look-up table **(LUT)**.

98 Once the sea surface heights and wave conditions at coastal locations have been determined, these can be translated into their potential for generating inundation along the coast given the local bathymetry and defense system using experiences from past events or some kind of a formulae (e.g. wave overtopping formula).

99 A coastal hazard forecast system based on this method, though not very accurate, is easy to set-up and does not need complex and detailed numerical models that would require major computer resources. It merely requires sea surface height data and wave data from a limited number of stations (or from a coarse grid numerical model) to produce a forecast over the entire coastal area. Although this method is still being applied, it is being gradually replaced by numerical storm surge and wave models thanks to the increasing availability of affordable computing power with high performance.

5.2.2 Deterministic approach

100 For a slow evolving weather system with a good short term predictability (e.g. 48 hours), deterministic forecast for coastal hazard based on a single prevailing weather forecast could be applied for determining the associated upcoming surge, wave set-up or flood event. An example of slow evolving system that can be predicted quite reliably in short term is for example extra-tropical storm systems. As the weather forecast is updated on regular intervals

(3, 6 or 12 hourly), the flood / surge hazard computation is also updated with the same interval to follow the evolvement of the risk. The deterministic approach yields a single forecast value of the hazard at each coastal location for the forecast cycle and its accuracy depends mainly on the accuracy of the weather forecast. To increase the accuracy of the forecast often data assimilation techniques are applied to take into account observed data further away from the area of interest.

101 An example of a country that applies this approach is The Netherlands. Its forecast system is used to determine whether or not to close the storm surge barriers automatically which protects the Southern part of the Netherlands from high surge levels and flooding. The model sets applied contains a limited-area atmospheric model, the output of which drives a surge forecast and wave model called the Dutch Continental Shelf Model (Gerritsen et al . 1995; see **Figure 16**).

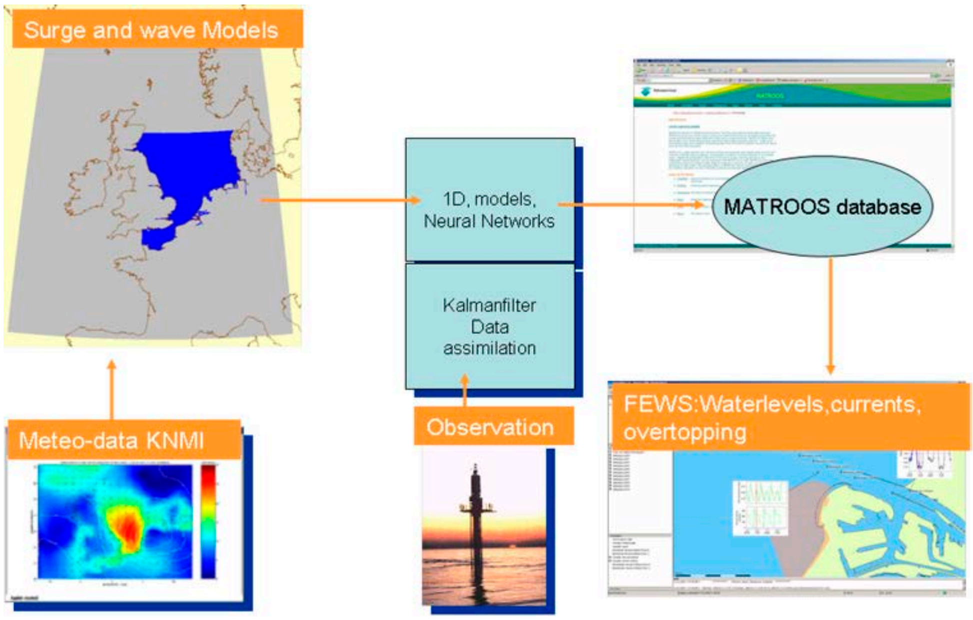


Figure 16 — Dutch coastal hazard forecast system

102 Another reason for applying a deterministic approach for forecasting coastal hazard, even for less predictable weather systems such as tropical cyclones, is the limitation of computation resources of the forecasting agency. An example of such kind of system is the operational Storm Surge and Flood Forecast System for the East coast of India (Vatvani, 2002; **see Figure 17**). This system is embedded in a GIS-based decision support system containing models for the prediction of:

i atmospheric pressure and wind speed and direction;

ii tides and storm surges;

iii rainfall;

iv flooding of low-lying coastal areas;

v wind damage.

103 The main driving force for the surge model is the high spatial and temporal resolution representation of the cyclone wind and pressure based on the forecast cyclone parameters

(tracks, intensities and pressure drop). A novel feature of the system at that time was the coupling to the river models to simulate the overland flooding of the coastal zone and river delta areas. The system has been validated using a number of actual cases including the super-cyclone Orissa. It was demonstrated that the surge and flooding model was able to reproduce the inundation with a high degree of accuracy.

104 The same system was also used to produce probabilistic flood hazard maps with different recurrence intervals linked to the cyclone strength. So the warning issuance is decided not only by looking into deterministic result, but also by taking into account the track uncertainties and link it to the flood hazard maps available for the expected cyclone strength.

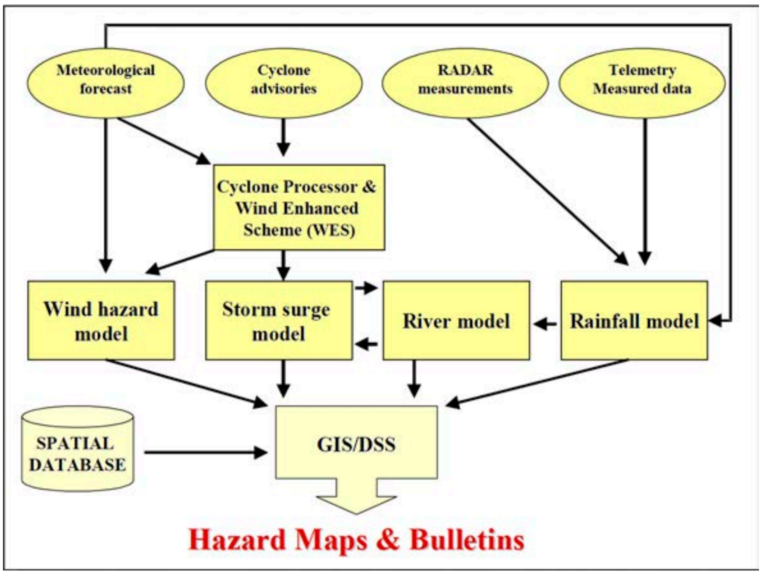


Figure 17 — Components of a real time early warning system for cyclones in Andhra Pradesh, India

5.2.3 Probabilistic approach

105 For less predictable (i.e. fast evolving) weather systems, forecast of hazards in real time dictates that probabilistic modelling methods should be applied. Different variations of the weather conditions with statistically different probabilities of occurrences will yield different prediction of the hazard with the same probability of occurrence as the weather forecast used to predict the hazard. Prediction of tropical cyclone tracks, intensity and size, even 48 hours before landfall, can show a large error. Figure 18 shows the development of track error prediction in the Atlantic basin for the last 40 years. The figure shows that occurrence of extreme surge on the coast using the track prediction with 48 hours lead time may still shift in location with +/-80 nm (150 km).

