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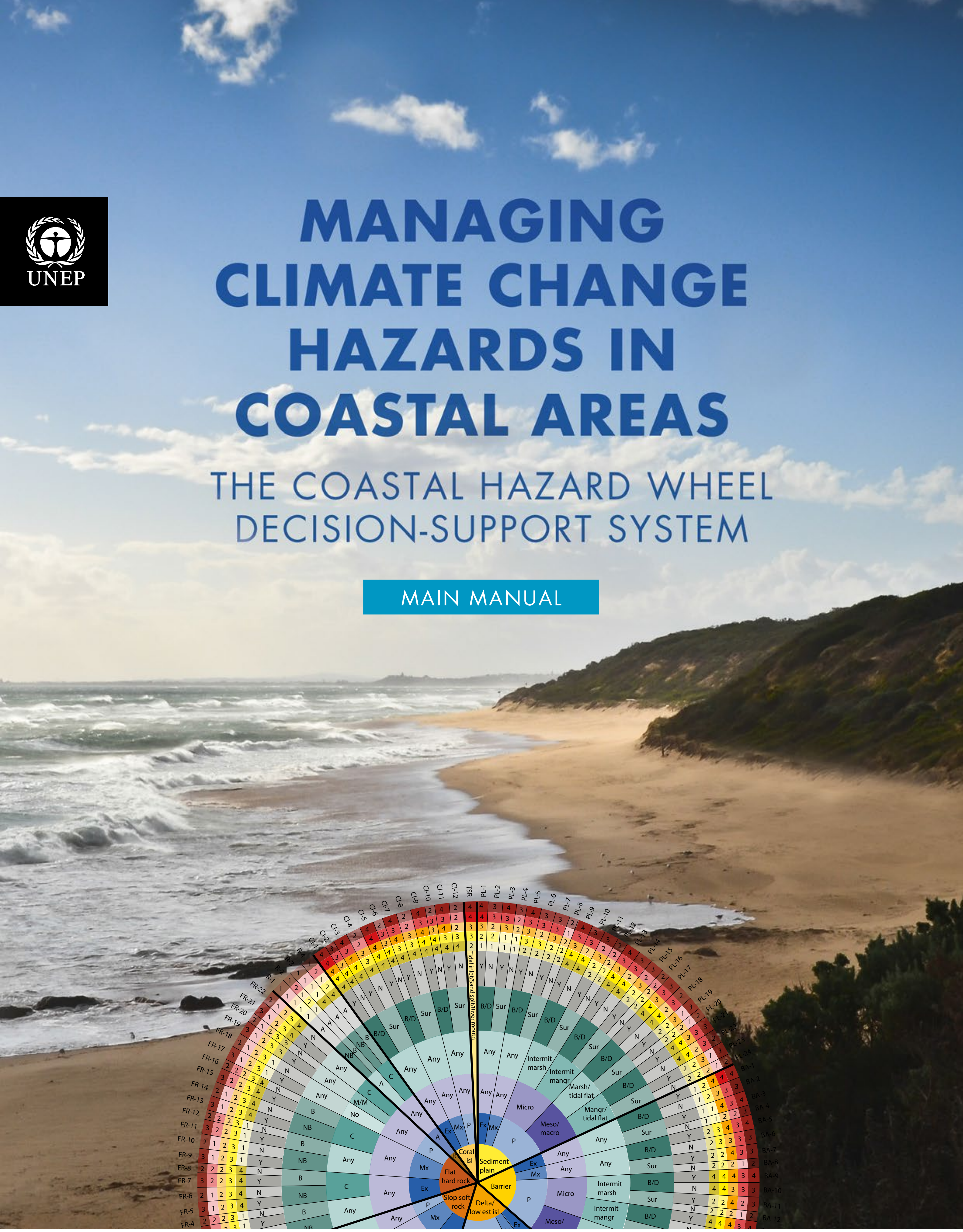
MANAGING CLIMATE CHANGE HAZARDS IN COASTAL AREAS

THE COASTAL HAZARD WHEEL DECISION-SUPPORT SYSTEM

MAIN MANUAL



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Managing climate change hazards in coastal areas

The Coastal Hazard Wheel decision-support system

Main manual

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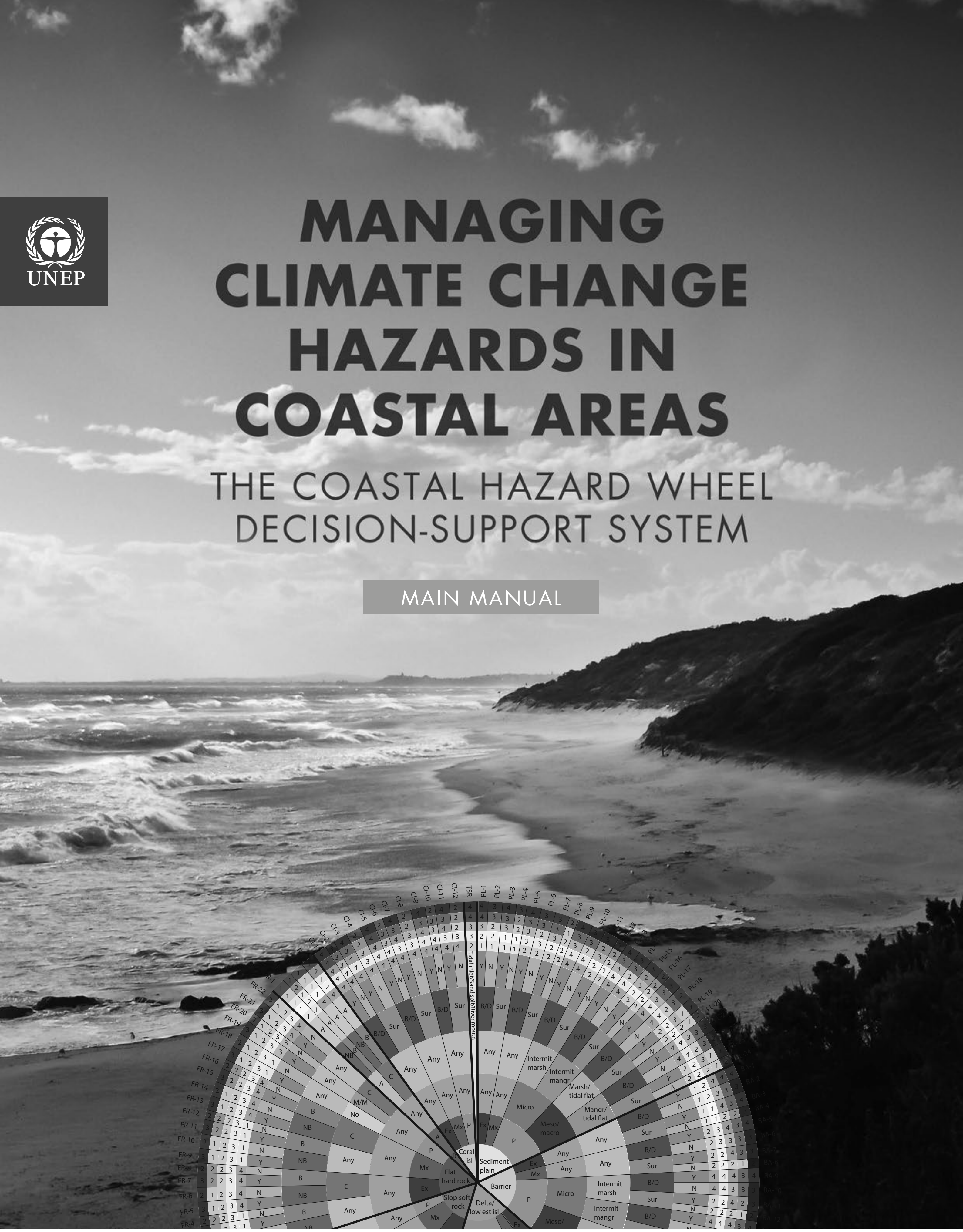

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1 INTRODUCTION

Since early civilisation, coastal areas have been attractive settling grounds for human population as they provided abundant marine resources, fertile agricultural land and possibilities for trade and transport. This has led to high population densities and high levels of development in many coastal areas and this trend is continuing into the 21st century. Currently about 1.2 billion people live in coastal areas globally and this number is predicted to increase to 1.8-5.2 billion by the 2080s due to a combination of population growth and coastal migration (IPCC 2007b; Small and Nicholls 2003). This will be followed by major investments in infrastructure and in the built environment.

The character of coastal environments, however, poses some great challenges to human habitation. Coastlines are highly dynamic natural systems that interact with terrestrial, marine and atmospheric processes and undergo continuous change in response to these processes. Over the years, human society has to a great extent failed to recognize this dynamic character of coastal areas, and this has led to major disasters and societal disruption of various degree. Even today, coastal development is often taking place with little regard to natural dynamics, and this problem is especially pronounced in developing countries where data, technical expertise and economic resources are limited and coastal populations are growing rapidly.

The predicted climate change adds an extra risk factor to human activities in coastal areas. While the natural dynamics that shape our coasts have been relatively stable and predictable over the last centuries, much more rapid change is now expected in processes as sea level rise, ocean temperature, ocean acidity, tropical storm intensity and precipitation/runoff patterns (IPCC 2013). The world's coastlines will respond to these changes in different ways and at different pace depending on their bio-geophysical characteristics, but generally society will have to recognize that past coastal trends cannot be directly projected into the future. Instead, it is necessary to consider how different coastal environments will respond to the predicted climate change and identify relevant management options. Furthermore, improved coastal communication is essential for development of management strategies within the broader framework of Integrated Coastal Zone Management (ICZM).

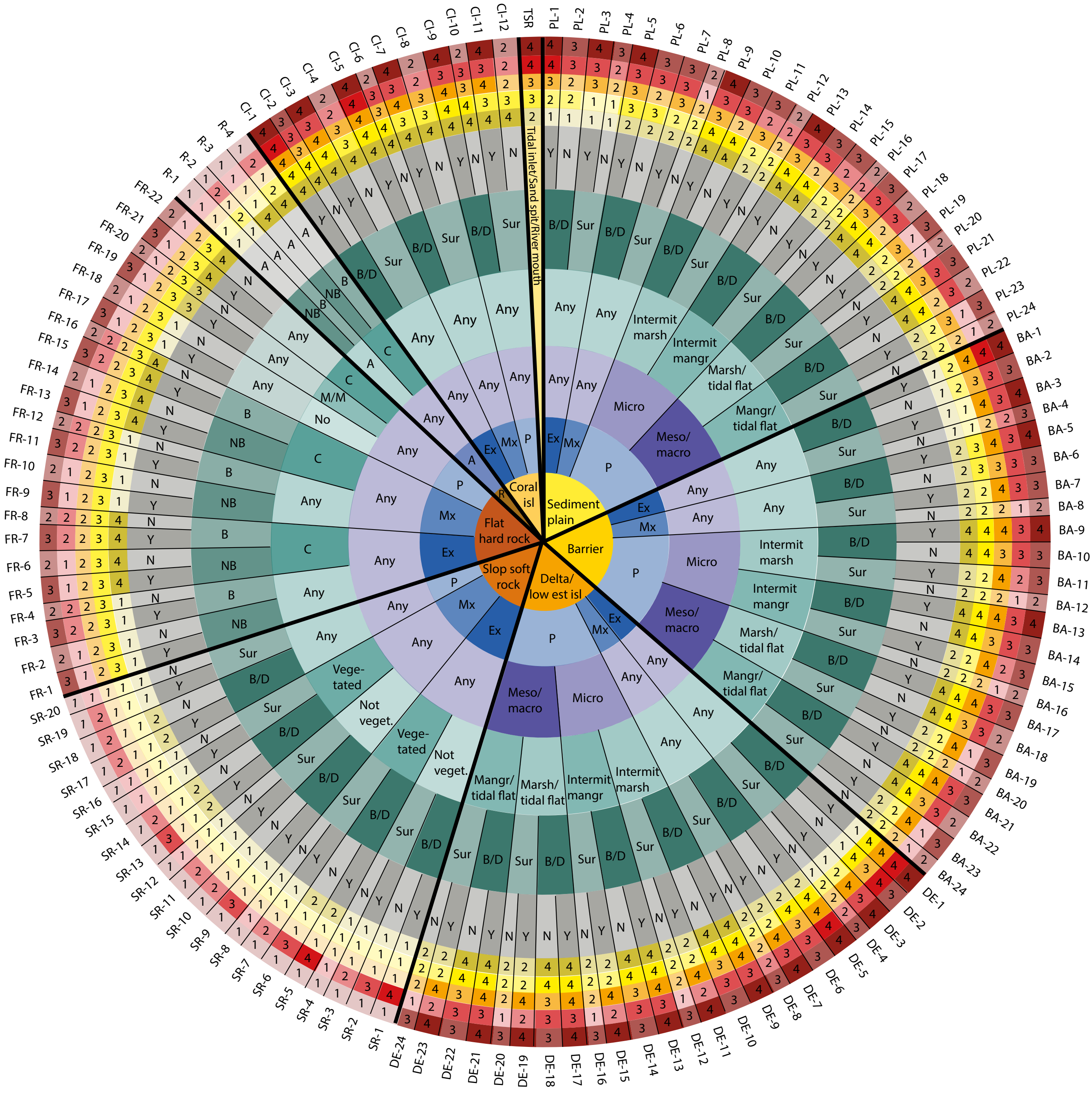
The Coastal Hazard Wheel (CHW) is an information and decision-support system developed to address these challenges. It can be used for multi-hazard-assessments, for identification of relevant management options for a specific coastline and as a standardized coastal language to communicate coastal information. It can be applied in areas with limited data availability and technical capacity and can therefore be used in both developed and developing countries. Since the CHW incorporates climate change effects in the hazard evaluations, it is especially suited for climate change adaptation. Furthermore, it is suited for Disaster Risk Reduction under the Sendai Framework (UNISDR 2016) and can support Source-to-Sea governance.

The CHW is designed to support coastal decision-making and information exchange at local, regional and national level and covers all the main coastal hazards, including ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. It is developed as a universal coastal classification system that contains 131 generic coastal environments and a total of 655 individual hazard evaluations. The initial version of the system was presented in 2012 and based on assessments for the Indian State of Karnataka, the Republic of Djibouti, a great number of local assessments and feedback from coastal experts, the system has been refined to a CHW 3.0 and a standardized application procedure has been developed. The CHW 3.0 presented in this publication is in most aspects similar to the CHW 2.0 presented in Rosendahl Appelquist and Halsnæs (2015) but due to some minor procedural changes it has been labelled 3.0 to ensure clarity.

This publication package aims to provide a complete guide to the use of the CHW for coastal decision-support and communication worldwide. The Quick start guide provides a brief introduction on how to use the CHW for coastal decision-making and information exchange. This Main manual and the accompanying Catalogue of hazard management options provide more detailed instructions on the use of the CHW and the technical background for the different management options. Generally, the CHW is well-suited for facilitating communication and information exchange between different management levels, scientists and policy-makers, as the CHW codes can be easily communicated and interpreted.

The publication is based on the scientific background papers on the CHW and further details can be found in these papers (Rosendahl Appelquist and Halsnæs 2015; Rosendahl Appelquist and Balstrøm 2015; Rosendahl Appelquist and Balstrøm 2014; Rosendahl Appelquist 2013). The CHW 3.0 is shown in Fig 1 and is used by starting in the wheel centre, moving outwards through the coastal classification and ending with the hazard evaluations and coastal classification codes in the outermost circles.

THE COASTAL HAZARD WHEEL 3.0



COASTAL CLASSIFICATION (start in wheel center)

Geological layout	🟨 🟨 🟧 🟧 🟧 🟫 🟨	
Wave exposure	Ex	Exposed
	Mx	Moderately exposed
	P	Protected
Tidal range	🟪 🟪	
Flora/fauna	🟩 🟩 🟩 🟩 🟩 🟩	
Sediment balance	B/D	Balance/deficit
	Sur	Surplus
	NB	No Beach
	B	Beach
Storm climate	Y	Yes to tropical cyclone activity
	N	No to tropical cyclone activity

Note: R= Sloping hard rock; C=Corals; M/M=Marsh/Mangrove; A=Any

INHERENT HAZARD LEVEL

	Low	Moderate	High	Very high
Ecosystem disruption	1	2	3	4
Gradual inundation	1	2	3	4
Salt water intrusion	1	2	3	4
Erosion	1	2	3	4
Flooding	1	2	3	4

Fig. 1. *The Coastal Hazard Wheel 3.0 consisting of six coastal classification circles, five hazard circles and the coastal classification codes. It is used by starting in the wheel centre moving outwards through the coastal classification (modified from Rosendahl Appelquist and Halsnæs 2015 and Rosendahl Appelquist 2013).*

2

THE CHW AND THE UNIVERSAL COASTAL CLASSIFICATION SYSTEM

To date, several different methodologies and approaches have been developed to assess and manage coastal vulnerability and climate-related hazards. Generally, one can distinguish between index based methods, indicator based methods, GIS-based decision support systems and dynamic computer models that are developed for different purposes and with different requirements for data and expertise (Ramieri et al. 2011).

Index based methods are the most simple to use, can be applied at various scales and are useful for screening assessments and for supporting the identification of vulnerable coastal areas. However, they do not provide information on the range of different hazards to a coastal location, require elaboration of assumptions to avoid a black-box effect, need relatively detailed input data and cannot be used directly to identify management strategies. Indicator based methods allow for a greater sector-specific detail while remaining relatively simple but still require a significant level of input data and technical expertise. Both GIS based decision-support systems and dynamic computer models are very advanced systems that can incorporate large amounts of data and variables and can be used for both single- and multi-sector assessments and for design purposes. However, these systems require significant amounts of data, technical expertise and operational resources and are therefore difficult to use directly for coastal managers and decision-makers.