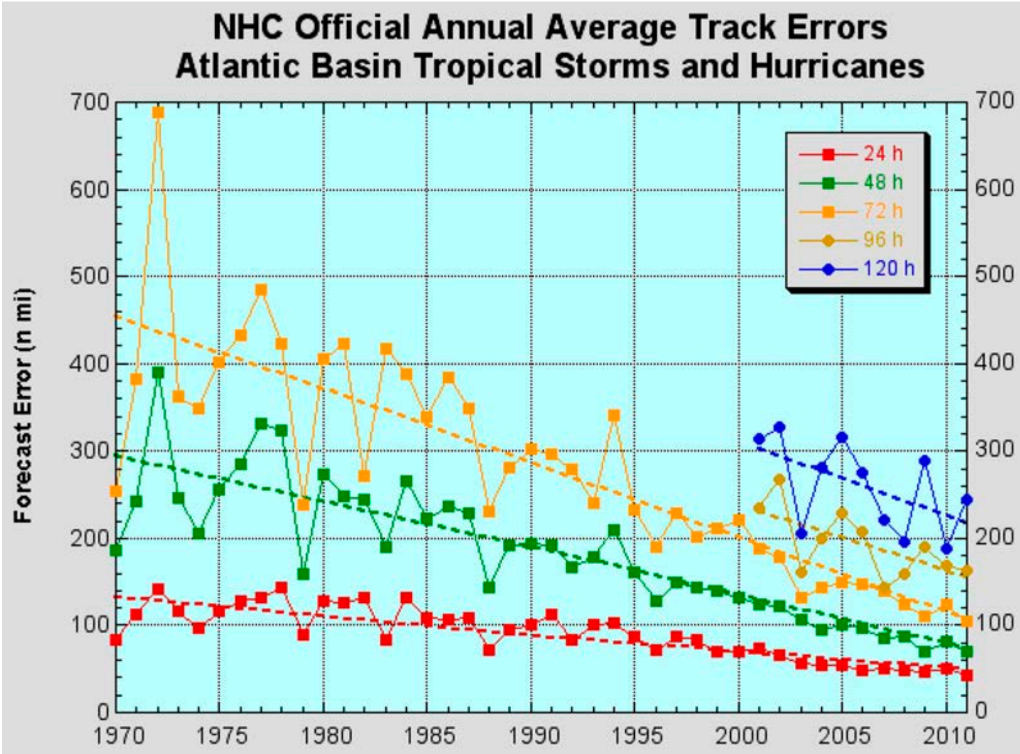


Figure 18 — 40-year development of forecast track errors of tropical cyclone in the Atlantic basin (NHC NOAA)

106 To overcome this issue, forecast of coastal hazard for tropical cyclone system should in principle be carried out in probabilistic mode, by synthesizing variations to the predicted tracks (strength and size) and attaching different probabilities to them and run the coastal model to produce storm surge, wave and flooding with the associated probabilities attached to it. The probabilistic method will yield different values for the hazard at each coastal location and one of the challenges is how to present the different model outcome in a comprehensible manner **(example in Figure 19)**.

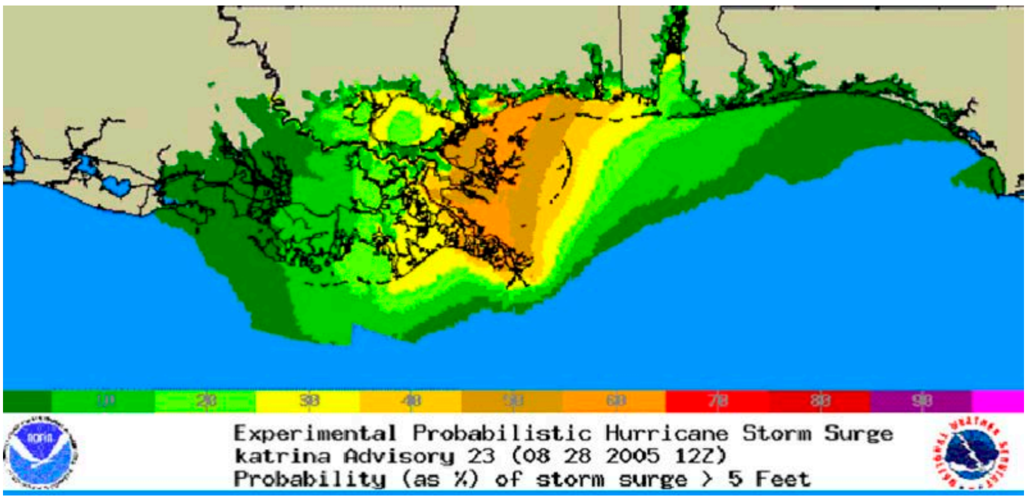


Figure 19 — Probability of storm surge at landfall based on variations of track prediction 1.5 days before landfall

107 Another source of unpredictability for the weather is the nature of the weather systems which is complex and non-linear, where small errors can quickly grow to produce significantly different

outcomes, especially for predictions with longer lead times **(see Figure 20)**. To overcome this issue, one resorts to ensemble predictions where several forecasts are run, using slightly different initial conditions, boundary conditions, and/or model physics. These are chosen to sample the range of uncertainty in model inputs and formulation so that the corresponding forecasts will sample the range of possible results that are consistent with those uncertainties (Flowerdew, 2009).

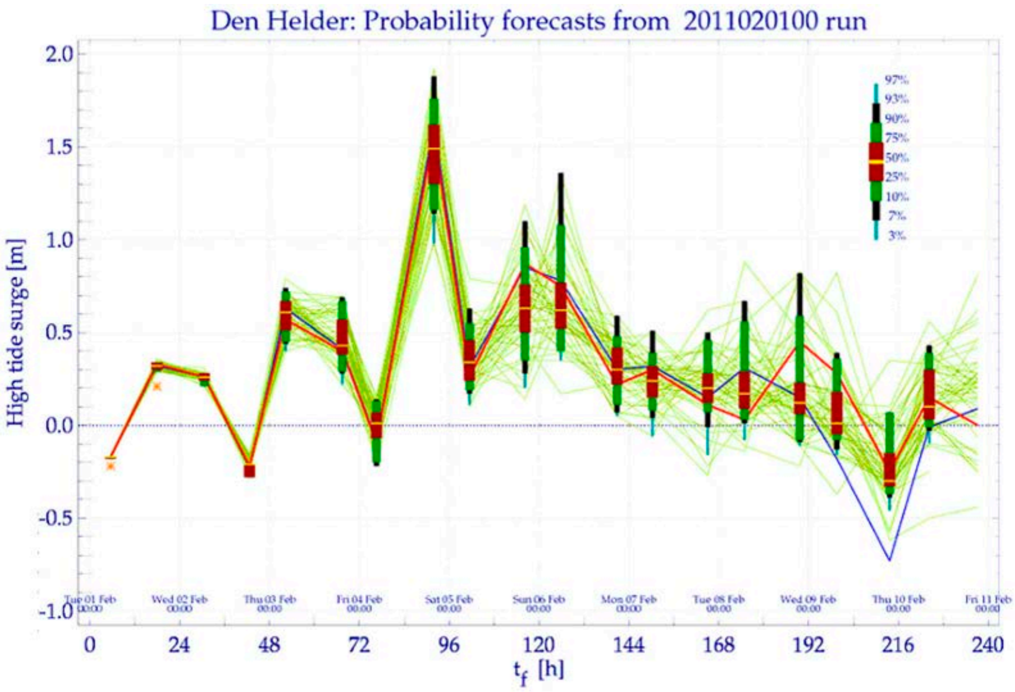


Figure 20 — Outcome of a 10 day storm surge run for Den Helder (in the Netherlands) using an ensemble weather forecast (Verlaan, 2005)

5.2.4 Recent developments

108 Since 2010, WMO/JCOMM has initiated a new initiative to improve inundation forecasting under tropical cyclone conditions called *Coastal Inundation Forecasting Demonstration Project* or CIFDP **(Figure 21)**. The CIFDP concept is meant to be applied in operational forecast settings. The selection of the model components depends on the dominant effects in the coastal areas that need to be modelled. The effects of Mean Sea Level Anomalies (MSLA) and meso-scale eddies that combined can add up 1 m to the prevailing water levels during the storm events is included. The effects of riverine flooding due to heavy rainfall often associated with tropical cyclone, just as the system developed for India, is included as well.

109 The implementation of CIFDP is currently underway in Bangladesh, the Dominican Republic and in Fiji using different model components.

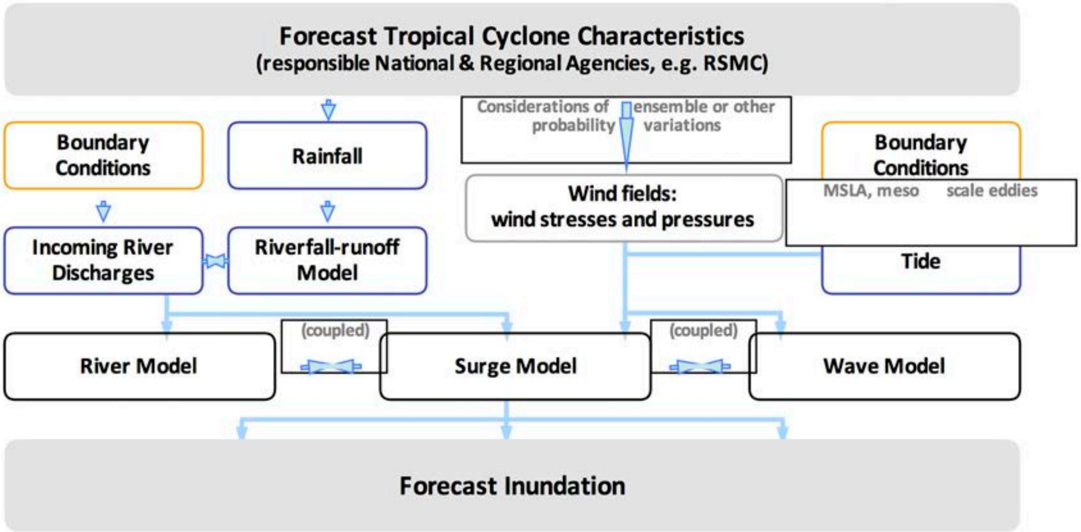


Figure 21 — Operational forecast model concept (CIFDP)

5.3 Vulnerability assessments

110 A vulnerability assessment **(VA)** can be described as a systematic evaluation of the vulnerability of an entity (a household, a community, region, nation, etc.) with respect to different types of hazards, often with the aim to reduce that vulnerability. The procedure and approach of a VA logically depends on the specific context as well as on the definition of vulnerability that is chosen.