Compared to the existing systems, the CHW is developed as a multi-tool that can address the key coastal management issues collectively and is directly accessible for coastal decision-makers at all management levels. The CHW is therefore well-suited as a general information and decision-support system that can be supplemented with other available methods and models when considered appropriate.

The universal coastal classification system constitutes the foundation for the CHW and is developed particularly for decision-support. The system is based on the bio-geophysical parameters that are considered most important for the character of a particular coastal environment and the parameters included are geological layout, wave exposure, tidal range, flora/fauna, sediment balance and storm climate. In order to avoid a disproportionate large number of categories, the system applies an *"Any"* phrase in cases where a particular classification parameter is of minor importance and variables such as local isostatic uplift/subsidence and sediment grain size are not directly included as they to some extent are covered through the other parameters.

Since the bio-geophysical variables can change significantly over short spatial distances, a generic coastal environment will according to the classification system theoretically apply to a particular spot along a coastline. For practical application, however, a single application of the CHW will apply to a coastal stretch of ca. 200-300 meter coastline and larger regional and national assessments consist of e.g. hundreds of individual sections classified with the CHW. In some areas, the same coastal type may extend for many kilometres while in others it changes every few hundred meters. Often there is a gradual transition between the different coastal environments and hence it is up to the user to make the best possible judgement on the appropriate coastal classification. This can lead to some inaccuracies but is considered an unavoidable precondition for using the system.

Human alterations of the coastline may affect the coastal characteristics and hazard profile but since it is very difficult to determine the effect of a particular alteration or hazard management measure, the classification of a coastal site should reflect the generic "coastal environment".

Human modifications of the coastal layout should therefore only be considered if they can be seen as a permanent modification of the "coastal environment". This core classification can then be supplemented with information on relevant human activities and management measures as described in chapter 6 on application of the CHW as a standardized coastal language.The different classification components have been clearly defined in order to differentiate the generic coastal environments and the definitions and data requirements for the classification components are further described below. Depending on the data availability and accuracy requirements, the CHW can be applied at three different classification steps and information on the data requirements for the different steps is included in the sections below and further covered in chapter 4 on local, regional and national multi-hazard-assessments.

2.1. GEOLOGICAL LAYOUT

The geological layout constitutes the basis on which the dynamic processes act and has been created by various past dynamic processes including glacial, fluvial, marine, volcanic and tectonic (Davis and Fitzgerald 2004). The coastal landscape continues to be modified by these processes over different timescales and making an assessment of a particular geological layout will therefore be a snapshot that will change gradually over time. However, as most major changes in geological layout take place on timescales of decades or more, the effect of these changes on the classification is limited. Furthermore, the subsequent layers in the classification system include the major short-term coastal processes, meaning that most gradual natural changes are handled by the system.

The geological layouts included in the classification system are defined based on a thorough analysis of the world's costal environments and are framed in a way so they cover all major types of geological layouts worldwide. They are defined to include important generic characteristics while still maintaining an appropriate simplicity. The geological layout categories included in the CHW 3.0 are *sedimentary plain*; *barrier*; *delta/low estuary island*; *sloping soft rock coast*; *flat hard rock coast; sloping hard rock coast*; *coral island*; *tidal inlet/sand spit/river mouth*. The first four categories are sedimentary geological layouts generally found on trailing edge coastlines[1] such as the Atlantic coast of North- and South America, whereas the *sloping hard rock coast* is commonly found on leading edge coastlines[2] such as the Pacific coast of North and South America. The *flat hard rock coast* can appear in various settings such as raised coral reefs, whereas the coral island category is largely depending on tectonic and climatic conditions (Davis and Fitzgerald 2004; Masselink and Hughes 2003). The final category *tidal inlet/sand spit/river mouth* constitutes a group of special dynamic geologic environments.

In many coastal locations, there is a gradual transition between related geological layouts, e.g. between *barriers* and *delta/low estuary islands* and in these cases it is up to the user to decide on the most appropriate layout category. Table 1 provides an overview of the key characteristics of the different geological layout categories, which are further elaborated below.

	Low-lying coast	Sloping coast
Sedimentary/soft rock material	Sedimentary plain	Sloping soft rock coast
	Barrier	
	Delta/low estuary island	
	Tidal inlet/sand spit/river mouth	
Hard rock material	Flat hard rock coast	Sloping hard rock coast
Mixed	Coral island	

Table 1. *Key characteristics of the different geological layout categories.*

The *sedimentary plain* category is defined as coasts with an average elevation of less than 6-8 meters 500 meter inland of the Mean Sea Level (MSL), and which are composed of sedimentary deposits such as clay, silt, sand, gravel, till or larger cobbles. If coastal dunes are present, the elevation may locally be higher at the dune peaks, but the coast will still fall into the *sedimentary plain* category. *Sedimentary plains* are often formed by glacial and fluvial processes or through coastal progradation[3] (Davis and Fitzgerald 2004; Masselink and Hughes 2003).

The *barrier* category is defined as coasts that consist of non-sloping/low-lying, shore parallel sedimentary bodies with cross distances ranging from less than 100 meters to several kilometres, and lengths ranging from less than 100 meters to over 100 kilometres (Davis and Fitzgerald 2004). Narrow *barriers* often exist where the sediment supply is or has been limited while broad barriers are formed in areas with sediment abundance (Masselink and Hughes 2003). The seaward side of a *barrier* often contains a wave dominated beach environment, while the landward side consists of protected lagoons and estuaries with various kinds of marsh or mangrove vegetation depending on climatic conditions and tidal range. In meso-tidal and macro-tidal environments, *barriers* are frequently cut by tidal inlets.
In the classification system, a *barrier* can occur in parallel to coastlines of other geological layouts, located landwards of

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[1] Trailing edge coasts occur where tectonic plates rift apart, creating a wider continental shelf.

[2] Leading edge coasts occur where a continental plate converges with an oceanic plate, creating a narrow continental shelf and a mountainous coastline.

[3] Coastal progradation is the seaward advance of a coastline due to sediment accumulation or sea level fall.

the barrier. This would e.g. be the case where a *sedimentary plain* or *sloping soft rock coast* is located landwards of a barrier. *Barriers* may occur as part of a delta and in that case the most appropriate categorisation would be the *delta/low estuary island* category (described below).

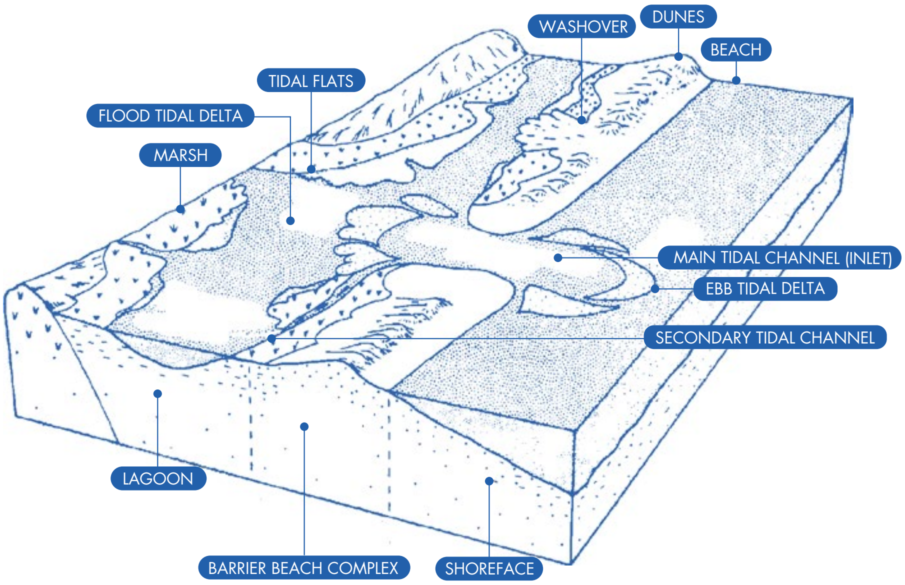

Fig. 2. *Barrier system with outer beach environment and protected backbarrier environment (From: Reinson 1984. Copyright ©1984, Geological Association of Canada).*

The *delta/low estuary island* category is defined as coasts composed of fluvial transported sediment that is deposited in front of a river mouth. These landforms form in the coastal-fluvial interface where riverine sediment supplied to the coastline is not removed by marine processes. The formation of *deltas/low estuary islands* is therefore strongly dependent on the fluvial sediment discharge as well as the waves, tides and currents of a particular location. Plate tectonics and regional geological conditions also influence delta formation. Larger deltas are generally found on trailing edge and marginal sea coastlines[4] where large drainage basins provide a high fluvial discharge and wide continental shelves provide a relatively shallow depositional area (Schwartz 2005). Examples of major deltas developed under these conditions are the Mississippi and Amazon deltas in the Atlantic Ocean and the Yangtze delta in the South China Sea (Davis and Fitzgerald 2004). Small deltas might form along leading edge coastlines but their extension is limited by the smaller drainage basins and steep coastal gradient that does not allow for significant sediment accumulation. Fig 3 provides an overview of the broad variety of delta formations and all light blue areas of the delta illustrations will in the CHW classification system fall into the *deltas/low estuary islands* category. It is important to note, however, that sloping estuary coastlines do not fall into the *delta/low estuary island* category.

8 GEOLOGICAL LAYOUT CATEGORIES

The geological layouts included in the classification system are framed so they cover all major types of geological layouts worldwide.

> “In many coastal locations there is a gradual transition between related geological layouts and in these cases it is up to the user to decide on the most appropriate layout category.”

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[4] Marginal sea coastlines occur where tectonic plate convergence takes place offshore and these coasts have a relatively wide continental shelf.

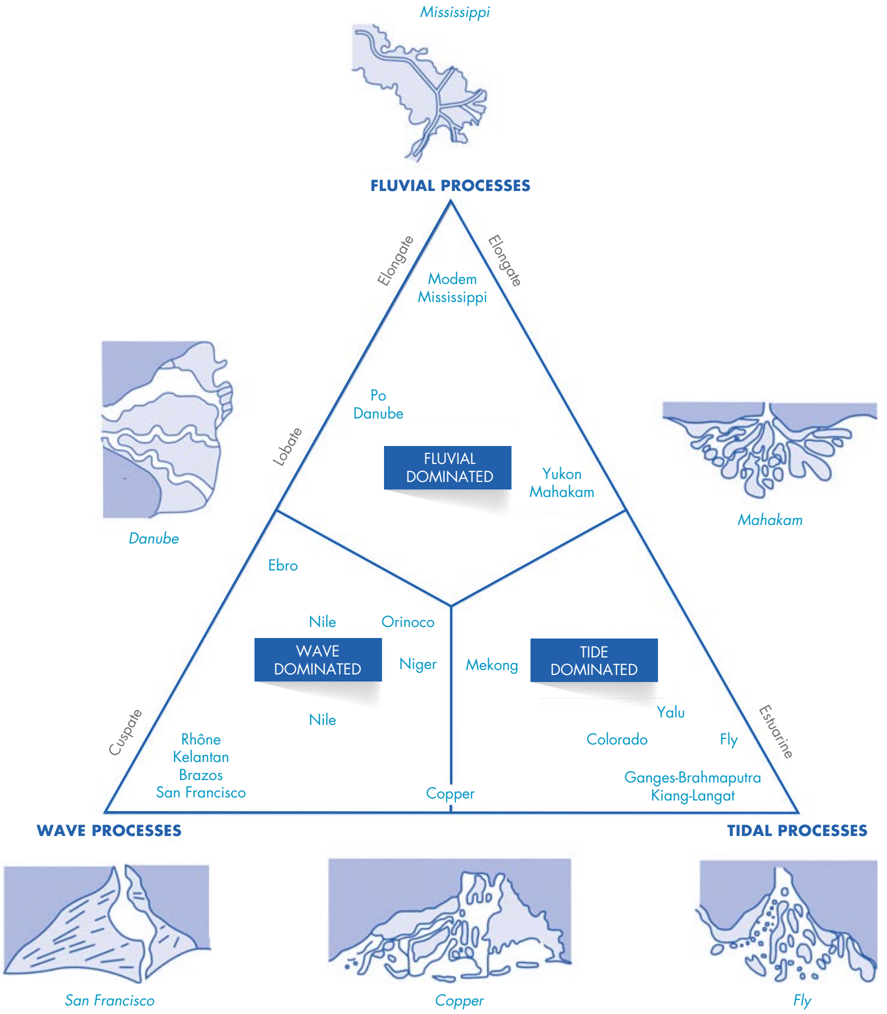

Fig. 3. *Different delta formations (After Galloway 1975. From: Fundamentals of the Physical Environment 3ed, Peter Smithson, Ken Addison & Ken Atkinson, Copyright ©2002 Routledge, reproduced by permission of Taylor & Francis Books UK).*

The *sloping soft rock coast* category is defined as coasts comprised of soft rock material with an average elevation of more than 6-8 meters 500 meter inland of the MSL. *Sloping soft rock coasts* can be comprised of a range of different sedimentary deposits such as chalk, moderately cemented laterite, clay, silt, sand and till with larger pebbles or cobbles. Their geological origin can range from old uplifted seabed to more recent glacial deposits (Schwartz 2005). Hard sedimentary rocks are not included in this category and it can therefore be necessary to assess the level of sediment cementation in order to determine whether a particular coast should be classified as soft or hard rock. In the classification system, a rock will fall into the soft rock category if the sediment is poorly cemented and as a general rule, it should be possible to push a knife some centimetres into the rock material without using excessive force. However, assessing this in the field is not always straightforward as hard rock material may be covered by a layer of sediments. The recommended approach is therefore to make use of a basic geologic map, if possible combined with field observations. Sloping soft rock coasts can both be present as coastal cliffs and vegetated hills.

The flat hard rock coast category is defined as coasts consisting of igneous, sedimentary and metamorphic rock with an average elevation of less than 6-8 meters 500 meter inland of the MSL. Igneous rocks are formed from magma and are comprised of a range of different minerals and grain sizes depending on their chemical composition and solidification process. Sedimentary rocks consist of sediment that has undergone different stages of diagenesis, where the sediment has been compacted and cemented under increased temperature and pressure, creating a solid rock structure. Metamorphic rocks have formed from both igneous and sedimentary rocks when they have undergone recrystallization under high temperature and pressure (Press and Siever 2001). The specific physical and chemical rock properties influence the weathering and erosion processes, but for the coastal classification system, hard rock material is considered as one uniform group. *Flat hard rock coasts* can be present in different forms such as rocky coastal plains, islands and archipelagos and the hard rock can sometimes be partly hidden by a layer of weathered rock/ loose sediments.

The *sloping hard rock coast* category is defined as coasts consisting of igneous, sedimentary or metamorphic rock with an average elevation of more than 6-8 meters 500 meter inland of the MSL. *Sloping hard rock coasts* can be present in different forms such as coastal mountain chains, hills, headlands, islands and archipelagos and the hard rock can sometimes be partly hidden by a layer of weathered rock/ loose sediments.

The *coral island* category is defined as low-lying coral islands in the form of tropical atolls and coral cays. Tropical atolls are open ocean coral islands that rest on a subsiding volcanic foundation. The coral base can be as old as 30 million years and reef material can be found at depths of over 1000 meters beneath the atoll. Atolls have a round shape with diameters ranging from a few kilometres to more than hundred (Schwartz 2005). Coral cays are younger islands formed on top of coral reefs or adjacent to atolls due to the accumulation of reef-derived sediment in one location as a result of wave action. These islands can rise up to three meters above high water level and can be composed of coarse reef fragments or fine carbonate sand. The beaches of both atolls and coral cays can have cemented to form beachrock and coral sandstone that help stabilize the islands (Haslett 2009).

The *tidal inlet/sand spit/river mouth* category is established as a separate grouping in the classification system as these environments can be highly morphologically active and respond quickly to changes in other coastal processes (Mangor 2004). In the classification system, *tidal inlets* are defined as the coastline of a tidal inlet itself and one kilometre parallel to the shore on each side of the inlet. *Tidal inlets* are found along barrier coastlines throughout the world and provide water exchange between an open coast and adjacent lagoons and estuaries. Their morphology depend on a range of different parameters such as tidal range, wave climate and sediment availability (Davis and Fitzgerald 2004). In special cases, where the tidal inlet side consists of a hard rock headland, the inlet side should fall into one of the hard rock categories. *Sand spits* are defined as elongate sedimentary deposits that are formed from longshore currents losing their transport capacity and subsequently depositing sediment at particular locations. They can be present in different shapes and are generally classified into simple linear spits, recurved spits with hook-like appearances, and complex spits with plural hooks (Schwartz 2005). River mouths are defined as the coastline one kilometre on each side of a well-defined river mouth. *Tidal inlets*, *sand spits* and *river mouths* are assigned high priority in the CHW classification system, meaning that e.g. a *sedimentary plain* will fall into this category if it is located less than one kilometre on each side of a river mouth.

Data requirements for determining the geological layout

The core data requirements for classifying the geological layout at step 1 are a basic geologic map of the assessment area, Google Earth's satellite images and Google Earth's terrain elevation function.

The classification of the geological layout is done by combing information from these three data sources, and the geological map is used to assess whether the coastline is composed of soft or hard rock material, Google Earth's satellite images are used to get an overview of the coastal outline and identify form-features as barriers, deltas, tidal inlets, sand spits, river mouths and islands, and Google Earth's terrain elevation function and ruler is used to assess whether the coastline has a flat or sloping character (the elevation values are shown in the button of the Google Earth window when the cursor is hovered over the coastline). One should be particularly aware that Google Earth's elevation numbers can be affected by dense vegetation and buildings which can lead to overestimated elevation numbers for some areas. This can necessitate supplementary elevation data e.g. from advanced elevation surveys, local topographic maps, communication with local contacts or judgements based on landforms.

For a step 2 classification, the data should be supplemented by representative field verification e.g. in areas where there are doubts about the geological base material or elevation. A step 3 classification would require additional high quality data on coastal geology and elevation.

To support the classification of continues coastal stretches especially at step 1-2, it is recommended to draw a shore-parallel line-feature in Google Earth, landwards of the coastline in all areas with an elevation over 6-8 meter 500 meter inland of the MSL. This can be done using Google Earth's New Path function and should be reassessed for every 200-300 meter coastline. In this way, sloping coastal sections can be easily identified during subsequent implementation of manual multi-hazard-assessments in ArcGIS (described further in chapter 4).

2.2. WAVE EXPOSURE

The wave exposure is the dominant energy source in the nearshore environment and a highly important parameter for the coastal morphodynamics. Although some incoming wave energy is reflected by the shoreline, most energy is transformed to generate nearshore currents and sediment transport and is a key driver of morphological change (Masselink and Hughes 2003). The wave height is the generally applied measure for incoming wave energy and is defined as the difference in elevation between the wave crest and wave trough (Davis and Fitzgerald 2004). Since the wave energy increases as the square of the wave height, coastal environments with high wave heights have a relatively high energy intensity compared to coasts with lower wave heights (Thieler et al. 2000).

Gravity waves generated by wind stress on the ocean surface constitute the main type of waves affecting coastal systems. The restoring force for this wave type is earth's gravity and gravity waves are generally composed of sea- and swell waves (Masselink and Hughes 2003). Sea waves are formed under direct influence of the wind on the ocean surface and have peaked crests and broad troughs. They are often complicated with multiple superimposed sets of different wave sizes and whitecaps can be present during high wind speeds. Swell waves develop when the wind stops and when the waves travel outside the area where the wind is blowing. They have a sinusoidal shape and commonly have long wavelengths and small wave heights (Masselink and Hughes 2003). Whether a coast is primarily affected by sea or swell waves is largely determined by the general climatic conditions and coastline geography.

The CHW applies a wave environment perspective and distinguishes between *exposed*, *moderately exposed* and *protected* coastlines based on the wave height. The simplified way of estimating the wave exposure makes use of information on the general wave climate, the waterbody size (fetch length) and the wind conditions and is done through the following process:

1) The general wave climate of an area is determined based on Fig 4. All coastlines falling into “West coast swell”, “East coast swell” and “Trade/monsoon influences” are classified as swell wave climates, while the remaining types are classified as non-swell wave climates.
2) The specific exposure level for a coastal site is determined based on Table 2.

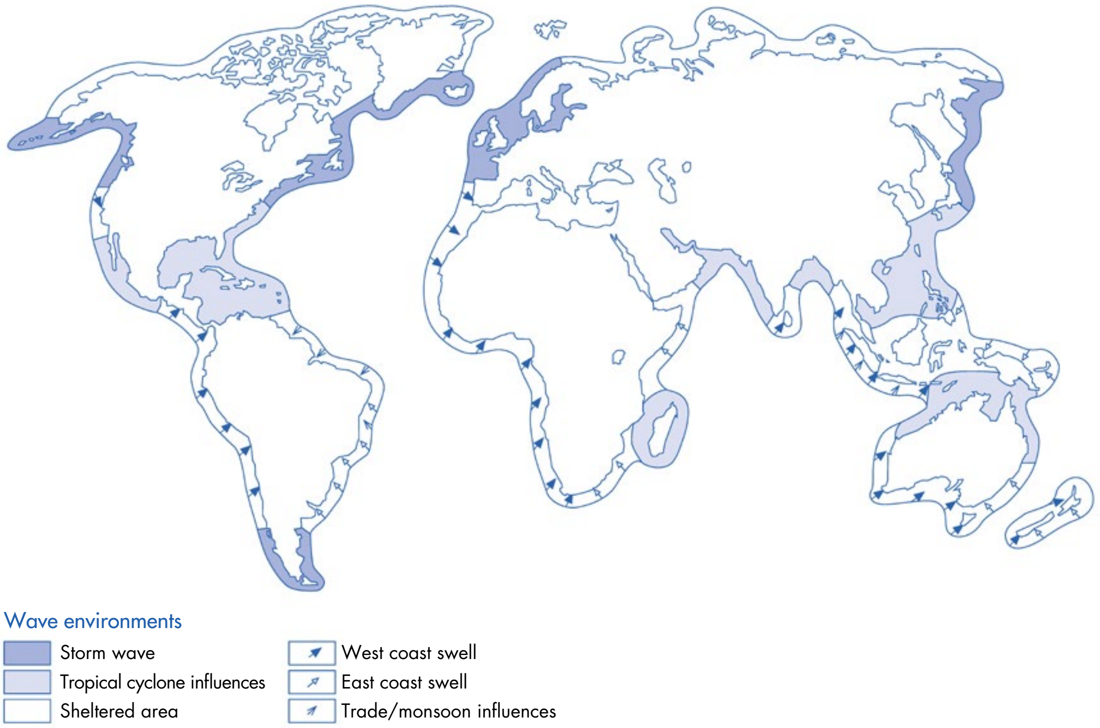

Fig. 4. *Global wave environments (Davies 1980, modified by Masselink and Hughes 2003 and Rosendahl Appelquist).*

General wave climate	Waterbody size (fetch length)	Specific coastal conditions	CHW classification
Swell wave climate (West coast swell, East coast swell, Trade/ monsoon influences)	Any	Extreme swell (West coast swell south of 30°S)	Exposed
		Swell	Moderately exposed
		Backbarrier, inner waters, inner estuary, fjord	Protected
Non-swell wave climate (Storm wave, Tropical cyclone influences, Sheltered area)	> 100 km	Stronger on-shore winds	Exposed
		Weak on-shore winds	Moderately exposed
	10 - 100 km	Stronger on-shore winds	Moderately exposed
		Weak on-shore winds	Protected
	< 10 km	Any	Protected

Table 2. *Wave exposure classification for the CHW system.*

If detailed wave data is available, including for inner waters, the wave exposure should ideally be determined based on the significant wave height occurring continuously for 12 hours per year, the Hs 12h/yr. In that case, a coastline with a Hs 12h/yr > 3 m is classified as *exposed*, a Hs 12h/yr = 1-3 m is classified as *moderately exposed* and a Hs 12h/yr < 1 is classified as *protected*. Using this procedure, however, requires detailed wave data with a resolution in order of ~ 1 km.

Data requirements for determining the wave exposure

The core data requirements for classifying the wave exposure at step 1-2 are Fig 4 and Table 2, Google Earth and basic information on the local wind climate.

Areas with extreme swell can be identified using Fig 4 and the latitude displayed in Google Earth. The waterbody size (fetch length) can be determined using Google Earth's satellite images and ruler and should as far as possible take off-shore archipelagos/reefs into account. The presence of weak on-shore winds can be determined with basic knowledge of the regional wind climate and one should be particularly aware of possible weak on-shore winds in regions categorized as "Sheltered area" in Fig 4. Generally, the whole "Sheltered area" of Southeast Asia can be considered as having weak on-shore winds.

For islands not covered by Fig 4, one should try to obtain local data on the presence of swell or non-swell wave environments or data on the Hs 12h/yr. For ice affected coastlines, the fetch length may fluctuate due to presence of winter sea ice, but as sea ice is expected to be highly vulnerable to climate change, the same approach as for ice-free coasts should be used unless the ice is considered very stable. The same exposure level may in some cases apply to long coastal stretches, but can also apply to very short stretches in locations with a diverse coastal configuration.

For a step 3 classification, detailed wave data is required in order to determine the wave exposure based on the Hs 12h/yr.

2.3. TIDAL RANGE

Tides can have major impact on shoreline processes and on the development of coastal landforms. They are a manifestation of the moon's and sun's gravitational force acting on earth's hydrosphere and are present in the form of oceanic waves with wavelengths of thousands kilometres, resulting in periodic fluctuations in coastal water levels (Davis and Fitzgerald 2004). Tides fluctuate on a daily basis following diurnal, semidiurnal and mixed tidal cycles (Davis and Fitzgerald 2004). Diurnal tides exhibit one tidal cycle daily whereas semidiurnal tides exhibits two cycles daily. Mixed tides have components of both diurnal and semidiurnal tides varying throughout the lunar cycle (Davis and Fitzgerald 2004). Globally, semidiurnal and mixed tides are dominating coastal areas (Haslett 2009).

From a morphodynamic perspective, it is the tidal range that significantly influences coastal processes and controls the horizontal extent of the intertidal zone, the vertical distance over which coastal processes operate and the area being exposed and submerged during a tidal cycle (Haslett 2009). The tidal range is defined as the height difference between the high water and low water during a tidal cycle (Schwartz 2005) and the tidal range of a particular coastal location is controlled by a range of different parameters including the distance from an oceanic amphidromic point[5], the local bathymetry, the width of the continental shelf and the coastal configuration (Haslett 2009). Generally, the tidal range increases with distance from an amphidromic point, with a bathymetric focus of the tidal wave on a particular coastal stretch, with a shallow continental shelf and with a coastline restriction as in the case of gulfs and estuaries (Haslett 2009).

The numerical value of the tidal range vary significantly between coastal locations and span from almost zero to about 16 meters in funnel shaped embayments such as the Bay of Fundy, Canada (Davis and Fitzgerald 2004). The tides of a particular location also fluctuate on a daily basis depending on planetary positions.

For classification purposes, coastlines can be grouped into various tidal environments based on tidal range and a generally used classification system operates with the three main categories micro-tidal, meso-tidal and macro-tidal (Schwartz 2005). Micro-tidal environments are defined as coasts where the tidal range does not exceed 2 meters and can be found on open ocean coastlines such as the southern seaboard of Australia and the majority of the African Atlantic coast (Haslett 2009). Meso-tidal environments are defined as coasts with a tidal range of 2-4 meters and examples of these are found on the Malaysian and Indonesian coasts and on the eastern seaboard of Africa (Haslett 2009). Macro-tidal environments are defined as coasts where the tidal range exceeds 4 meters and examples of these are found on some of the northwest-European coasts and in parts of north-eastern North America (Haslett 2009). The global distribution of micro-, meso- and macro-tidal environments is shown in Fig 5.

> “The tidal range is defined as the height difference between the high water and low water during a tidal cycle (Schwartz 2005).”

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[5] An amphidromic point is the zero amplitude location for a harmonic tidal wave.

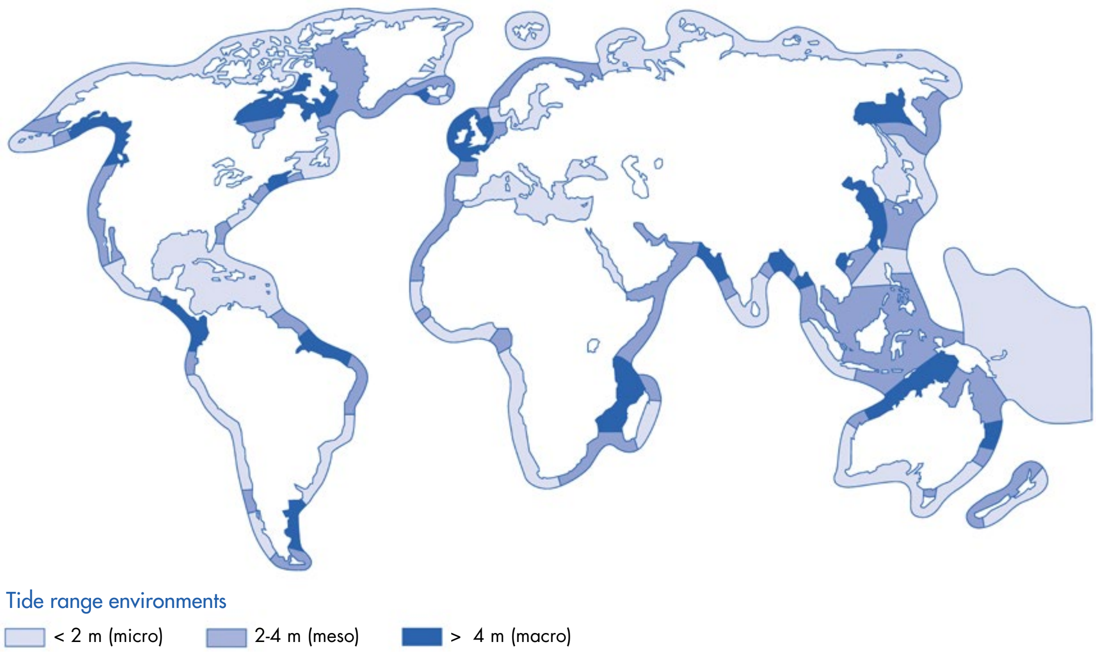


Fig. 5. *Map over global tidal environments (Davies 1980, modified by Masselink and Hughes 2003).*

The effect of the tidal range on coastal morphodynamics is largely controlled by the level of wave exposure. Therefore, the relative size of tides and waves of a particular location is - seen from a morphodynamic perspective - more important than the magnitude of the tidal range itself (Masselink and Hughes 2003). This relationship is illustrated by the relative tidal range expression that states that the relative morphodynamic importance of the tidal range decreases with increasing wave exposure (Masselink and Hughes 2003). This principle is applied in the classification system that uses the three different tidal categories, *micro, meso/macro* and *any* that are applied in accordance with wave exposure. Where the coastline is exposed or moderately exposed, the classification uses the any tide category as these environments are considered to be largely dominated by wave processes. At *protected* coastlines, the tidal range can have major impact on the coastal morphodynamics and the classification system therefore distinguishes between *micro* and *meso/macro-tidal* conditions. Under *micro-tidal* conditions, these coastlines will still be partly wave dominated whereas they will be largely tide dominated under *meso/macro-tidal* conditions. The merging of *meso/macro tides* is regarded as an acceptable simplification without significant implications for a reliable hazard valuation except under extreme high tidal range conditions. Since the effect of tidal range on the characteristics and hazard profile of *sloping soft rock coasts*, *flat hard rock coasts*, *sloping hard rock coasts* and *coral islands* is considered to be minor, the any tide category has been applied to these layouts for simplification purposes. In the case of tidal inlets, tidal forces play a key role for their morphodynamics, but these environments are included in a separate category due to their special properties.

Data requirements for determining the tidal range

The core data requirements for classifying the tidal range at step 1-2 is the map in Fig 5 which is used to determine whether the tidal range for a coastal location is of the micro or meso/macro types. For a step 3 classification, supplementary data on tidal range should be obtained e.g. in the form of tide tables from commercial harbours. For islands not included in Fig 5, one has to obtain local information on the tidal range for a classification at any level.

The same tidal range category often applies to long coastal stretches and once the tidal conditions are determined for a particular area, it is relatively easy to go through this classification layer in the CHW.

2.4. FLORA/FAUNA

For some coastal environments, the flora/fauna constitutes an important parameter for their characteristics and hazard profile. In the CHW system, the flora/fauna has been included where it is considered to play an important role for the coastal characteristics. The integration of the flora/fauna component in the classification system is complicated by its interdependence with other physical classification parameters and this is reflected in the application of the flora/fauna categories. In total, the classification system operates with nine different categories namely *intermittent marsh; intermittent mangrove; marsh/tidal flat*; *mangrove/tidal flat*; *marsh/mangrove*; *vegetated*; *not vegetated*; *coral* and *any*.

The *intermittent marsh* and *marsh/tidal flat* categories are applied to coastlines whose geological layout falls into the categories *sedimentary plain*, *barrier* and *delta/low estuary island*. The *marsh* is a grass-like vegetation of salty and brackish areas along *protected*, low energy coastlines.
It colonizes higher parts of the intertidal environment, forming coastal wetlands that act as a sediment trap for fine grained sediment. Marsh areas gradually build up from continuous flooding and subsequent sediment deposition which can be particularly large during storm events. Due to the continuous accumulation of sediment, marsh areas can to some degree follow sea level rise but will eventually drown if sea level rises too rapidly. In locations with a high tidal range, marsh areas are often continuous and combined with extensive tidal flats, and the classification therefore distinguishes between the *intermittent marsh* category applied to areas with *micro-tidal* conditions and the *marsh/tidal flat* category applied to areas with *meso/macro-tides*.

Fig. 6. *Marsh vegetation in Denmark.*

The *intermittent mangrove* and *mangrove/tidal flat* categories are applied to coastlines falling into the geological layout categories *sedimentary plain*, *barrier* and *delta/low estuary island*. Mangrove is a woody shrub vegetation that grows along *protected*, low energy coastlines, forming a swampy environment. It is very dependent on air temperature and cannot tolerate a freeze and its geographical extension is therefore limited to low and moderate latitudes. The extensive root network of mangroves acts as an efficient trap for fine grained sediment and reduces wave erosion of the coastline. Like marsh areas, mangrove forests are rich ecosystems that provide nursing grounds for many animals and in addition limit erosion and flooding from tropical storms. In the classification system, the *intermittent mangrove* category is applied to areas with *micro-tidal* conditions, while the m*angrove/tidal flat* category is applied to areas with *meso/macro-tides* (although mangroves often colonize most of the tidal flats). The combined *marsh/mangrove* category is applied to *protected, flat hard rock coasts* that have a band of marsh/mangrove vegetation. If a *sloping hard rock coast* has a significant band of marsh/mangrove vegetation, it will automatically fall into the flat hard rock category.