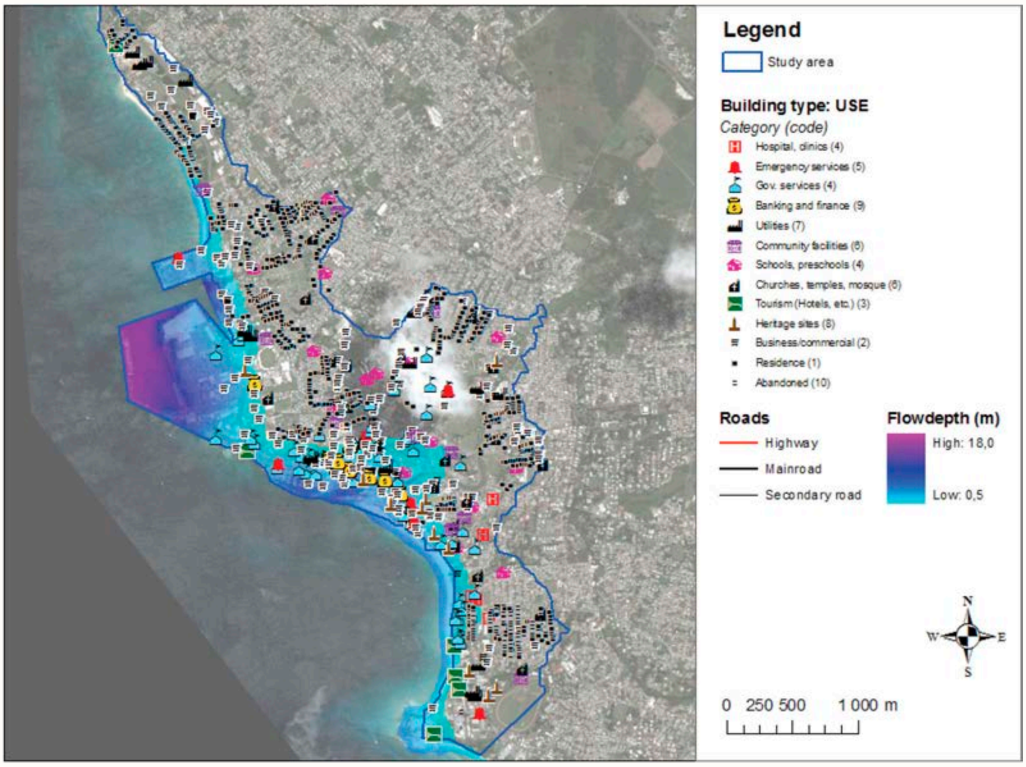
111 A wide range of methods has emerged that models the hazard and its direct consequences (but leaving out the longer term consequences). Covering only a part of the vulnerability equation, these damage and casualties assessments do provide essential quantitative information to assess vulnerability. And they are probably the most widely used quantitative assessments worldwide. Examples are damage and casualty assessments **(DCA)** of a large scale flooding in the low lying parts of the Netherlands (Anonymus 2005; Van der Veen & Logtmeijer 2005), flood risk maps for the Scheldt river in Belgium (Strubbe et al. 2005); and tsunami vulnerability mapping for Barbados **(Box 7)**. The use of these sophisticated models is mostly to identify areas at risk, which can then be published as 'hazard maps' and used in spatial planning, for insurance purposes and for evacuation plans. An example is the Flood Insurance Rate Map (FIRMS) of FEMA (USA). A recent modernization of these maps includes the effects of a tsunami (Wong et al. 2005). Also 'HAZUS-MH' needs to be mentioned here. HAZUS-MH is a nationally standardized risk assessment model developed by FEMA to estimate damage and loss from natural and man-made hazards. It includes modules to assess the damage and economic loss by earthquakes, hurricanes and floods (FEMA 2007).

112 An example of a more qualitative based risk map is given in **Box 8**, for the islands of Sao Tome and Principe. This example shows that even without sophisticated models and coastal data a first indication can be given as to which areas are most vulnerable to flooding.

Box 7 — Tsunami vulnerability mapping for Barbados

Together with the University of the West Indies and with support from the support from the Coastal Zone Management Unit Barbados **(CZMU)**, NGI has completed. Within a two years capacity building program on natural disaster mitigation in the Caribbean, a pilot study of vulnerability mapping for tsunamis was prepared for Bridgetown, Barbados (NGI, 2009). The numerical modelling of tsunami inundation in Bridgetown is based on the tsunami earthquake scenario east of Guadeloupe ("Lesser Antilles scenario") with a return period in the order of magnitude of 500 years. The example study shows the following results for the "Lesser Antilles scenario":

- The "banking & finance" sector would be considerably affected: 8 out of 8 surveyed banking & finance buildings would be affected.
- Emergency services would be considerably affected: 4 out of 7 surveyed emergency services would be affected.
- The commercial sector in the city centre (around the river mouth) would be affected considerably.
- The coastal road would be unserviceable within almost the entire study area.
- Tourism would be considerably affected, due to the fact that the harbour, the beaches, and many heritage sites would be affected.



Critical facility map of all surveyed buildings in the city of Bridgetown, Barbados for the "Lesser Antilles scenario" (NGI, 2009)

From the analysis conducted by this study, it can be stated that the study area within the city of Bridgetown is clearly vulnerable to a tsunami event. This statement is supported by the observations of high population densities and high structural vulnerability. The apparent lack of preparedness adds to the already high vulnerability of this area. Moreover, a significant proportion of the governmental services are located within the study area. This could significantly affect the country's ability to recover after a natural disaster.

Box 8 — Flood risk mapping for Sao Tome & Principe

As part of a study on Climate Change and Coastal Adaptation, UNESCO-IHE and Deltares prepared a risk map for the village of Malanza. This is a small fishing village on the island of Sao Tome at the Atlantic Ocean. Although there was little hydrological and coastal data available, qualitatively defined flooded areas were determined from the river and from the sea. A storm surge event with a return period of 100 years, combined with the run-up due to a 1-in-100 year wave height was assumed. Also the area was indicated which may be additionally flooded if the sea level would rise by 0.79m by the end of the century. The results were used to prepare a flood risk map, showing risk classes from high to very low.

Risk map class	Characteristics, qualitatively defined, on the basis of information on Google image of 30-7-2005
1a high risk	Flooded from the river 1-2 times per year for a number of days, in the period Nov-Dec; largely build up with houses; additionally flooded by the sea due to sea level rise of 0.79m by 2100
1b high risk	Flooded by the sea 1-2 times per year for a number of days, in the period June-Sept; largely build up with houses, including some important community buildings
2 medium risk	Flooded by the sea 1-2 times per year for a number of days, in the period June-Sept; only partly build up with houses; suffers from stagnant water during rains due to malfunctioning of drainage system
3a low risk	Flooded by the river 1-2 times per year for a number of days, in the period Nov-Dec; only partly build up with houses. Additionally flooded by the sea due to sea level rise of 0.79 cm by 2100;
3b low risk	The part east of the river is only flooded by the sea due to sea level rise of 0,79m by 2100 and suffers from stagnant water during rains, due to malfunctioning of drainage system
4 very low risk	Only flooded by the sea at sea level rise of 0.79 m by 2100

Flood risk map Malanza Risk map class

6 MAINSTREAMING COASTAL FLOOD RISK MANAGEMENT

6.1 From disaster response to risk reduction

The Hyogo Framework **(Box 9)** is an important point of reference with regard to the overall approach and philosophy of disaster management. Many countries have their own disaster management department or agency in order to streamline and coordinate disaster emergency relief, recovery and rehabilitation activities. They mostly began as or are response oriented organisations. Increasingly these agencies are concerned with disaster preparedness and risk reduction activities. But while doing so, they need to cooperate with line departments working in different fields such as housing, water management and regional planning. In many countries, however, there is a lack of sufficient national and intersectoral coordination impeding the wider implementation of national strategies (UNISDR 2005). And although implementation takes time, it is a great advantage that governments increasingly recognize the important shift from disaster response to risk reduction, taking into account the entire spectrum of the disaster cycle.