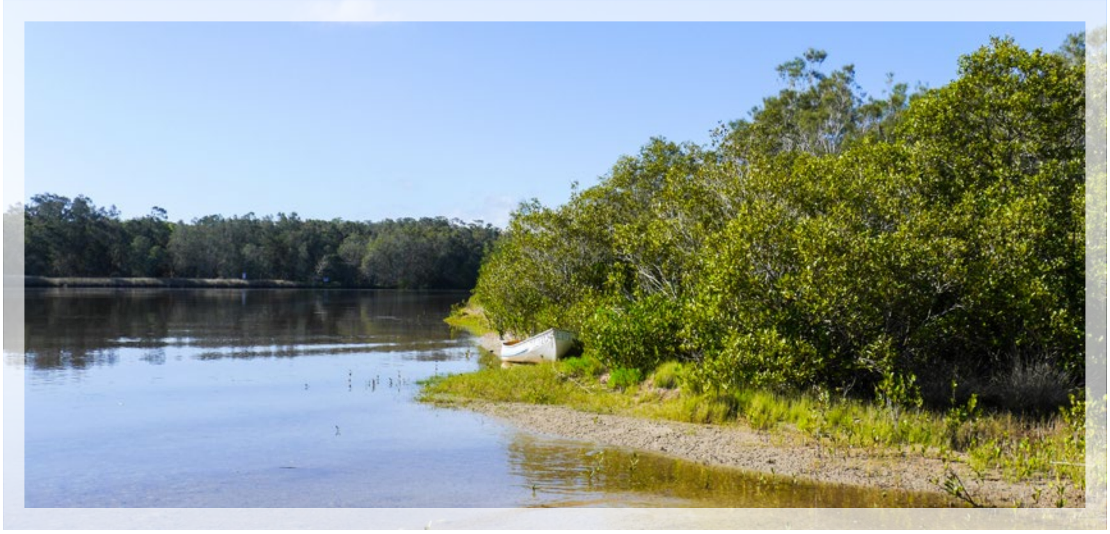


Fig. 7. *Mangrove vegetation in Australia.*

The *vegetated* and *not vegetated* categories are applied to the geological layout category *sloping soft rock coast* where vegetation of the coastal slopes plays an important role for the coastline characteristics and determines whether it can be considered a coastal cliff. The *vegetated* category is applied when more than 25% of the initial coastal slope is covered with vegetation while the *not vegetated* category is used when less than 25% of the initial slope is vegetated. Possible vegetation includes different grasses, scrubs and trees depending on the soft rock properties, slope and climatic conditions. Although some types of vegetation have a better stabilizing effect than others, the important criteria from a coastal classification perspective is whether the coastal slope is vegetated or not. *Sloping soft rock coast*s may be fronted by a narrow band of marsh or mangrove vegetation but this is not considered of major importance from a coastal classification perspective. In cases where the fronting marsh or mangrove areas are more extensive, the coastline will automatically fall into one of the non-sloping geological layout categories.

The *coral* category is only available for *flat hard rock coasts* and *sloping hard rock coasts* where the corals have a hard substrate to thrive on. Corals are carnivorous suspension feeders, living in large colonies as polyps with an external skeleton of calcium carbonate (Masselink and Hughes 2003). Since they generally attach to hard substrates, rocky shorelines provide suitable coral habitats (Masselink and Hughes 2003). Reef building coral species only thrive in water temperatures between 18°C and 34°C and are thus limited to tropical and subtropical environments (Davis and Fitzgerald 2004). Reef building corals are very light sensitive and reefs are rarely being created at depths greater than 50 meters. Locally, water turbidity and salinity can be important parameters for reef formation, and high turbidity can decrease light penetration and increase sedimentation, thereby inhibiting coral growth. Salinity levels outside the range of 27-40 ppt also limit reef formation, and low salinity combined with high turbidity often explain the reef openings found close to river mouths (Masselink and Hughes 2003). Corals can survive in high energy wave environments and even shows enhanced growth on exposed coastlines (Masselink and Hughes 2003). In the classification system, the *coral* category includes both fringing and barrier reefs fronting rocky coastlines. The separate geological layout category for *coral island*s is also assumed to be surrounded by coral reef environments.

Fig. 8. *Coral reef environment in the Red Sea (Photo: Oleksandr Chub/ Shutterstock).*

The *any* category (also indicated with an *A* in the CHW) is used when the flora/fauna is not considered to play an important role for the coastal characteristics and hazard profile. In some cases, the flora/fauna may have relevant functions such as the ability of lyme grasses to reduce aeolian sediment transport, but compared to the other classification parameters it is not expected to influence the coastal character significantly.

Data requirements for determining the flora/fauna

The core data requirements for classifying the flora/fauna at step 1 are Google Earth's satellite images, information on the latitude of the assessment area and the UNEP-WCMC global coral reef database available at http://data.unep-wcmc.org/datasets/1 (UNEP-WCMC 2015). The Google Earth satellite images are used to visually evaluate the extension and type of coastal vegetation, the information on latitude is used to determine whether coastal wetlands are vegetated with marsh or mangroves (local photos from Google Earth can also be used for this), and the coral reef database is used to identify stretches of coastal coral reefs. It may be difficult to determine the percentage of vegetation cover for *sloping soft rock* coasts based on Google Earth's satellite images and to avoid underestimating the hazard levels, it is recommended to assume that the coastline has no vegetation in cases where there are doubts about the actual percentage.

For a step 2-3 classification, the data mentioned above should be supplemented by representative field verification of vegetation cover, vegetation type and if relevant coral presence.

2.5. SEDIMENT BALANCE

The sediment balance is an essential morphodynamic parameter and particularly important for coastlines falling into the sedimentary/soft rock categories. The sediment balance determines whether there is a net balance, deficit or surplus of sediment at a particular coastline over time and is largely determined by the sediment transport/availability and the relative sea level change.

The sediment transport environment can be divided into two main types, namely transport of non-cohesive and cohesive sediment. Transport of non-cohesive, sand-sized sediment, termed littoral transport, plays an essential role for the sediment balance of *exposed* and *moderately exposed* sedimentary coastlines. This type of transport is mainly controlled by the wave height, wave incidence angle and sediment grain size, and large quantities of sediment can be transported down the coastline by this process (Davis and Fitzgerald 2004; Mangor 2004). Coastlines dominated by littoral sediment transport generally respond to physical changes by adjusting their theoretical equilibrium profile, which is the average characteristic form of a coastal profile, controlled by sediment grain size and to some degree wave conditions. Changes in sediment availability, storm conditions or sea level will cause the theoretical equilibrium profile to shift to a new equilibrium state that matches the changing framework conditions. Because of this mechanism, a coastal profile will require more sand to maintain its existing shoreline position if a new equilibrium profile is created due to sea level rise. This will lead to shoreline erosion if no net sediment supply is present.

Transport of fine, cohesive sediment or mud plays an important role in the sediment balance of protected coastal areas. Cohesive sediment particles have a relatively low fall velocity compared to sand grains and the individual grains have the ability to cohere to each other. These particles cannot form stable coastal profiles in *exposed* and *moderately exposed* coastlines since they easily go into suspension. Fine grained, muddy coasts are therefore only found in *protected* coastal areas where there is abundance of cohesive sediment. Such coastlines are generally vegetated with marsh or mangrove vegetation, sometimes combined with tidal flats (Mangor 2004). Coastlines dominated by cohesive sediment can respond to a rising sea level by growing vertically by increasing the sediment accumulation rate, but may also suffer from inundation and erosion depending on sediment availability and tidal dynamics.

In the classification system, the sediment balance section includes the two main categories *balance/deficit* and *surplus* and the two special categories *no beach* and *beach* that applies to the hard rock coastlines. It has been decided to group the *balance/deficit* categories together to simplify the classification system and to ease the difficult evaluation of the sediment balance. Coastal areas that are currently experiencing sediment deficits or only have sufficient sediment to remain stable at current conditions are likely to suffer from sediment deficits with a rising sea level unless new sediment sources emerge (Haslett 2009). Coastal areas that currently experience sediment surplus might suffer deficits at a later stage if sea level rises sufficiently or there is a change in local sediment supply, but these coastlines are less likely to experience severe sediment deficits in the near future.

For achieving an optimal accuracy of the sediment balance evaluation, detailed temporal data on coastline stability would be valuable. As the CHW system is intended to be usable in areas with limited data availability, however, it is designed to rely on basic temporal data. Direct short-term observations are complicated by the fact that single storm and high-wave events can lead to temporal coastline erosion that is reversed during calm conditions. The CHW system therefore makes use of basic historical satellite data available in Google Earth to evaluate the sediment balance. In case there is any doubt about the sediment balance evaluation, the user should assume a *balance/deficit* as this is the default category for the CHW system. This is also recommended where there are any indications of short-term human alteration of the sediment balance.

For hard rock coastlines, the classification system does not require a sediment balance evaluation but simply apply a *no beach* category if the coast consists of bare rock and a *beach* category if some kind of beach environment is present.

Data requirements for determining the sediment balance

The core data requirements for classifying the sediment balance at step 1 are Google Earth's satellite images and Google Earth's timeline function. The sediment balance is evaluated in two different ways depending on whether the geological layout falls into the sedimentary/soft rock or hard rock classification categories.

For all sedimentary/soft rock coastlines, it is determined whether the coastline in question has a sediment balance/deficit or a sediment surplus using Google Earth's historical imagery function.

To facilitate this evaluation, it is recommended to draw a shore-parallel line in Google Earth at the approximate vegetation line, based on the most recent satellite image layer in Google Earth. The sediment balance can then be estimated by shifting back and forth between current and historical satellite images, determining whether the vegetation line has been stable (sediment balance), retreating landwards (sediment deficit) or advancing seawards (sediment surplus). In some locations e.g. in desert coastlines, the vegetation line might not be visible and in that case the approximate vegetation line or MSL can be used. However, one should be cautious of using the visible land-water interface from a few satellite images, as the water level fluctuates between different images e.g. due to tidal variations and hence does not provide a real picture of the coastline stability. In case there are any doubts about the sediment balance evaluation or possible human alterations such as sand mining or beach nourishment, the user should assume a *balance/deficit* as this is the default category for the CHW system.

For all hard rock coastlines, the sediment balance is classified by determining if some kind of beach environment is present based on Google Earth's satellite images.

For a classification at step 2, the data should be supplemented by representative field verification of signs of longer term erosion/accretion, changes in the vegetation line and human alterations. For hard rock coastlines, representative field verification can be used for assessing presence of beach environments. Step 3 would require systematic temporal data on shoreline stability.

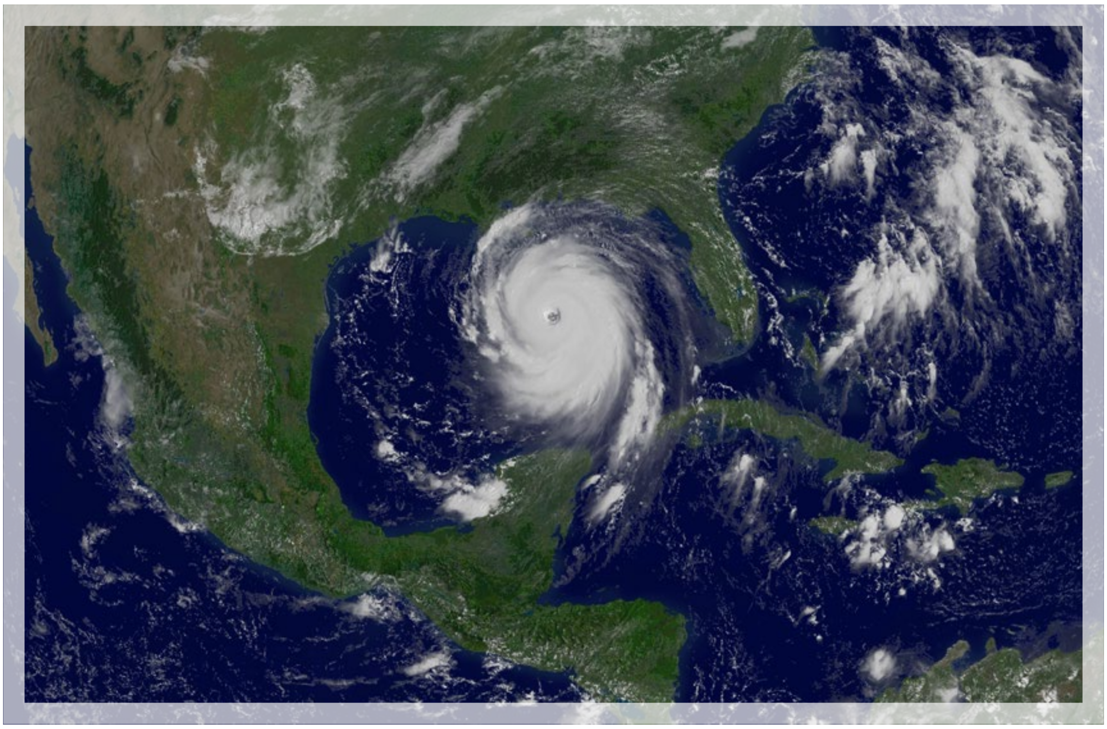
2.6. STORM CLIMATE

In areas with tropical cyclones, coastal areas can experience extreme wind, wave, and precipitation conditions that significantly affect the coastal morphodynamics and hazard profile. Tropical cyclones are generated over tropical seas where the water temperature exceeds 27° C. They are normally generated between 5°-15°N and 5°-15°S and about 60 tropical cyclones are generated annually worldwide with peak periods in September in the Northern Hemisphere and in January in the Southern Hemisphere (Mangor 2004). Wind speeds in tropical cyclones exceed 32 m/s and can cause extreme wave heights, storm surges and cloudburst. Although tropical cyclones have a great impact on the coastal morphology when they hit, the general coastal morphology of an area is largely determined by the local wave climate (Mangor 2004).

The classification system distinguishes between locations with and without tropical cyclone activity, without considering their frequency. This is decided as tropical cyclones contribute to the hazard profile in all areas where they occur regardless of their frequency. The classification system uses the map shown earlier in Fig 4 to categorize the influence of tropical cyclones on coastal areas (Masselink and Hughes 2003). In areas indicated to be under "Tropical cyclone influence" the classification system applies a *yes* to tropical cyclone activity while it applies a *no* for locations outside these areas. For islands not included in Fig 4, one should rely on local information on tropical cyclone presence.

Data requirements for determining the storm climate

The data requirement for evaluating tropical cyclone presence is the same for all steps 1-3, namely Fig 4.



Tropical cyclone Katrina seen from space (Photo: NASA).

3 THE HAZARD VALUATION COMPONENT

The hazard values are displayed in the outermost circles of the CHW and are defined as the hazards being an inherent part of the bio-geophysical properties of a coastal environment when exposed to the predicted climate change over the coming decades (IPCC 2013; IPCC 2007a). The hazards included in the CHW describe the following:

- **Ecosystem disruption:** The possibility of a disruption of the current state of the coastal ecosystems under a changing climate.
- **Gradual inundation:** The possibility of a gradual submergence of a coastal environment under a changing climate.
- **Salt water intrusion:** The possibility of salty sea water penetrating into coastal surface waters and groundwater aquifers under a changing climate.
- **Erosion:** The possibility of erosion of a coastal environment under a changing climate.
- **Flooding:** The possibility of a sudden and abrupt inundation of a coastal environment caused by a short term increase in water level due to storm surge and extreme tides under a changing climate.

The hazard levels of the CHW are based on a scientific literature review of the characteristics of the world's coastal environments and their susceptibility to climate-related parameters. As the literature mainly addresses the susceptibility of different coastal sub-systems, the hazard graduation is based on a qualitative analysis of how the various hazards apply to the coastal categories defined in the CHW classification system.

The hazard levels should be seen as the hazard presence in a particular coastal environment in the coming decades. Since this approach is surrounded by some uncertainty, the hazard graduation simply distinguishes between four different hazard levels, depending on the hazard presence. It is believed that the four-grade system provides sufficient information to be relevant for decision-support, while at the same time appropriately reflecting the uncertainties associated with the hazard graduation methodology. The four levels included are defined so that *4* equals *very high* hazard presence, *3* equals *high* hazard presence, *2* equals *moderate* hazard presence and *1* equals *low* hazard presence. Each generic coastal environment has been assigned a specific hazard level for each of the hazard types, and in the CHW, the graduation is displayed as a combined number/colour code to give the user the best possible overview of the hazard profile of a particular coastal environment. A total of 655 individual hazard evaluations are assigned to the 131 different coastal environments of the CHW 3.0. The specific conditions for the assigned hazard levels are briefly outlined in the following sections for the five hazard types coved by the CHW system.

The hazard of tsunami has not been included as a separate hazard circle in the CHW as it depends on tectonic activities up to thousands of kilometres from a particular coastal site and possible sub-sea landslides, and therefore is very difficult to determine with certainty. Also, tsunami hazards are not directly related to climate change. However, due to their potential devastating effects on coastal areas, tsunami are addressed together with the other hazard types in this section and also covered in the sections on hazard management options and standardized communication codes.

3.1. ECOSYSTEM DISRUPTION

The graduation of the hazard for ecosystem disruption is based on the complexity, sensitivity and expected response to climate change of a particular coastal ecosystem. Where the flora/fauna category is specified in the classification system, the ecosystem hazard applies to this particular biological framework, whereas it applies to the general biological framework for coastlines where the flora/fauna category has not been explicitly specified.

For *exposed* and *moderately exposed* sedimentary/littoral coastal environments, the hazard levels are generally low, as these environments represent hostile places for biota. The sedimentary coastlines have a limited flora, and the fauna are mainly composed of micro- and meiofauna living beneath the sand surface. The projected increase in sea surface temperature is unlikely to cause significantly disruption of these ecosystems as the animals living here are used to adjust to large temperature fluctuations. The ecosystems may, however, to some degree be sensitive to beach erosion (Brown and McLachlan 2002).