Box 9 — The Hyogo Framework of Action 2005-2015

Governments around the world united at the World Conference on Disaster Reduction (2005) to adopt the *Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters*. It is a global blueprint for disaster risk reduction efforts during the next decade. Its goal is to substantially reduce disaster losses by 2015 – in lives, and in the social, economic and environmental assets of communities and countries. It has three strategic goals:

1. The more effective integration of disaster risk considerations into sustainable development policies, planning and programming at all levels, with special emphasis on disaster prevention, mitigation, preparedness and vulnerability reduction;
2. The development and strengthening of institutions, mechanisms and capacities at all levels, in particular at the community level, that can systematically contribute to building resilience to hazards;

Box 9 — The Hyogo Framework of Action 2005-2015 *(cont'd)*

3 The systematic incorporation of risk reduction approaches into the design and implementation of emergency preparedness, response and recovery programmes in the reconstruction of affected communities.

Priorities for action have been formulated to guide states, organisations and other actors at all levels in designing their approach to disaster reduction:

1 Make disaster risk reduction a priority: ensure that disaster risk reduction is a national and a local priority with a strong institutional basis for implementation.

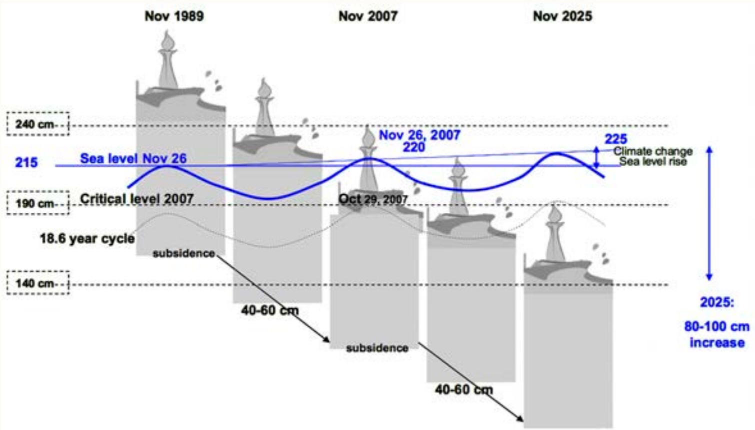
2 Know the risks and take action: identify, assess, and monitor disaster risks – and enhance early warning.

3 Build understanding and awareness: use knowledge, innovation and education to build a culture of safety and resilience at all levels.

113 An example of an integrated approach that combines flood risk reduction with urban development and spatial planning is the Jakarta Coastal Defence Strategy. Because the flood risk is a function of many factors, its solution includes traditional flood protection but also aims to solve drinking water supply problems, water pollution and traffic jams **(Box 10)**.

Box 10 — Jakarta Coastal Defence Strategy (JCDS)

Jakarta is a rapidly developing city, located on the north coast of Java, Indonesia. Flood risks in Jakarta can be characterized by flooding from the sea, from rivers and from rainfall, aggravated by land subsidence as a consequence of excessive deep groundwater extraction for water supply. The JCDS is a project to develop a coastal defence strategy.



Land subsidence in Jakarta compared to the flooding event induced by the 18.6 year tidal cycle in November 26, 2007. The upper blue line shows that expected effect of sea level rise is only marginal.

The overall aim of JCDS is to protect Jakarta against coastal flooding. To do this, a strategic plan has been developed that "integrates effective technical solutions to prevent flooding (dikes, retention ponds, pumps) with additional measures to make the technical solutions sustainable (piped water supply, sewerage and sanitation, resettlement), and with investment opportunities to make the overall plan financially feasible based on internal cross-subsidies and public-private partnership (land reclamation, toll roads, and deep seaport)". An important aspect of the plan is integration. It therefore also aims to solve drinking water shortages, river pollution, and traffic jams, and to turn Jakarta into an "attractive place to live, work and invest". Measures to prevent flooding and measures to decrease the amount of subsidence will be planned in three phases until 2030.

6.2 Development of adaptation strategies for climate change

114 Making coasts climate-proof requires new adaptation strategies which are timely, technically sound, economically feasible and socially acceptable. However, both climate change and socio-economic developments come with large uncertainties. In order to develop adaptation strategies for climate-proof coasts, fundamental questions need to be answered, such as:

- What are the requirements which the key economic sectors (e.g. agriculture, transport, energy, tourism, industry) and nature put on coastal zone management?
- Under what circumstances do current strategies fail to meet those requirements (when, where, how often)?
- What are the adaptation options that will allow us to keep on living and working in the coasts?
- How much time is available to implement this adaptation?

115 To answer such questions an integrated method is required to assess the vulnerability of coasts and to determine adaptation paths for the different sectors. One of the key-elements in such method is the so-called adaptation tipping point. An adaptation tipping point identifies the point where a policy on water management or spatial planning needs to be revised and where a new strategy needs to be implemented. It can be determined by the level where natural (physical) boundary conditions exceed technical, economic, spatial or societal acceptable limits (Deltares, 2008).

116 **Figure 22** presents an example on the suitability of a coastal zone for human settlement as a function sea level rise. The solid line represents the present flood protection strategy, which can cope with a 1.5m sea level rise. The dotted line represents a new adaptation strategy, which is able to cope with a much larger sea level rise. The adaptation tipping points are indicated as an (*). The risk of coastal flooding might at first be reduced to an acceptable level by intensified shoreline management. If that strategy reaches its limits it needs to be replaced by another strategy, for instance the construction of super levees.

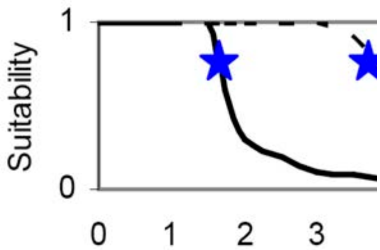


Figure 22 — Examples of the relationship between natural boundary conditions and the suitability of a strategy.

117 The adaptation tipping points method takes the requirements of key sectors of water management and spatial planning as a starting point to identify the need for adaptation to climate change. The degree of climate change to which each key sector can cope is determined. Climate change scenarios are then used to show in which time period those adaptation tipping points may be reached. This provides insight into the vulnerability to climate change of deltas and coasts. Combining the adaptation tipping points with local scenarios will identify the vulnerability of a sector and the possible need for new adaptation strategies.