Protected coastal environments often have greater ecological diversity than littoral coastlines, when coral coasts are not considered (Schwartz 2005). This is especially the case for coastlines with a large tidal range, as these environments frequently host complex and extensive ecosystems such as marsh, mangrove and tidal flat environments (Haslett 2009). Marshes are generally characterized by high primary production and high species diversity and provides nursing grounds for a range of different marine animals including fish species (Simas et al. 2001). Together with adjacent tidal flat environments, these areas also constitute important habitats for bird populations (Hails 1997). Their response to climate change highly depends on their ability to keep up with sea level rise and hence the sediment availability (IPCC 2014; IPCC 2007b). Mangrove environments are highly complex ecosystems with a high primary productivity. They are among the most productive ecosystems on earth and material export from mangrove forests provide organic matter that acts as an food and energy source for marine primary and secondary production (McMullen and Jabbour 2009; Jennerjahn and Ittekkot 2002). Climate change combined with stressors from human activities such as clearing of mangroves for aquaculture pose a risk to the diversity of coastal mangroves (IPCC 2014; IPCC 2007b). Yet, mangroves have demonstrated a high resilience to change over historic time scales (Gilman et al. 2008). Climate change is projected to cause a maximum loss of global mangrove forests of 10-15 percent which is secondary to current rates of human deforestation (Alongi 2008). Mangroves occupying low relief islands or carbonate beaches with limited sediment supply are generally considered especially vulnerable (Alongi 2008). *Protected* coastal environments with a low tidal range can have an increased risk of wetland loss (Nicholls 2004).

Coral reef environments are among the most biologically diverse ecosystems on the planet (Hoegh-Guldberg et al. 2007). They are expected to be highly sensitive to climate change and especially at risk from increasing ocean temperature and ocean acidification (McMullen and Jabbour 2009). Mass coral bleaching is clearly correlated with rises of sea surface temperature of short duration above summer maxima (Lesser 2004; McWillams et al. 2005) although it is unclear whether bleaching takes place as an adaptive symbiotic strategy or as a symptom of damage caused by changing environmental conditions (Douglas 2003). It is considered very likely that a projected sea surface temperature increase of 1-3 °C will result in more frequent bleaching events and coral mortality if significant thermal adaptation is not taking place (IPCC 2007b; Sheppard 2003). With the currently predicted temperature increase, bleaching could eliminate shallow-water corals within a few decades (Hallock 2005). The increased acidification of sea water and the decreasing carbonate-ion concentration will reduce the calcification rates of marine organisms including reef-building corals (Hoegh-Guldberg et al. 2007; Guinotte et al. 2003). Experimental studies have shown that a doubling of pre-industrial atmospheric CO_2 concentrations decreases coral calcification rates and growth by up to 40 percent (Hoegh-Guldberg et al. 2007). The projected reduction in oceanic pH can be as much as 0.4 pH units by the end of this century and ocean carbonate levels may drop below the level for sustaining coral reef accretion by 2050 (Hoegh-Guldberg et al. 2007). Coral reefs are expected to be able to keep up with sea level rise over the next decades, but this may be of minor importance as they are likely to suffer from the changes in water temperature and acidification (IPCC 2014; IPCC 2007b). Furthermore, intensification of tropical cyclones could have very damaging effects on coral reefs (IPCC 2007b). Together with the sensitive coral reef ecosystems associated with *coral island*s, freshwater dependant ecosystems on these sites also harbour rare and endemic species. These ecosystems are highly sensitive to sea level rise and the associated risk of salt water intrusion (McMullen and Jabbour 2009).

Table 3 provides an overview of the key coastal characteristics influencing the allocation of hazard levels for ecosystem disruption. The specific allocation of hazard levels is carried out by expert judgement for each of the 131 coastal environments of the CHW.

	Key coastal characteristics
Contribute to high hazard levels	Corals
	Marsh vegetation
	Mangrove vegetation
	Sediment balance/deficit
	Low-moderate wave exposure
	Slope vegetation
	Tidal inlet/sand spit/river mouth
Contribute to low hazard levels	Sediment surplus
	No designated flora/fauna systems
	High wave exposure

Table 3. *Key coastal characteristics determining the hazard levels for ecosystem disruption.*

3.2. GRADUAL INUNDATION

The hazard for gradual inundation reflects the possibility of a gradual submergence of a coastal environment under a changing climate. Contrary to flooding, gradual inundation takes place over years to decades when the sediment deposition and growth of biological organisms cannot follow suit with the rising sea level.

Coastlines with a flat geological layout such as *sedimentary plains*, *barriers*, *delta/low estuary islands, flat hard rock coasts* and *coral islands* generally have a higher hazard level. Delta environments are considered particularly sensitive to sea level rise (Ericson et al. 2006; Woodroffe et al. 2006) and current rates of sea level rise in deltas tend to be greater than the global average due to delta subsidence (IPCC 2014; IPCC 2007b). Gradual inundation of delta environments largely depends on the fluvial sediment supply and most deltas no longer maintain their natural sediment supply due to upstream damming activities and are thus experiencing sediment deficits as they are subsiding due to the weight of the accumulated sediment (IPCC 2007b; Masselink and Hughes 2003). Other human activities such as withdrawal of oil, gas and groundwater contribute further to delta subsidence (Ericson et al. 2006) and many delta environments are already changing rapidly, even before human induced sea level rise has started to accelerate (IPCC 2014; IPCC 2007b).

Exposed and *moderately exposed* littoral coastlines are generally expected to respond to sea level rise through adjustments in their theoretical equilibrium profile with associated coastal erosion if no additional sediment is supplied to the coast (Masselink and Hughes 2003). Gradual inundation will therefore often be a secondary effect of sea level rise for these coastlines. *Protected* coastlines, on the other hand, will be particularly susceptible to gradual inundation and for these coastlines, the sediment balance is essential for their ability to follow sea level rise through vertical sediment accretion (Haslett 2009; Richards et al. 2008). If enough sediment is available, marsh, mangrove and tidal flat areas may be able to follow a rising sea level through vertical accretion, while they are likely to drown in locations with a low sediment supply. Along with sediment availability, tidal range may also influence inundation hazards, as marsh environments with a high tidal range are considered to be less vulnerable to sea level rise (Simas et al. 2001).

Although marsh and tidal flat areas may be able to follow a rising sea level in areas with sufficient sediment supply, they are still at risk if sea level rises too rapidly. Studies conclude that a widespread submergence of the Wadden Sea is projected if the sea level rise exceeds 10 mm/yr (Van Goor et al. 2003). If a marsh area cannot keep pace with a rising sea level, it will begin to migrate inland if enough accommodation space is available. If human activities are limiting this migration, the total marsh area is likely to decrease due to coastal squeeze (Haslett 2009).

For mangrove environments, sea level rise is considered the greatest climatic threat and currently most mangrove sediment surfaces are not keeping pace with sea level rise (Gilman et al. 2008). Some studies indicate, however, that mangroves may be able to tolerate significant sea level rise (Morris et al. 2002). The stability of mangrove forests is likely to depend on the sediment availability along with the ability of mangroves to produce sufficient organic material to maintain their peat foundation during a rising sea level (Simas et al. 2001). As with marsh environments, coastal squeeze may limit the landward migration of mangrove forests, decreasing their total areal extension (Haslett 2009).

Coral reef environments may be at risk from gradual drowning if they fail to keep up with the rising sea level. Calculations of coral reef growth and geological core studies estimate the upward growth of coral reefs to 1-10 mm/year (Masselink and Hughes 2003) and it is expected that a sea levels rise greater than 20 mm/year would lead to coral drowning (Spencer 1994). Although gradual inundation of corals may become an issue with a rapid sea level rise, it is considered a smaller component compared to the expected increase in sea surface temperature and ocean acidification (IPCC 2014; Hoegh-Guldberg et al. 2007).

Table 4 provides an overview of the key coastal characteristics influencing the allocation of hazard levels for gradual inundation. The specific allocation of hazard levels is carried out by expert judgement for each of the 131 coastal environments of the CHW.

	Key coastal characteristics
Contribute to high hazard levels	Coral island
	Delta/low estuary island
	Other low-lying geological layout
	Sediment balance/deficit
	Low-moderate wave exposure
	Beach environment at hard rock coasts
Contribute to low hazard levels	Sediment surplus
	Sloping geological layout

Table 4. *Key coastal characteristics determining the hazard levels for gradual inundation.*

3.3. SALT WATER INTRUSION

The graduation of the hazard for salt water intrusion reflects the possibility of salty sea water penetrating into coastal surface waters and groundwater aquifers under a changing climate. Many coastal groundwater aquifers are already experiencing salt water intrusion and it is expected that this phenomenon will be exacerbated by future sea level rise (Essink 2001). Shallow water aquifers are particularly at risk and in many places they already suffer from extensive salt water problems due to both natural and anthropogenic causes (Essink 2001). The intrusion of salt water can pose a great threat to future public water supply, agriculture and horticulture (Essink 2001) as well as pose a threat to existing natural ecosystems (Burkett and Kusler 2000).

The hazard of salt water intrusion is controlled by a combination of coastal geology, aquifer dimensions, human groundwater withdrawal, surface water recharge, submarine groundwater discharge and local precipitation (IPCC 2007b). Coastal areas with a flat geological layout are generally more susceptible for salinization of shallow aquifers as gradual inundation, erosion and higher flooding levels increases the landward reach of salty sea water (IPCC 2014; IPCC 2007b). Shoreline retreat can affect coastal aquifers by reducing the width and area of sand dunes, thereby diminishing the length over which groundwater recharge occurs (Essink 2001). *Deltas/low estuary islands* will experience increased salt water intrusion from sea level rise if these environments cannot keep pace with the rising sea level, and in locations with low sediment availability nearby aquifers can be especially threatened (Essink 2001).

Salt water encroachment from sea level rise may eliminate some species living in brackish coastal wetland habitats and climate change is likely to have an impact on brackish and freshwater marshes due to changes in hydrological regimes (Sun et al. 2002; Burkett and Kusler 2000). In areas with decreasing rainfall and increasing evaporation, mangroves can experience decreased productivity and decreased seedling survival due to conversion of upper tidal zones to hypersaline flats (Gilman et al. 2008). Many small islands are likely to experience increased water stress and depletion of freshwater lenses due to changing precipitation patterns and rising sea level (IPCC 2014; IPCC 2007b).

Nevertheless, the risk of salt water intrusion is largely related to human water extraction and the presence of this hazard therefore arises from a combination of natural and human conditions (IPCC 2014; Essink 2001). In the CHW system, however, the focus is solely on the natural hazards.

Table 5 provides an overview of the key coastal characteristics influencing the allocation of hazard levels for salt water intrusion. The specific allocation of hazard levels is carried out by expert judgement for each of the 131 coastal environments of the CHW.

	Key coastal characteristics
Contribute to high hazard levels	Coral island
	Delta/low estuary island
	Barrier
	Other low-lying geological layout
	Tropical cyclone activity
	Sediment balance/deficit
Contribute to low hazard levels	No tropical cyclone activity
	Sloping geological layout
	Sediment surplus

Table 5. *Key coastal characteristics determining the hazard levels for salt water intrusion.*

3.4. EROSION

The graduation of the hazard for erosion reflects the possibility of coastline erosion and is controlled by a range of classification parameters. The geological layout expresses the potential erodibility of the coastline and thus determining if any significant erosion can happen in the first place (Davis and Fitzgerald 2004). Geological layouts of sedimentary/soft rock origin have a relative high erodibility, while hard rock coastlines show little erosion over timescales used in coastal management (IPCC 2007b). Where beach environments are present along hard rock coastlines, erosion of the beach environment may occur while the rocky coastline itself is likely to remain stable (Masselink and Hughes 2003). The slope of the geological layout also influences the erosion rates as coastlines with a flat layout generally retreat faster than steeper coastlines (Thieler et al. 2000). Barrier coastlines may due to a rising sea level migrate landwards through erosion, overwash and loss of sediment and in some cases barrier overstretching can lead to barrier breaching and disintegration (Haslett 2009). Sloping soft rock coasts are also likely to retreat more rapidly in the future due to an increased erosion of a possible cliff profile. Soft rock cliff erosion often takes place in episodic intervals and the rate of erosion is controlled by a range of parameters including wave exposure, sediment balance, precipitation intensity and groundwater levels (IPCC 2014; IPCC 2007b). Infilling of estuaries and lagoons with sediment during a rising sea level can lead to major sediment deficits and erosion at coastlines in the vicinity of tidal inlets (Van Goor et al. 2003).

In *exposed* and *moderately exposed* littoral environments, the wave exposure is a key parameter for sediment transport, and in areas with negative sediment balance, high wave exposure can lead to significant coastal erosion due to loss of large quantities of sediment by offshore and longshore transport (Mangor 2004). In areas with current sediment surplus, high wave exposure will not necessarily lead to erosion, unless future sea level rise happens faster than additional sediment is supplied to compensate the changing theoretical equilibrium profile. Moreover, at any coastline with littoral sediment transport, there is a risk that local changes in wave and currents due to climate change could modify the rate and direction of the littoral transport (Masselink and Hughes 2003). Increased frequency and intensity of storms are likely to lead to escalated beach erosion (Brown and McLachlan 2002) and changes in sediment sources such as fluvial sediment supply can shift a sediment surplus into a deficit. Generally, the Bruun rule can be used to estimate the effects of sea level rise on littoral coastlines and a horizontal shoreline retreat is estimated to be 50-200 times the rise in relative sea level (IPCC 2007b).

In *protected* coastal environments, the tidal range is an important parameter for the sedimentation processes. In environments with a high tidal range, a sediment surplus can lead to a gradual sediment accumulation on the tidal flats that keep pace with the sea level rise. A sediment deficit, on the other hand, will lead to gradual inundation and various degrees of erosion (Masselink and Hughes 2003). The flora/fauna is important in protected coastal areas as marsh and mangrove vegetation can trap sediment and keep it deposited during extreme storm events. If marsh areas are gradually inundating due to a rising sea level, they may suffer from erosion as increased water depths enable increased wave action on the marsh edges (Masselink and Hughes 2003; Simas et al. 2001). The seaward margins of mangrove forests can also erode as a consequence of a rising sea level (Alongi 2008; Gilman et al. 2008). Vegetation of *sloping soft rock coasts* has an important effect in reducing erosion and gully formation from heavy precipitation events and groundwater seeping.

Degradation of coral reef systems may result in more wave energy across the reef flat reaching the shore, increasing the potential for erosion (IPCC 2007b; Sheppard et al. 2005). The reduced calcification rates in the oceans due to climate change may lead to a reduction of coral skeleton density. This could increase the vulnerability of coral reefs to wave exposure and tropical storms, leading to increased coastal erosion (Hoegh-Guldberg et al. 2007). The rising sea level combined with increased tropical storm intensity also mean that *coral island*s are likely to experience significant erosion and a possible reduction of island size (IPCC 2014; IPCC 2007b).

Table 6 provides an overview of the key coastal characteristics influencing the allocation of hazard levels for erosion. The specific allocation of hazard levels is carried out by expert judgement for each of the 131 coastal environments of the CHW.

	Key coastal characteristics
Contribute to high hazard levels	Sediment balance/deficit
	Tidal inlet/sand spit/river mouth
	Coral island
	Delta/low estuary island
	Other low-lying sedimentary layout
	Sloping soft rock
	High wave exposure
	Tropical cyclone activity
	No vegetation on coastal slopes
	Beach environment at hard rock coasts
Contribute to low hazard levels	Hard rock layout
	Sediment surplus
	No tropical cyclone activity
	Vegetation on coastal slopes
	No beach environment at hard rock coasts

Table 6. *Key coastal characteristics determining the hazard levels for erosion.*

3.5. FLOODING

The graduation of the hazard for flooding is related to the possibility of a sudden, abrupt and often dramatic inundation of a coastal environment caused by a short term increase in water level due to storm surge, extreme tides and seasonal variations (Mangor 2004). A gradual relative sea level rise will also lead to higher extreme water levels.

The flooding hazard is closely related to the geological layout, with *sedimentary plains*, *barriers*, *delta/low estuary islands, flat hard rock coasts* and *coral island*s being particularly vulnerable (IPCC 2014; IPCC 2007b). In delta environments, a rising sea level combined with a storm surge, heavy precipitation and associated peak river flow can lead to extensive flooding. This is further exacerbated in areas with tropical cyclone activity, and increased cyclone intensity due to climate change can also increase flooding hazards (IPCC 2014; IPCC 2007b).

Tidal range influences the flooding hazard of coastal environments by affecting the daily and maximum water levels. Different arguments have been put forward about the relationship between tidal range and flooding hazards, but it is generally accepted that the flooding risk increases with decreasing tidal range (Thieler et al. 2000). This is the case as there is only a certain, relatively low, probability that a storm will occur at the same time as a high tide. In *micro-tidal* environments, the water level is always near its maximum level and therefore has little space for further increase before passing the normal high tide level. In *meso/macro-tidal* environments, water levels can most of the time increase significantly during storm events before reaching the high tide level (Thieler et al. 2000).

Marsh and mangrove environments are often flooded as part of their natural dynamics. It is well established that mangrove forests protects the coastline from tropical cyclone and flooding events, and degradation of these systems due to human activities may increase the extension and damage from flooding due to climate change (IPCC 2014).

Table 7 provides an overview of the key coastal characteristics influencing the allocation of hazard levels for flooding. The specific allocation of hazard levels is carried out by expert judgement for each of the 131 coastal environments of the CHW.