118 The timing of adaptation tipping points is crucial knowledge for decision makers. Knowing how long it will take before adaptation tipping points are exceeded makes the timeframe for decision-making explicit. The timeframe for a certain adaptive measure can be estimated by using climate change scenarios and socio-economic scenarios. Some adaptive measures will have to be implemented soon; others in the next 20 or 50 years or even later.

119 The method may also help to develop a sequence of adaptations strategies, so-called, adaptation paths **(Figure 23)**. Replacing Strategy 1 by Strategy 2 will happen at a certain level of climate change. It could even lead to a higher efficiency in use of the coastal area. When the efficiency of the final strategy becomes too low, retreat from the coast becomes unavoidable. The Thames Estuary 2100 project in the UK is a nice example of adaptive management using tipping points: the strategy for flood risk management will vary depending on the expectations of sea level rise.

Figure 23 — Adaptation paths to climate change for water management.

6.3 Governance of coastal flood risk management

120 Governance has many dimensions: political, organizational, social and economic. In the context of this tool paper, governance is related to creating the proper conditions for a sustainable coastal development. Good governance should promote that plans and visions for coastal development are actually brought into practice through development projects. Governance should also provide adequate arrangements for maintenance of infrastructure preventing early deterioration of the infrastructure.

121 The governance structure of coastal zones may be strengthened through different ways:

- Promoting a better co-operation between different levels and sectors of government taking into account trends of decentralization and the need for (national) coordination.
- Facilitating the cooperation between government and the private sector taking into account trends of privatization but also the need to safeguard the public interest.
- Better involving stakeholders and citizens in development and management issues to promote the societal acceptance of development projects as well the long term sustainability of development projects (arrangements and incentives for maintenance).
- Creating arrangements for dealing with uncertainties and sharing of risks (insurance).

6.3.1 Linking river basin management and coastal zone management

122 Since the UNCED Conference in Rio de Janeiro, the link between river basins and coastal areas has been increasingly highlighted in several fora. Two key management approaches have been promoted in the post UNCED years to promote sustainable development of river

basins and coasts: Integrated Water Resources Management **(IWRM)** and Integrated Coastal Zone Management **(ICZM)**. The concepts of IWRM and ICZM have been developed rather independently from each other by separate management organisations, frequently with different objectives and modes of operation. Often estuaries and coastal areas were not considered to be part of the river basin.

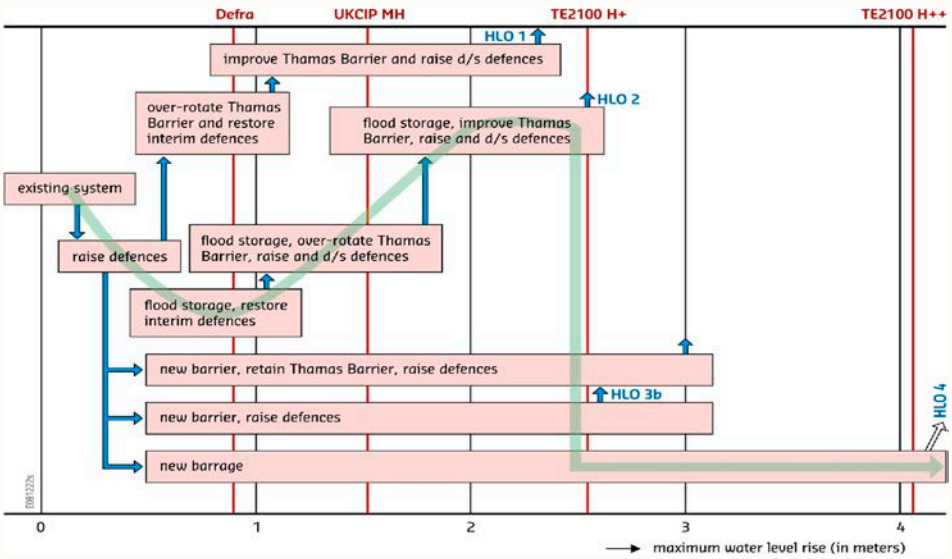
123 The IWRM paradigm encouraged a shift from single sector water planning to multi-objective planning and integrated consideration of land and water resources. IWRM also recognizes the wider socio-economic and development goals and promotes crosssectoral coordination. ICZM is a process by which rational decisions are made concerning the conservation and sustainable use of coastal and ocean resources and space. The process is designed to overcome the fragmentation inherent in single-sector management approaches (such as fishing operations, oil and gas development).

124 The last ten years have made clear that the advancement of coastal or river basin issues cannot be solved by ICZM programmes and river basin management **(RBM)** programmes working in isolation. Linked management is often the only realistic way to maintain or improve the ecological integrity and socio-economic viability of the coastal and marine areas. Recently, the linked management of river basins and coastal and marine areas is recognized to be a characteristic feature of an Ecosystem-based Management. This is also illustrated by the publication Ecosystem-based Management: Markers for Assessing Progress (UNEP/GPA, 2006).

Box 11 — Thames Estuary 2100: adapting to sea level rise

Climate change will cause sea levels to rise and will also affect the scale and frequency of tidal surges, but there is uncertainty on the nature of this change. Thames Estuary 2100 is looking at how to manage tidal flood risk through the century. It includes an assessment of the useful life of the existing defenses as well as the development of an understanding of the 'drivers' for change in the estuary (i.e. climate change, urban development, social pressures and the environment).

The plan will be adaptable to climate change and to a changing estuary. Depending on the scenario for sea level rise various types of measures are being considered, including raising of existing embankments and the construction of a new barrier. The figure shows a number of strategies over time in relation to projected sea level rise.



REFERENCES

A

Ali, A. and J.U.Chowdhury, 1997 *Tropical cyclone risk assessment with special reference to Bangladesh.* Mausam, 48 (1997), pp. 305–322

Amendola, A. (2004) *Management of change, disaster risk and uncertainty: an overview.* Journal of Natural Disaster Science 26: pp. 55-61.

Anonymous (2005) Veiligheid Nederland in Kaart: *Hoofdrapport onderzoek overstromingsrisico's.* DWW-2005-081. Delft, Rijkswaterstaat DWW.

Ariza,E., Jiménez,J.A. & Sardá,R. (2008) *A critical assessment of beach management on the Catalan coast.* Ocean & Coastal Management, 51, 141-160.

B

Badola, R. & Hussain, S.A. (2005). *Valuing ecosystem functions: an empirical study on the storm protection function of Bhitarkanika mangrove ecosystem, India.* Environmental Conservation, 32 (2005), pp. 85–92

Barlow, Paul M. (2003). *Ground water in fresh water-salt water environments of the Atlantic Coast.* U.S. Geological Survey circular; 1262.

Battjes, J.A. & H. Gerritsen (2002). *Coastal modelling for flood defence.* Phil. Trans. R. Soc. Lond. A. 260, 1461-1475

Birkmann, J. (2006) *Measuring vulnerability to natural hazards -towards disaster resilient societies.* United Nations University Press, Tokyo, New York, Paris.

Blaikie, P., Cannon, T., Davis, I. & Wisner, B. (1994) *At Risk -Natural hazards, people's vulnerability, and disasters.* Routledge: *London.*

Bormann , P. (2006). *Tsunami Information Sheet (Version 06/03).* GeoForschungsZentrum Potsdam

Borsje, B. W., B. K. van Wesenbeeck, F. Dekker, P. Paalvast, T. J. Bouma, M. M. van Katwijk, and M. B. de Vries (2011). *How ecological engineering can serve in coastal protection.* Ecological Engineering 37:*113-122.*

C

Chavoshian, A., K. Myake, T. Sugiura, P.T. Hai & L. Rajapakse (2009). *Charting ICHARM's strategy for integrated flood risk management in the Lower Mekong River Basin.* AMFF-7.

Clark, G. E., Moser, S.C., Ratick, S.J., Dow, K, Meyer, W.B., Emani, S., Jin, W., Kasperson, J.X., Kasperson, R.E. & Schwarz, H.E. (1998), *Assessing the vulnerability of coastal communities to extreme storms: the case of Revere, Ma., USA.* Mitigation and Adaptation Strategies for Global Change3: pp. 59-82.

Cruz, A.M. (2012). *Protection of infrastructure.* Chapter 56 in: *B.* Wisner, J. C. Gailard and Ilan Kelman (editors). *The Routledge handbook of hazards and disaster risk reduction.* Routledge, London and New York.

Cutter, S. L., & Emrich, C.T. (2006) *Moral hazard, social catastrophe: the changing face of vulnerability along the hurricane coasts.* Annals, AAPSS604: pp. 102-112.

E

EEA (2003). *Europe's water: An indicator-based assessment.* Topic report No 1/2003.

EM-DAT (2013). *The OFDA/CRED International Disaster Database.* Université Catholique de Louvain, Brussels (Belgium)
www.emdat.be

F

FEMA. HAZUS-MH (2007) *Hurricane Wind Model Validation Study - Florida.* Report: *FEMA HMTAP 440.*

Flowerdew, J., Horsburgh, K. , Mylne, K. (2009). *Ensemble forecasting of storm surges.* Marine Geodesy, 32 (2), pp. 91-99

Folkard, A. M., and J. C. Gascoigne (2009). *Hydrodynamics of discontinuous mussel beds: Laboratory flume simulations.* Journal of Sea Research 62:250-257.

G

Guard, P.A., T. Baldock& P. Nielsen (2005). *General solutions for the initial run-up of a breaking tsunami front.* International Symposium Disaster Reduction on Coasts. Scientific-Sustainable-Holistic-Accessible. 14 – 16 November 2005 Monash University, Melbourne, Australia

H

Harborne, A. R., P. J. Mumby, F. Micheli, C. T. Perry, C. P. Dahlgren, K. E. Holmes, and D. R. Brumbaugh (2006). *The functional value of Caribbean coral reef, seagrass and mangrove habitats to ecosystem processes.* Advances in Marine Biology, Vol 50, pp 57-189.

Hwang, D., M. Francis, B. H. Choi, J.P.Sing, S. Stein, J. Borrero, H. K. Thio, C.Ratti& D. Bergado (2005). *Mitigating the Risk from Coastal Hazards: Strategies & Concepts for Recovery from the December 26, 2004 Tsunami.*

I

IOC-UNESCO (2012)
tic.ioc-unesco.org/

IPCC (2012). *Summary for Policymakers.* In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.*B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 3-21.

J

Jonkman, B., H. Gerritsen& M. Marchand (2012). Chapter 19. *Coastal Storm.* In: *Handbook of Hazards and Disaster Risk Management and Reduction.* Edited by B. Wisner, J. C. Gaillard and I. Kelman. Routledge., Oxon.

K

Kench, P. S., and R. W. Brander (2006). *Wave processes on coral reef flats: Implications for reef geomorphology using Australian case studies.* Journal of Coastal Research 22:209-223.

Knutson, T.R., Sirutis, J.J., Garner, S.T., Vecchi, G.A. and Held, I.M. (2008) *Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions.* Nature geoscience, 1-6.

Kohl, Patrice A., Ann P. O'Rourke, Dana L. Schmidman, Wendy A. Dopkin, Marvin L. Birnbaum (2005). *The Sumatra-Andaman Earthquake and Tsunami of 2004: The Hazards, Events, and Damage.* Prehospital and Disaster Medicine vol. 20 No. 6.

Komen, G. K., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S. & Janssen, P. A. E. M. (1994) Dynamics and modelling of ocean waves. Cambridge University Press. Lavell, A., J.C. Gaillard, B. Wisner, W. Saunders & D. van Niekerk (2012). *National planning and disaster. Chapter 51* in: *B.* Wisner, J. C. Gailard and Ilan Kelman (editors). *The Routledge handbook of hazards and disaster risk reduction.* Routledge, London and New York.

L

Linnerooth-Bayer, J. (2012). *Financial mechanisms for disaster risk. Chapter 54* in: *B.* Wisner, J. C. Gailard and Ilan Kelman (editors). *The Routledge handbook of hazards and disaster risk reduction.* Routledge, London and New York.

M

Mangor, K. (2004). *Shoreline Management Guidelines.* DHI Water and Environment, 294 pp

Marchand, M. (2009). *Modelling Coastal Vulnerability. Design and evaluation of a vulnerability model for tropical storms and floods.* PhD thesis. Delft University of Technology

Marchand, M. (2010). *Concepts and Science for coastal erosion management. Concise report for policy makers.* Deltares, Delft.