	Key coastal characteristics
Contribute to high hazard levels	Delta/low estuary island
	Coral island
	Barrier
	Sedimentary plain
	Flat hard rock coast
	Tropical cyclone activity
	Low tidal range
	Sediment balance/deficit
Contribute to low hazard levels	Sloping geological layout
	No tropical cyclone activity
	Sediment surplus
	High tidal range

Table 7. *Key coastal characteristics determining the hazard levels for flooding.*

3.6. TSUNAMI

Tsunami are produced by a number of different mechanisms including displacement of the seafloor by submarine earthquakes, large ocean landslides, volcanic eruptions, calving glaciers and an asteroid impact (Haslett 2009; Schwartz 2005; Masselink and Hughes 2003). In the open ocean, tsunami waves can have wavelengths of hundreds of kilometres and wave heights of less than a few meters and can travel across ocean basins at a speed of around 800 Km/h, hardly being noticed by ships (Masselink and Hughes 2003). With that speed they can rapidly cross large ocean basins such as the Pacific.

When tsunami cross the edge of the continental shelf, they rapidly begin to shoal, meaning that they slow down, become shorter in wavelength and larger in wave height. By the time they reach the coastline they can be over ten meters high, have run-up heights of tens of meters and can cause enormous damage as witnessed with the Indian Ocean tsunami in 2004 and the Great East Japan tsunami in 2011 (UNEP 2015; Haslett 2009; Masselink and Hughes 2003). A tsunami-generating event will usually create a series of tsunami waves that may repetitively affect a coastline for up to 24 hours (Haslett 2009). The highest tsunami may even occur hours after several lower ones have passed (Schwartz 2005).

It can be difficult to project the occurrence of tsunami and many world regions normally not associated with tsunami events have geological record of tsunami occurrence. For example, there is geological evidence that the UK coast has been affected by a tsunami and this is also the case for the coast of Norway, Portugal and Italy (Haslett 2009; Schwartz 2005). The Atlantic Coast of North America is also considered potentially at risk from a destructive tsunami because of slope instabilities on the continental shelf (Schwartz 2005). However, the Pacific Ocean remains the region where 90 percent of all destructive tsunami occur, with an average occurrence of two per year (Haslett 2009; Schwartz 2005).

In the CHW system, coastal environments that have a geological layout of the type *sedimentary plain, barrier, delta/low estuary island, flat hard rock, coral island and tidal inlet/sand spit/river mouth* could have a significant inherent hazard for tsunami impacts if they border waterbodies with possible tsunami occurrence. Coasts with geological layouts of the type *sloping soft rock* and *sloping hard rock* with *beach* environment that are used for e.g. recreational activities could also have an inherent hazard for tsunami impacts on human activities. Coastal planners should therefore take possible tsunami hazards into account in the planning process and acquaint themselves with tsunami management activities in their region.

4 APPLICATION FOR LOCAL, REGIONAL AND NATIONAL MULTI-HAZARD-ASSESSMENTS

The CHW can be applied for local, regional and national multi-hazard-assessments and for spot-assessments to identify the hazard profile and possible management options for a particular coastal site. Depending on the data availability and accuracy requirements, coastal multi-hazard-assessments can be implemented at any of the three classification/assessment steps mentioned earlier. It should be noted, however, that the coastal classification always applies to coastal sections of 200-300 meters regardless of assessment step; the steps only describe the data requirements and general accuracy, with the following guiding principles:

- Step 1 is designed for hazard assessments where data availability and accuracy requirements are relatively low. This step can generally be implemented based on remote sensing and publicly available data and is useful for hazard screening and for getting an initial picture of the hazard presence in a cost-efficient manner.
- Step 2 is designed for hazard assessments with moderate accuracy and this step generally requires additional field verification of the data obtained though remote sensing and public data sources.
- Step 3 is designed for hazard assessments with a relatively high accuracy and this step requires field verification combined with high quality datasets for key classification parameters.

Generally, step 1 and 2 are recommended for larger sub-regional, regional and national screenings, while step 3 can be used for coastlines where more comprehensive information is needed. Spot-assessments for a specific coastal site can be carried out at any step depending on accuracy requirements, but it is important to be aware of the associated uncertainties if the assessment is carried out at step 1-2.

4.1. MANUAL ASSESSMENT PROCEDURE

For use for local/spot-assessments, it may be appropriate simply to note down the results from the CHW, i.e. the coastal classification code and hazard values. For regional and national assessments, a manual assessment procedure for ArcGIS is outlined below which allows for development of high-quality hazard maps and hazard layers for Google Earth. Further information on ongoing data activities can be found at www.coastalhazardwheel.org.

The manual assessment procedure can be carried out when the preparatory data collection and analysis mentioned in chapter 2 has been completed. This includes having created the necessary supporting line features in Google Earth for properly evaluating the coastal slope and sediment balance.

The assessment is carried out using the CHW and is done through a range of continuous assessments along the coastline with an approximate distance between each assessment of 200-300 meters. Sometimes a coastline can maintain the same properties for many kilometres, while at others, it changes for every few hundred meters. If the same coastal type extends for longer distances, a single classification segment can extend for more than 200-300 meters when classified in ArcGIS to ease the practical classification procedure.

This section describes the procedure for carrying out the coastal classification and multi-hazard-assessment in ArcGIS, using Esri’s ArcGIS Desktop ver. 10.3 (at all license levels). First, it is explained how to digitize a coastline if not already available. Next, how to split up the coastline into segments in accordance with the CHW system. Finally, it is described how to visualize the data and present a summary of the classification. All data are saved in an ArcGIS file geodatabase that automatically updates the lengths of segmented features. The segmentation will be based on images available online from Esri's Online services. Therefore, it is assumed that the PC used is connected to the internet.

The procedure for carrying out the coastal classification and multi-hazard-assessment in ArcGIS contains the following components:

- Prepare a folder, a file geodatabase and feature classes
- Digitize the coastline
- Split the coastline into segments and assign CHW values
- Symbolize categories
- Save categories as layer files
- Summarize segment lengths by categories
- Create layouts from the layers
- Export layers to a PDF file
- Conversion of layers in ArcMap to Google KMLs

Prepare a folder, a file geodatabase and feature classes

To prepare the storage of the coastline, a folder and a file geodatabase with an empty line feature class must be established first with a suitable projected spatial reference.

1) **Create a new folder** on your hard drive to store your data.

2) **Open ArcGIS Desktop**. Open ArcGIS Desktop with a blank map document and from the main menu select Windows -> Catalog. When opened ArcMap may look as shown in Fig 9 and the Catalog can be locked in place by clicking the pin in the upper right corner.

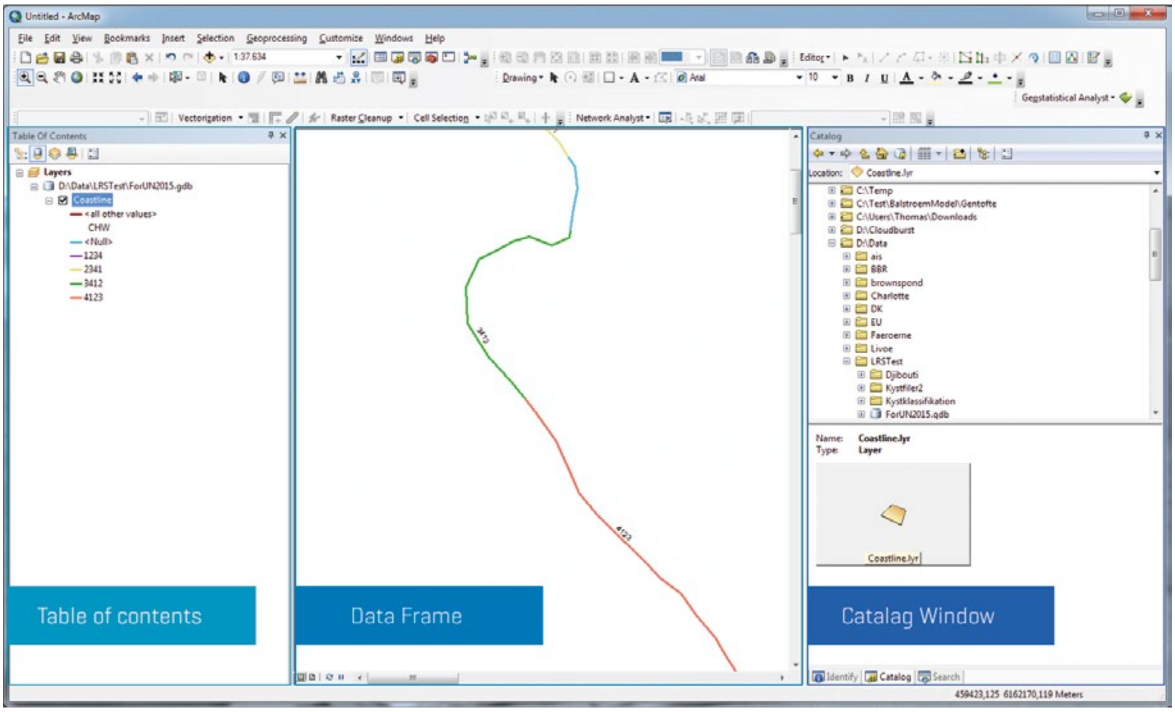


Fig. 9. *ArcMAP main window.*

3) **Establish a new folder**. In the Catalog window click the Folder Connection icon , navigate to the new folder you created in step 1 and click OK. A file connection is now established to your folder and will appear as an entry in your Catalog.

4) **Create a new file geodatabase.** In the Catalog window right click your new folder, select New -> File Geodatabase, enter a suitable name for it (without spaces and special characters) and press Enter.

5) **Create a new empty Coastline feature class.**

   a) Expand your folder in the Catalog window, right click the name of your new file geodatabase and select New -> Feature Class. Enter a name for it, for example Coastline, make sure that the “Type of features …” is set to Line Features and press Next.

   b) Choose a projected coordinate system for your digitized coastline (preferably use the UTM projection that covers your area) by entering the Projected Coordinate Systems section -> UTM -> <region> -> <Specific projection>. For example for the eastern part of Denmark select Projected Coordinate Systems -> Europe -> ETRS 1989 Zone 32N and press Next.

   c) Accept the next default value for the XY tolerance and Database Storage Configuration by pressing Next 3 times and click Finish to close the setup. Now, a new empty feature class should be visible in your file geodatabase, see Fig 10, and also loaded automatically to your Table of Contents. Being loaded onto ArcMap the feature class is now represented by a Layer (although empty at this moment) in the Layers section located in the leftmost pane of ArcMap.

Fig. 10. *Feature class view.*

6) **Enable a default file geodatabase**. In order for ArcGIS to remember the path to your file geodatabase please right click the new file geodatabase and select Make Default Geodatabase.

Digitize the coastline

Now, a coastline can be digitized from an image already available from ArcGIS Online as so called basemaps. By default most online basemaps are saved in a Web Mercator map projection which is not appropriate for our purposes because it's not true to distances. However, if your new empty Coastline feature class is loaded into ArcMap first, and the basemap is added next, the basemap will be converted on-the-fly to the Coastline's map projection. As your empty Coastline feature class is already loaded as a layer, everything is okay.

7) **Add basemap**. Click the tiny arrow to the right of the Add Data icon in the main menu, select Add Basemap -> Imagery and click Add. Be patient and await the display of the image that will be transformed on-the-fly to match the spatial reference of your Coastline layer (the drawing may take a while depending on the speed of your internet connection. While loading the basemap you will notice a globe spinning below the Catalog window). Please notice that it can be important to have a fast internet connection in order to ensure a fast reload of the basemap.

8) **Zoom in**. Use the Zoom and Pan tools to focus on your area of interest and where you want to start digitizing in a moment. If your mouse has a scroll wheel you can turn it to zoom in or out of your map – just be patient until the display is refreshed.

9) **Add the Editor toolbar**. From the main menu select Customize -> Toolbars -> Editor and move the new toolbar, see Fig 11, to a suitable location. All the icons are dimmed out because an edit session hasn't been started, yet.

Fig. 11. *The Editor toolbar.*

10) **Start digitizing**. From the Editor toolbar dropdown click Start Editing and notice that some of the icons are ready for activation. Click Create Features . A new window pops up to the right of your Catalog window. In there click the name of the layer: Coastline, move your cursor to the imagery (notice that a crosshair is appearing) and click the starting point to digitize, the next point to mark the coastline and so forth. You may zoom in and out by scrolling your mouse wheel but if you need to pan you must click the first, and when done go back to the Create Features pane and click on the Coastline name to continue digitizing. Keep on clicking your mouse to digitize points along the coastline with varying densities (few points along straight coastlines and several where it bends). Double-click to finish your digitizing. If you want to add more points re-click the name of the feature class, Coastline, in the Create Features pane, move your cursor to the imagery and you'll see that if you move your cursor to a position close to the endpoint where you stopped your previous digitizing, it will automatically snap to it, see Fig 12.

Fig. 12. *Digitization of coastline.*

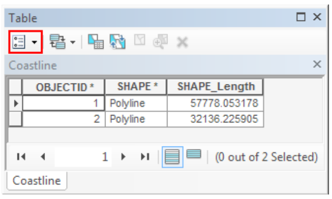
11) **Stop digitizing**. In the Editor dropdown select Stop Editing and answer Yes to save your edits.

12) **Create a backup copy**. Create a backup copy of your digitized coastline by right-clicking the feature class' name in the Catalog window, choose Copy, right-click on the name of your file geodatabase and select Paste. In a popup window press OK to confirm the copy process. Finally, right-click the copy by default named Coastline_1, select Rename, type the name Coastline_original and press Enter.

Split the coastline into segments and assign CHW values

Having digitized the coastline you're ready to split it into segments and assign CHW classification codes to it.

13) **Open the Coastline's attribute table**. Right click the Coastline layer name in the Table of Contents pane and select Open Attribute Table. The attribute table is then shown as in Fig 13. Keep the Attribute Table open but maybe move it a little aside from your Data Frame. For example put it into the bottom of your Table of Contents pane.

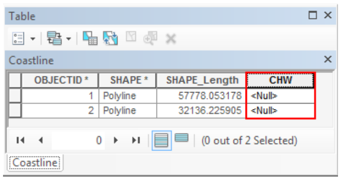


OBJECTID *	SHAPE *	SHAPE_Length
1	Polyline	57778.053178
2	Polyline	32136.225905

(0 out of 2 Selected)

Fig. 13. *Attribute table for the Coastline.*

14) **Add a new field to the attribute table**. In the attribute table window click the tiny arrow to the right of the upper left symbol for Table Options, see Fig 13 and select Add Field to insert a new attribute field into the table. For Name type CHW, set the type to Text and press OK. Notice that a new field with an empty value (<Null>) is inserted as shown in Fig 14. Keep the attribute table's view open, still.



Table

Coastline

OBJECTID *	SHAPE *	SHAPE_Length	CHW
1	Polyline	57778.053178	<Null>
2	Polyline	32136.225905	<Null>

0 (0 out of 2 Selected)

Coastline

Fig. 14. *New CHW field in the attribute table.*

15) **Begin segmentation**. From the Editor toolbar dropdown click Start Editing. By default the Edit tool is activated, so double-click somewhere on the coastline and you will see several green squares being drawn along it and the coastline itself highlighted in a turquoise colour, see Fig 15. The squares symbolize vertexes that are start and ending points for the line segments that you just digitized. However, all the segments are part of one big selected line feature (indicated by the turquoise colour). What you're going to do now is splitting up this line feature into individual features that you assign different CHW codes to.

Fig. 15. *Coastline with start and end-points for digitized line segments.*

16) **Create segments**.

a) Having your basemap imagery open as a background map go to the Editor toolbar and click the Split Tool. Zoom into your coastline close to the start or the ending point of it and decide where you want to split it to identify your first segment. Remember that if your mouse has a scroll wheel, you can turn it to zoom in or out of your map – just be patient until the display is refreshed. At a proper split location click your mouse and notice that all markers and selections disappear.

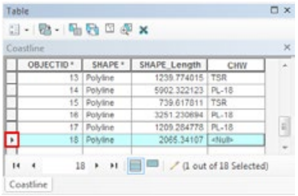
b) The Edit Tool is automatically re-activated so click on that part of your splitted coastline onto which you want to assign a CHW code. Notice that the line feature is highlighted which means that it's selected. In your attribute table the entire record representing your selected line feature is highlighted, too. So, click on the highlighted cell in the CHW column having a Null value, type your CHW code for the line feature (example: BA-18) and press Enter. Now this piece of the coastline has been coded.

c) In the Editor toolbar re-click the Edit Tool icon. Single or double click the next piece of coastline that you want to split up (if you double click you will notice all the vertexes digitized on the selected feature – if you single click the vertexes are not displayed). Activate the Split tool on the Editor toolbar, move your cursor to the position where you want to split the coastline and click your mouse. Go to the attribute table and enter the CHW code for the selected line feature like in the previous step.

d) Repeat steps a-c all along the coastline until all of it is segmented and coded with CHW codes. When appropriate during this process click the Editor toolbar dropdown and select Save Edits.

17) **Check segments**. Before stopping your edit session you must make sure that the entire coastline has been split at the right locations. If you need to subsplit a line feature already coded just select it using the Edit Tool, activate the Split tool and click at the location to split it. Now, as you've split a line that already had a CHW code, you must use the Edit Tool to select the proper line feature and change its CHW code in the attribute table.

Also, scroll through your attribute table and if you identify a line feature with a CHW code = Null, you can zoom to it quickly by right clicking its record's leftmost cell in the attribute table, see Fig 16, and select Zoom to Selected. Then you can inspect that piece of coastline and go back to your attribute table and enter the right CHW code.



Table

Coastline

OBJECTID *	SHAPE *	SHAPE_Length	CHW
13	Polyline	1239.774015	TSR
14	Polyline	5902.322123	PL-18
15	Polyline	739.617811	TSR
16	Polyline	3251.230694	PL-18
17	Polyline	1209.284778	PL-18
18	Polyline	2065.34107	<Null>

18 (1 out of 18 Selected)

Coastline

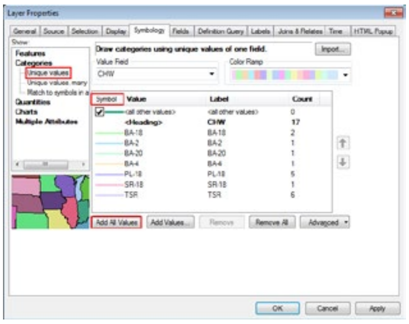
Fig. 16. *Attribute table with a line feature without CHW code.*

Symbolize categories

18) **Display the CHW codes as labels**. One way to display all your CHW codes along the coastline is to activate labelling of your feature layer. First, unselect all selected features by clicking the Clear Selected Features tool . Also, zoom to the extent of your Coastline layer by right clicking its name in the Table of Contents pane and select Zoom to Layer. Next, right click your Coastline layer's name in the Table of Contents, select the bottom option: "Properties", enter the "Labels" tab, check the upper left option: "Label features in this layer", go to "Label Field", from the pull down list select CHW and press Apply.

19) **Display CHW codes with different symbologies**. To symbolize your different CHW types along the coastline change the tab to "Symbology", select

Categories -> Unique Values, change the value Field to CHW and click “Add All Values”. Now, the line width may be a little small, so click the word “Symbol”, see Fig 17, select “Properties for All Symbols”, increase the Line Width to 2, press OK to return to the Symbology window and press OK there, too. Now, your labels should appear together with a colouring of your coastline features, see Fig 18. Before you proceed you can turn off your labels again by right-clicking your Coastline layer’s name in the Table of Contents, select the bottom option: “Properties”, enter the “Labels” tab, and uncheck the upper left option: “Label features in this layer” and press OK.



Draw categories using unique values of one field.

Value Field: CHW

Symbol	Value	Label	Count
☑	<all other values>	<all other values>	0
	<Heading>	CHW	17
	BA-18	BA-18	2
	BA-2	BA-2	1
	BA-20	BA-20	1
	BA-4	BA-4	1
	PL-18	PL-18	5
	SR-18	SR-18	1
	TSR	TSR	6

Fig. 17. *Changing the symbology for the coastline.*

20) **Stop editing**. When you’re done reviewing your edits click the Editor Tool, select Stop Editing and confirm that you want to save your edits.

21) **Join information about hazards to the CHW codes**. The CHW codes represent 5 hazard values: Ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. To add these values to the classified coastal segments, you can join a table with these values onto your coastal segments. The table describing the hazard values for every single CHW code is saved in a table named Hazard_values (available from www.coastalhazardwheel.org), see Fig 19. First, save it to the folder on your desk where you have your geodatabase and add this table to ArcMap by right-clicking on the Geodatabase, choosing Import table (multiple) and import it from where it is saved, and then drag its name from the Catalog Window and onto the Table of Contents, see Fig 20.

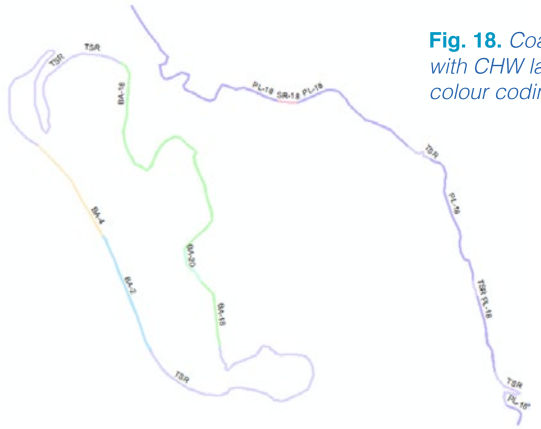
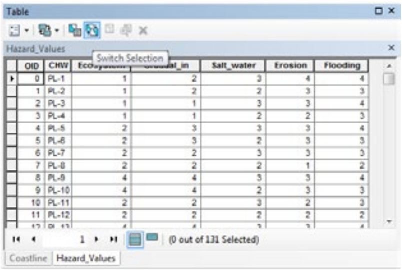


Fig. 18. *Coastline with CHW labels and colour coding.*



OID	CHW	Eco	al_in	Salt_water	Erosion	Flooding
0	PL-1	1	2	3	4	4
1	PL-2	1	2	2	3	3
2	PL-3	1	1	3	3	4
3	PL-4	1	1	2	2	3
4	PL-5	2	3	3	3	4
5	PL-6	2	3	2	3	3
6	PL-7	2	2	3	3	3
7	PL-8	2	2	2	1	2
8	PL-9	4	4	3	3	4
9	PL-10	4	4	2	3	3
10	PL-11	2	2	3	2	3
11	PL-12	2	2	2	2	2

Fig. 19. *The Hazard_values table.*

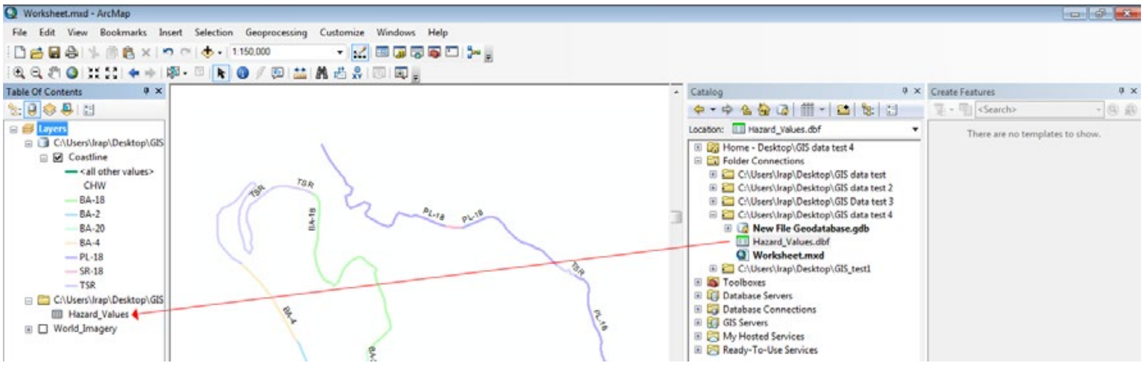
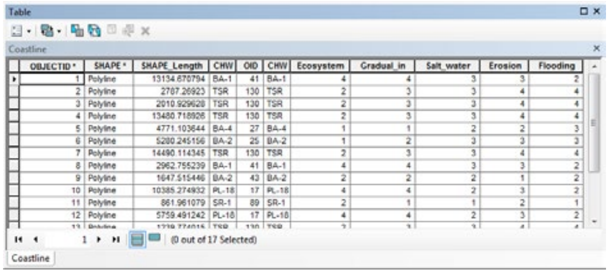


Fig. 20. *Dragging the Hazard_values table to the Table of Contents.*

Now, this table can be joined onto the digitized coastline by right-clicking the Coastline layer’s name, select Join and Relates -> Join. In the Join Data popup window select that you want to ‘Join attributes from a table’, click the tiny arrows to the right in the selectable fields that the join (1) will be based on to CHW, set the table to join (2) to this layer to Hazard_values, Choose the field in the table (3) to base this join on to CHW. Use the default for the rest of the settings and press OK. Now, right-click the Coastline layer's name in the Table of Contents pane, open its attribute table and notice how nicely the hazard value have been added to your CHW values, see Fig 21.



	OBJECTID *	SHAPE *	SHAPE_Length	CHW	OID	CHW	Ecosystem	Gradual_in	Salt_water	Erosion	Flooding
▸	1	Polyline	13134.670794	BA-1	41	BA-1	4	4	3	3	2
	2	Polyline	2787.26923	TSR	130	TSR	2	3	3	4	4
	3	Polyline	2010.929628	TSR	130	TSR	2	3	3	4	4
	4	Polyline	13480.718926	TSR	130	TSR	2	3	3	4	4
	5	Polyline	4771.103644	BA-4	27	BA-4	1	1	2	2	3
	6	Polyline	5280.245156	BA-2	25	BA-2	1	2	3	3	3
	7	Polyline	14490.114345	TSR	130	TSR	2	3	3	4	4
	8	Polyline	2962.755239	BA-1	41	BA-1	4	4	3	3	2
	9	Polyline	1647.515446	BA-2	43	BA-2	2	2	2	1	2
	10	Polyline	10385.274932	PL-18	17	PL-18	4	4	2	3	2
	11	Polyline	861.961079	SR-1	89	SR-1	2	1	1	2	1
	12	Polyline	5759.491242	PL-18	17	PL-18	4	4	2	3	2

(0 out of 17 Selected)

Fig. 21. *The joined attribute table.*

Save categories as layer files

22) **Save the hazard classifications as 5 individual layer files**. Like you displayed the CHW codes in step 18, you are now able to display the 5 individual hazard codes for the coastline and save them in 5 different layer files. In order to assign the same hazard level colours to all 5 themes you will re-use an already saved layer template.

a) First, you must save your joined output to a new feature class by right-clicking the Coastline layer's name, select Data -> Export Data, make sure that the output location is your file geodatabase, assign the name: CoastlineWithHazards to your output and press Save. When asked: 'Do you want to add the exported data to the map as a layer?' click Yes. When the layer appears your CHW symbologies are gone as they haven't been specified for this layer, but never mind that.

b) Double click the CoastlineWithHazards layer's name (this shortcut takes you directly into the layer's properties) and click on the Symbology tab.

c) Click the Import button -> Select 'Import Symbology definition from another layer …", click the yellow Folder button, navigate to your folder in which you have saved your geodatabase, click the Layer Template.lyr (can be downloaded to the folder from www.coastalhazardwheel.org), press Add.

d) In the new popup window's Value Field select Ecosystem_disruption, press OK to return to the Layer Properties window.

e) In the Layer Properties Window click the General tab, change the Layer Name to Ecosystem Disruption and click OK to close the Layer Properties. Now, the Ecosystem Disruption hazard values are displayed and can be saved as a layer file in a folder that you can reload whenever convenient.

f) To save it right click your renamed layer, select Save As Layer File, navigate to your folder in which you have your file geodatabase (but don't enter the file geodatabase), and enter Ecosystem Disruption as the layer's name and press save (the .lyr extension is automatically added to the file name).

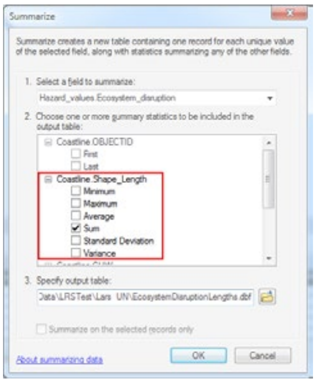
g) Finally, from now on when you open ArcMap you may just load that layer file into ArcMap from your Catalog window to restore your symbology.

Now, redo step 22 b through f and produce layer files for the 4 other hazard values. The only thing you must change is the name of the hazard category in substeps d), e) and f).

When done you may drag and drop all the layer files from the Catalog window into ArcMap.

Summarize segment lengths by categories

Summarize segment lengths by categories. If you want to summarize the lengths of the different hazard codes along the coastline open your specific layer's attribute table (for example Ecosystem Disruption), right-click the field name for the category with the same name as your layer, select Summarize, expand the Coastline Shape_length field, check Sum, specify a proper name (like EcosystemDisruptionLengths.dbf – for the filename omit any blank spaces) and location for your output and press OK, see Fig 22, click Yes to add the results to your Table of Contents, right-click it when it appears there and select Open to display the summarized lengths, see Fig 23.



Summarize creates a new table containing one record for each unique value of the selected field, along with statistics summarizing any of the other fields.

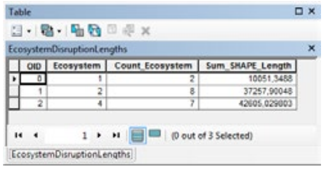
1. Select a field to summarize:
Hazard_values.Ecosystem_disruption

2. Choose one or more summary statistics to be included in the output table:
Coastline.OBJECTID
☐ First
☐ Last
Coastline.Shape_Length
☐ Minimum
☐ Maximum
☐ Average
☑ Sum
☐ Standard Deviation
☐ Variance

3. Specify output table:
Data\LRSTest\Lars UN\EcosystemDisruptionLengths.dbf

☐ Summarize on the selected records only

Fig. 22. *Summarizing the length of coastlines with different hazard levels.*



	OID	Ecosystem	Count_Ecosystem	Sum_SHAPE_Length
▸	0	1	2	10051,3488
	1	2	8	37257,90048
	2	4	7	42605,029803

(0 out of 3 Selected)

Fig. 23. *The display of the summarized lengths.*

Create layouts from the layers

To produce layouts of your individual layers in ArcMap first make sure that the only layer displayed in ArcMap is the layer in question and the basemap. Next, click the tiny Layout View icon in the lower left section of ArcMap's Data Frame (the 2nd from the left) .

Next, click the upper right corner mark and reduce the map's size like shown in Fig 24.

a) Insert a map title: From ArcMap's top main menu select Insert -> Title, enter a suitable title and press OK. If you want to enlarge the title double click it, click the Change Symbol button and increase the size.

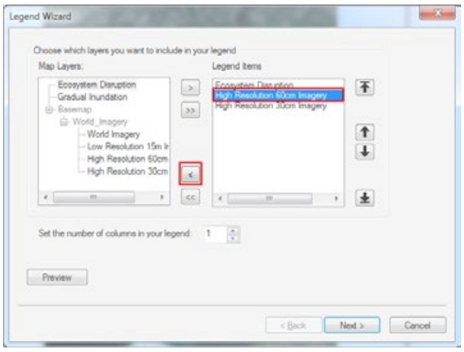
b) Insert a north arrow: From ArcMap's top main menu select Insert -> North Arrow, select a suitable one, click Ok and move it to a position in the lower left corner.

c) Insert a scale bar: From ArcMap's top main menu select Insert -> Scale Bar, select a nice one, enter the Properties and set the scale unit to either Km or Miles and press OK. Move the scale bar to the right of the north arrow.

4) Insert a legend: From ArcMap's top main menu select Insert -> Legend. In the Legend Wizard remove legend items by selecting them in the right pane and click the < button until only the layer name appears for the Legend Items, see Fig 25. Click Next, change the 'Legend' name, click Next 4 times to insert the first version of the legend. Move it to the bottom right of your map. In order to remove legend entries that don't occur right click the legend, enter the Properties, select the Items tab, check 'Only display classes that are visible in the current map extent' and press OK. Now, your map should look like Fig 26.

For each hazard layout, it is very important to remember to change the heading and legend name so it matches the correct hazard type. Also, it is recommended to double-check that no mix-up of the different hazard types has been made.

Fig. 24. *Reducing the map size by clicking the mark in the upper right corner.*



Set the number of columns in your legend: 1

Fig. 25. *Removing legend items that should not be displayed.*

Fig. 26. *Final layout of the hazard map.*

Exporting layers to a PDF file

To export a map to a PDF file select File -> Export Map, select the map's resolution (default is 600 dpi), select PDF as file type, locate the folder where you want to save the file, name it and click Save.

Conversion of layers in ArcMap to Google KMLs

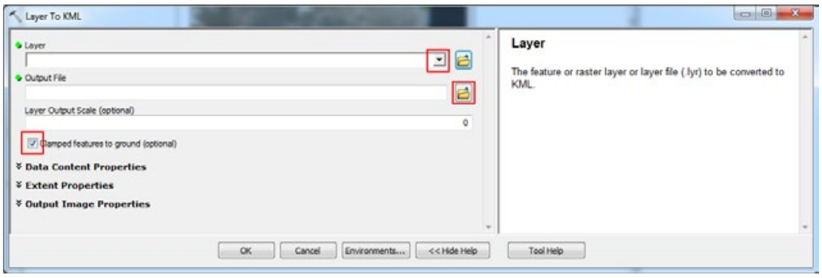
The conversion of ArcMap layers to Google KMLs is very straightforward. What gets converted is the symbology for your layers, and the attribute values for the segments along the coastlines will popup when clicked. Thus, assuming that you've added some symbology to your features the next step is to locate and open the Layer to KML tool.

Before you start the conversion please make sure that you have Google Earth installed on your desktop.

1) In ArcMap's main menu select Windows -> Search. A window opens and in the search field enter: Layer to KML

Hit the Search icon and from the returned list select Layer to KML (Conversion) (tool) by double clicking its name to open the tool.

2) Hit the tiny drop down arrow in the right side of the layer specification and select your CHW layer. Next, enter the name of the KML output file and its destination by clicking the yellow folder icon. Finally, make sure that the 'Clamped features to ground' setting is checked to ensure that the converted KML features are inserted don't respect elevation settings in Google Earth. When done press OK to establish the KML files, see Fig 27.



Layer

Output File

Layer Output Scale (optional)
0

☑ Clamped features to ground (optional)

Data Content Properties
Extent Properties
Output Image Properties

Layer

The feature or raster layer or layer file (.lyr) to be converted to KML.