Mascarenhas, A. (2004). *Oceanographic validity of buffer zones for the east coast of India: a hydrometeorological perspective.* Current Science, 86 (2004), pp. 399–406

Mascarenhas, A. & Jayakumar, S. (2008). *An environmental perspective of the post-tsunami scenario along the coast of Tamil Nadu, India: Role of sand dunes and forests.* Journal of Environmental Management Volume 89, Issue 1, October 2008, Pages 24– 34

MLIT (2011). *White Paper on Land, Infrastructure, Transport and Tourism In Japan, 2011.* Ministry of Land, Infrastructure, Transport and Tourism

Möller, I., T. Spencer, J. R. French, D. J. Leggett, and M. Dixon (1999). *Wave transformation over salt marshes: A field and numerical modelling study from north Norfolk, England.* Estuarine Coastal and Shelf Science 49: 411-426.

Munich Re (2010). *Group Annual Report 2010.*
www.munichre.com/publications/30206773_en.pdf

N

Nayak, S. R.; Sarangi, R. K.; Rajawat A. S. (2001) *Application of IRS-P4 OCM data to study the impact of cyclone on coastal environment of Orissa.* Current Science, 80 (2001), pp. 1208–1213

NGI (2009). *Natural Disaster Mitigation in the Caribbean; Local Tsunami Risk Assessment – The Bridgetown Demonstration Project.* Norwegian Geotechnical Institute report no. 20061575-1

NOAA (2013). *Basic definitions website*
www.prh.noaa.gov/cphc/pages/FAQ/Basic_Definitions.php

R

Rappaport E.N. (2000). *Loss of life in the United States associated with recent tropical Atlantic cyclones,* Bulletin of American Meteorological Society, Vol. 81 No. 9 pp. 2065-2073

Riehl, H. (1979). *Climate and weather in the tropics,* Academic Press, London.

Rygel, L., O'Sullivan, D. &Yarnal, B. (2005). *A method for constructing a Social Vulnerability Index.* Mitigation and Adaptation Strategies for Global Change11: *pp.* 741-764.

S

Sardá, R., J. Mora and C. Avila (2004). *Tourism development in the Costa Brava (Girona, Spain) – how integrated coastal zone management may rejuvenate its life cycle* In: *J.* Vermaat, W. Salomons and L. Turner, Editors, *Managing European Coasts: Past, Present and Future,* Springer, Berlin

Schut, G. (2003). *Floods in the Netherlands, an insurance perspective.* In: *M.* Marchand, K.V. Heynert, H. van der Most & W.E. Penning (eds.). *Dealing with flood risk. Proceedings of an interdisciplinary seminar on the regional implications of modern flood management.* Delft Hydraulics Select Series 1/2003. Delft University Press, Delft.

Schwartz, D., Avishay Goldberg, IssacAshkenasi, Guy Nakash, Rami Pelts, AdiLeiba, Yeheskel Levi, Yaron Bar-Dayan (2006). *Prehospital Care of Tsunami Victims in Thailand: Description and Analysis.* Prehospital and Disaster Medicine Vol. 21 No. 3.

Strubbe, J., Mostaert, F., and Maeghe, K. (2005) *Flood management in Flanders with special focus on navigable waterways.* Third International Symposium on Floods Defence. Nijmegen, May 2005.

T

Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A.L., Martello, M.L., Polsky, C., Pulsipher, A. and Schiller, A. (2003) *A framework for vulnerability analysis in sustainability science.* Proceedings of the National Academy of Sciences of the United States of America, 100, 8074-8079.

U

UNEP (2005). After the Tsunami.

UNISDR (20025). *Summary of national information on the current status of disaster reduction, as background for the World Conference on Disaster Reduction* (Kobe, Hyogo, Japan 18-22 January 2005). Geneva / Switzerland, United Nations International Strategy for Disaster Reduction.

V

Van der Plas T. (2007). *A Study Into The Feasibility Of Tsunami Protection Structures For Banda Aceh & A Preliminary Design Of An Offshore Rubblemound Tsunami Barrier,* Master's Thesis, technical University of Delft, 15 November 2007

Van der Veen, A. and Logtmeijer, C. (2005) *Economic hotspots: Visualizing vulnerability to flooding.* Natural Hazards, 36, 65-80.

Vatvani, D. K., Gerritsen, H., Stelling, G. S. & Krishna Rao, A. V. R. (2002). *Cyclone-induced storm surge and flood forecasting system for India.* In *Proc. Int. Conf. Solutions to Coastal Disasters,* San Diego, February 2002, pp. 473-487. Reston, VA: *ASCE.*

Verlaan, M., Zijderveld, A., de Vries, H., Kroos, J. (2005). *Operational storm surge forecasting in the Netherlands: developments in the last decade, Phil.* Trans. R. Soc. A 15 June 2005 vol. 363 no. 1831 1441-1453

W

Watts, A. (2012) *Duelling papers on tropical cyclone frequency.* http://wattsupwiththat.com/2012/10/16/dueling-papers-on-tropical-cyclone-frequency/ (Accessed 16 May 2013)

Williams, V.J. (2010). *Identifying the Economic Effects of Salt Water Intrusion after Hurricane Katrina.* J. of Sust. Dev. Vol. 3 No. 1.

Winchester P. (1992). *Power, choice and vulnerability -a case study in disaster mismanagement in South India 1977-1988.* James & James Science Publishers, Ltd.: *London.*

Winckel, P.R., J.K. Vrijling & J. van de Graaff (2007). *Developing a building policy for the erosion zone. Solutions to some key (Dutch) questions.* Coastal Engineering 55. pp. 79-92.

Wong, F. L., Geist, E. L., and Venturato, A. J. (2005) *Probabilistic tsunami hazard maps and GIS.* 2005 ESRI International User Conference, San Diego.

For more information, please contact:

Associated Programme on Flood Management
c/o Climate and Water Department
World Meteorological Organization

tel	+41 (0) 22 730 83 58
fax	+41 (0) 22 730 80 43
email	apfm@wmo.int
	www.floodmanagement.info

World Meteorological Organization
Communications and Public Affairs Office
7 bis, Avenue de la Paix – P.O. Box 2300
CH-1211 Geneva 2 – Switzerland

tel	+41 (0) 22 730 83 14/15
fax	41 (0) 22 730 80 27
email	cpa@wmo.int
	www.wmo.int

GWP Global Secretariat
Linnégatan 87D - PO Box 24177
SE-104 51 Stockholm – Sweden

tél	+46 8 1213 86 00
fax	+46 8 1213 86 04
email	gwp@gwp.org
	www.gwp.org