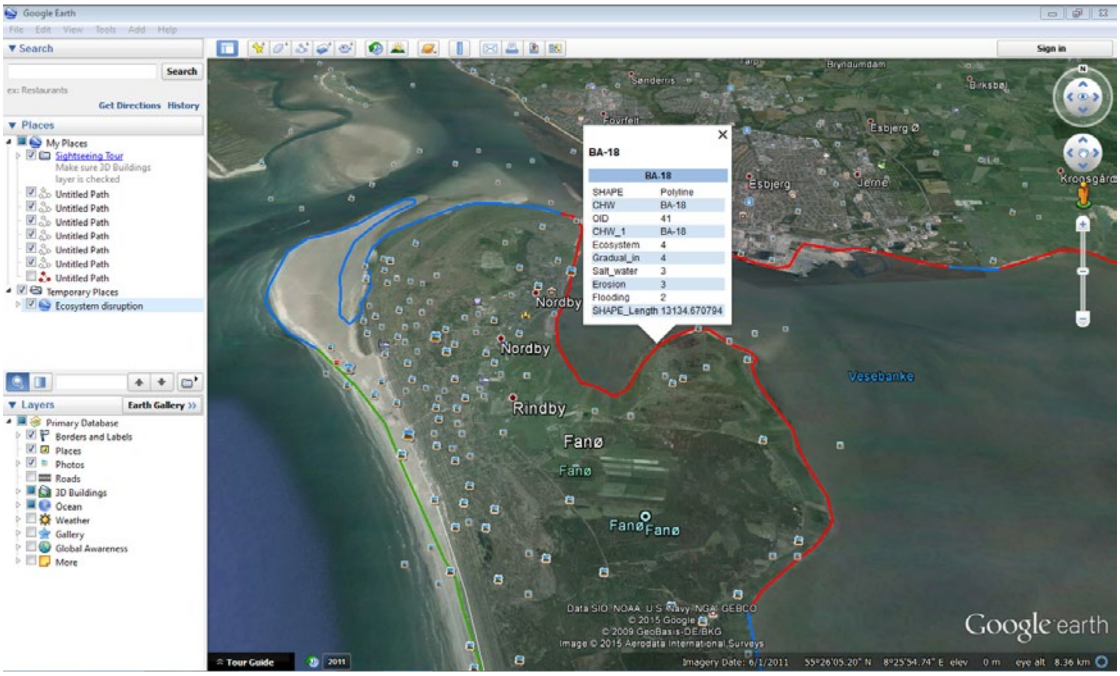
Fig. 27. *Conversion of the layers to Google KMLs.*

3) Minimize ArcMap by hitting the dash in the upper right corner of the application .

4) Open Google Earth, go to the main menu, select File -> Open, locate the KML file you created in step 2 and open it. When loaded Google Earth will zoom to the layer's extent. No matter which spatial reference system you may have entered when you created your feature class in ArcMap, the layer presented in Google Earth is displayed in a spherical coordinate system (notice the latitude and longitude displayed in the lower right corner in Google Earth).

5) Now, zoom into your layer and click on some part of the coastline. A popup window displays your CHW values, see Fig 28.

When all hazard layers are loaded in Google Earth, it is important to be aware of which layer is activated when used for planning.



BA-18

BA-18	
SHAPE	Polyline
CHW	BA-18
OID	41
CHW_1	BA-18
Ecosystem	4
Gradual_in	4
Salt_water	3
Erosion	3
Flooding	2
SHAPE_Length	13134.670794

Fig. 28. *KML file and popup window with CHW code and hazard values displayed in Google Earth.*

4.2. APPLICATION EXAMPLES

The CHW has been applied for complete multi-hazard-assessments in selected regions using ArcGIS as described above. Fig 29 shows an example from the application of the preliminary CHW 2.0 on the Republic of Djibouti. The figure shows the hazard of ecosystem disruption for the full length of Djibouti's coastline and as part of this project similar maps were developed for gradual inundation, salt water intrusion, erosion and flooding. Furthermore, hazard layers were developed for Google Earth that allowed users to zoom in on specific coastal stretches and hazard hotspots.

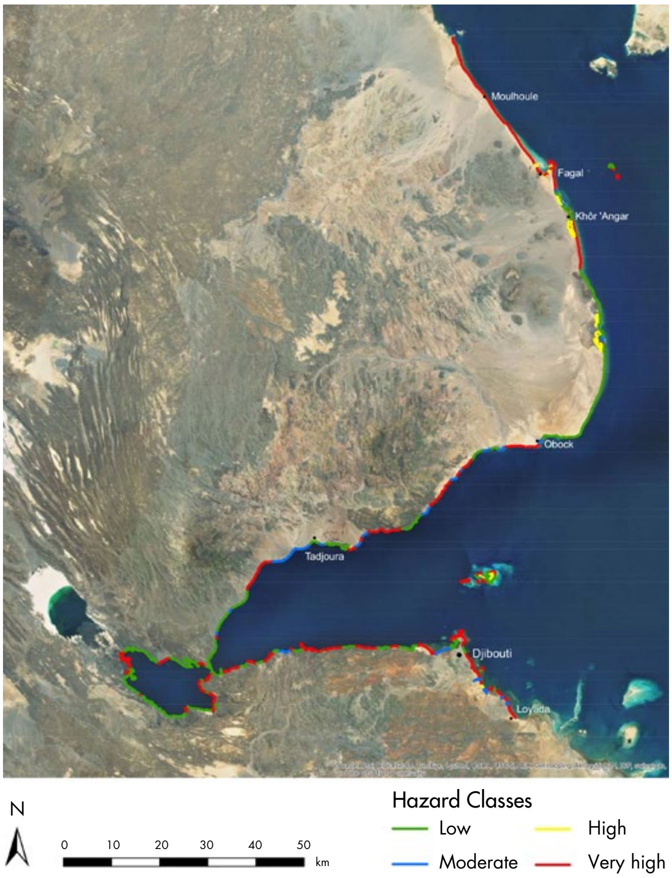

Ecosystem Disruption Hazards, Djibouti

Fig. 29. *National hazard map for the Republic of Djibouti showing the hazard of ecosystem disruption (Rosendahl Appelquist and Balstrøm 2014)*

Fig 30 shows an example from the application of the CHW 1.0 for a multi-hazard-assessment of the Indian state of Karnataka. The example shows two sub-regional hazard maps for northern Karnataka, displaying the hazards of erosion and flooding (Rosendahl Appelquist and Balstrøm 2015).

Coastal hazard maps for northern Karnataka

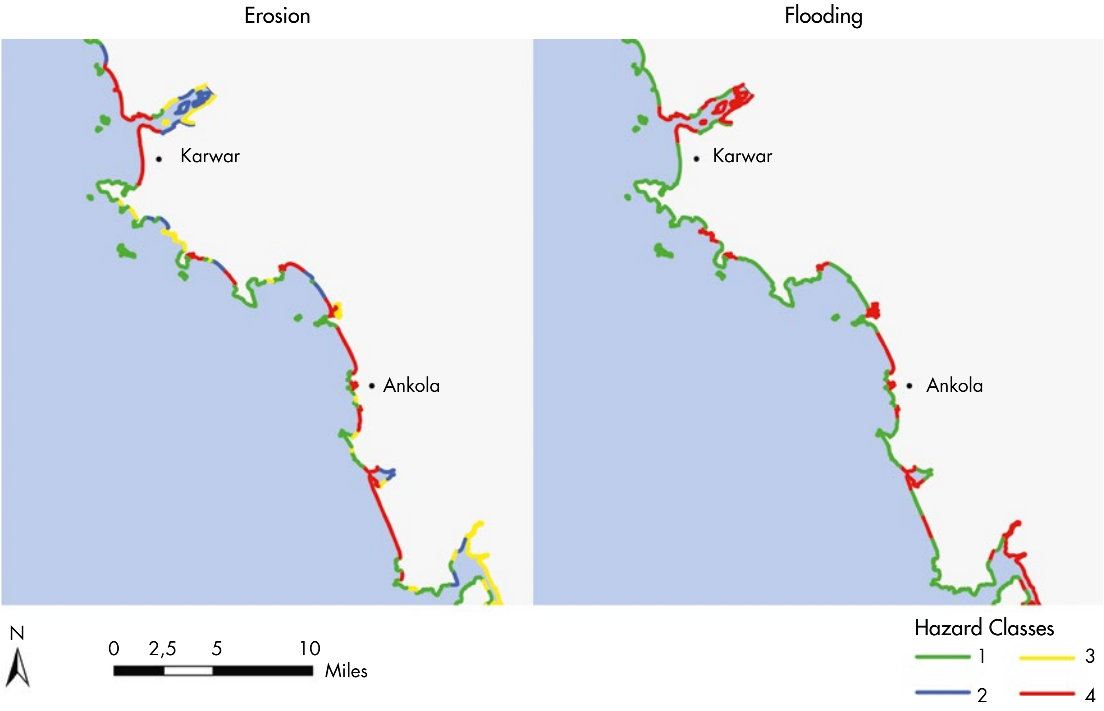


Fig. 30. *Sub-regional hazard maps for northern Karnataka, India showing the hazards of erosion and flooding (Rosendahl Appelquist and Balstrøm 2015).*

Generally, a standard multi-hazard-assessment will result in a series of hazard maps, coving the five hazard types included in the CHW system. The hazard maps shown in Fig 29 and Fig 30 are therefore mainly for illustration and the full range of hazard maps developed for Djibouti and Karnataka can be found in the related papers (Rosendahl Appelquist and Balstrøm 2015; Rosendahl Appelquist and Balstrøm 2014).

5 APPLICATION FOR IDENTIFICATION OF HAZARD MANAGEMENT OPTIONS

The CHW can be used for identification of relevant hazard management options for a specific coastal location. This is done using the matrix shown in Fig 31 that displays how the most commonly used management options apply to the different coastal environments and which hazard types they primarily address. The included management options can be used for mitigating one or more hazard types and can be used in isolation or as combined measures. It should be noted, however, that the choice of management option depends on a range of different factors beyond the technical effects of the management option including project costs, durability, simplicity, flexibility over time, availability of material, labour and equipment and the related socioeconomic and geographical context.

In the matrix, the geological layout categories *Sedimentary plain*, *Barrier* and *Delta/low estuary island* are considered together for simplification reasons, as the management options available for these layouts are relatively similar. The matrix is used by entering with the CHW coastal classification code and then identifying the relevant management options for the coastal environment in question. References to the Catalogue of hazard management options are provided in the second row from the top. In total the matrix includes 24 different management options, hereunder: *Beach nourishment, Breakwaters, Cliff stabilization, Coastal setbacks, Coastal zoning, Dikes, Dune construction/ rehabilitation, Ecosystem based management, Floating agricultural systems, Flood mapping, Flood proofing, Flood shelters, Flood warning systems, Fluvial sediment management, Ground water management, Groynes, Jetties, Land claim, Managed realignment, Revetments, Sea wall, Storm surge barrier/closure dam, Tsunami warning system and Wetland restoration.*

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In total the matrix includes 24 different management options,

> “The matrix is used by entering with the CHW coastal classification code and then identifying the relevant management options for the coastal environment in question.”

	Ecosystem disruption						Gradual inundation												Salt water intrusion								Erosion															Flooding													
Catalogue section no	5	7	8	14	15	24	1	4	5	6	9	11	14	15	18	19	22	24	5	6	7	9	14	15	22	24	1	2	3	4	5	7	14	15	16	17	18	19	20	21	24	4	5	6	7	9	10	11	12	13	14	19	22	23	24
Management options	Coastal zoning	Dune construction/rehabilitation	Ecosystem Based Management	Fluvial sediment management	Groundwater management	Wetland restoration	Beach nourishment	Coastal setbacks	Coastal zoning	Dikes	Floating agricultural system	Flood proofing	Fluvial sediment management	Groundwater management	Land claim	Managed realignment	Storm surge barriers & closure dams	Wetland restoration	Coastal zoning	Dikes	Dune construction/rehabilitation	Floating agricultural system	Fluvial sediment management	Groundwater management	Storm surge barriers & closure dams	Wetland restoration	Beach nourishment	Breakwaters	Cliff stabilization	Coastal setbacks	Coastal zoning	Dune construction/rehabilitation	Fluvial sediment management	Groundwater management	Groynes	Jetties	Land claim	Managed realignment	Revetments	Sea Walls	Wetland restoration	Coastal setbacks	Coastal zoning	Dikes	Dune construction/rehabilitation	Floating agricultural system	Flood mapping	Flood proofing	Flood shelter	Flood warning systems	Fluvial sediment management	Managed realignment	Storm surge barriers & closure dams	Tsunami warning system	Wetland restoration
PL/BA/DE-1	x	x	x	x			x	x	x	x		x	x	x	x	x			x	x	x		x	x			x	x		x	x	x	x		x		x	x	x	x		x	x	x	x		x	x	x	x	x	x		x	
PL/BA/DE-2	x	x	x	x			x	x	x	x		x	x	x	x	x			x	x	x		x	x			x	x		x	x	x	x		x		x	x	x	x		x	x	x	x		x	x		x	x	x		x	
PL/BA/DE-3	x	x	x	x			x	x	x	x		x	x	x	x	x			x	x	x		x	x			x	x		x	x	x	x		x		x	x	x	x		x	x	x	x		x	x	x	x	x	x		x	
PL/BA/DE-4	x	x	x	x			x	x	x	x		x	x	x	x	x			x	x	x		x	x			x	x		x	x	x	x		x		x	x	x	x		x	x	x	x		x	x		x	x	x		x	
PL/BA/DE-5	x	x	x	x			x	x	x	x		x	x	x	x	x			x	x	x		x	x			x	x		x	x	x	x		x		x	x	x	x		x	x	x	x		x	x	x	x	x	x		x	
PL/BA/DE-6	x	x	x	x			x	x	x	x		x	x	x	x	x			x	x	x		x	x			x	x		x	x	x	x		x		x	x	x	x		x	x	x	x		x	x		x	x	x		x	
PL/BA/DE-7	x	x	x	x			x	x	x	x		x	x	x	x	x			x	x	x		x	x			x	x		x	x	x	x		x		x	x	x	x		x	x	x	x		x	x	x	x	x	x		x	
PL/BA/DE-8	x	x	x	x			x	x	x	x		x	x	x	x	x			x	x	x		x	x			x	x		x	x	x	x		x		x	x	x	x		x	x	x	x		x	x		x	x	x		x	
PL/BA/DE-9	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-10	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-11	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-12	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-13	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-14	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-15	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-16	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-17	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-18	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-19	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-20	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-21	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-22	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-23	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-24	x		x	x		x		x	x	x	x	x	x	x	x	x		x	x	x		x	x	x		x				x	x		x				x	x			x	x	x	x		x	x	x		x	x	x		x	x
SR-1	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-2	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-3	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-4	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-5	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-6	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-7	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-8	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-9	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-10	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-11	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-12	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-13	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-14	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-15	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-16	x		x				x		x										x					x			x	x	x	x	x		x	x	x			x	x	x			x											x	
SR-17	x		x						x										x					x					x	x	x		x	x				x					x											x	
SR-18	x		x						x										x					x					x	x	x		x	x				x					x											x	
SR-19	x		x						x										x					x					x	x	x		x	x				x					x											x	
SR-20	x		x						x										x					x					x	x	x		x	x				x					x											x	
FR-1	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x	x	x		x		x	
FR-2	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x		x		x		x	
FR-3	x		x				x	x	x	x		x				x			x	x				x			x	x			x		x		x							x	x	x			x	x	x	x		x		x	
FR-4	x		x				x	x	x	x		x				x			x	x				x			x	x			x		x		x							x	x	x			x	x		x		x		x	
FR-5	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x	x	x		x		x	
FR-6	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x		x		x		x	
FR-7	x		x				x	x	x	x		x				x			x	x				x			x	x			x		x		x							x	x	x			x	x	x	x		x		x	
FR-8	x		x				x	x	x	x		x				x			x	x				x			x	x			x		x		x							x	x	x			x	x		x		x		x	
FR-9	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x	x	x		x		x	
FR-10	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x		x		x		x	
FR-11	x		x				x	x	x	x		x				x			x	x				x			x	x			x		x		x							x	x	x			x	x	x	x		x		x	
FR-12	x		x				x	x	x	x		x				x			x	x				x			x	x			x		x		x							x	x	x			x	x		x		x		x	
FR-13	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x	x	x		x		x	
FR-14	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x		x		x		x	
FR-15	x		x				x	x	x	x		x				x			x	x				x			x	x			x		x		x							x	x	x			x	x	x	x		x		x	
FR-16	x		x				x	x	x	x		x				x			x	x				x			x	x			x		x		x							x	x	x			x	x		x		x		x	
FR-17	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x	x	x		x		x	
FR-18	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x		x		x		x	
FR-19	x		x			x		x	x	x		x				x		x	x	x				x		x					x		x								x	x	x	x			x	x	x	x		x		x	x
FR-20	x		x			x		x	x	x		x				x		x	x	x				x		x					x		x								x	x	x	x			x	x		x		x		x	x
FR-21	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x	x	x		x		x	
FR-22	x		x					x	x	x		x				x			x	x				x							x											x	x	x			x	x		x		x		x	
R-1	x		x						x										x					x							x												x											x	
R-2	x		x				x		x										x					x			x	x			x		x		x								x											x	
R-3	x		x						x										x					x							x												x											x	
R-4	x		x				x		x										x					x			x	x			x		x		x								x											x	
CI-1	x		x		x		x	x	x	x		x				x			x	x				x			x	x		x	x				x			x	x	x		x	x	x			x	x	x	x		x		x	
CI-2	x		x		x		x	x	x	x		x				x			x	x				x			x	x		x	x				x			x	x	x		x	x	x			x	x		x		x		x	
CI-3	x		x		x		x	x	x	x		x				x			x	x				x			x	x		x	x				x			x	x	x		x	x	x			x	x	x	x		x		x	
CI-4	x		x		x		x	x	x	x		x				x			x	x				x			x	x		x	x				x			x	x	x		x	x	x			x	x		x		x		x	
CI-5	x		x		x		x	x	x	x		x				x			x	x				x			x	x		x	x				x			x	x	x		x	x	x			x	x	x	x		x		x	
CI-6	x		x		x		x	x	x	x		x				x			x	x				x			x	x		x	x				x			x	x	x		x	x	x			x	x		x		x		x	
CI-7	x		x		x		x	x	x	x		x				x			x	x				x			x	x		x	x				x			x	x	x		x	x	x			x	x	x	x		x		x	
CI-8	x		x		x		x	x	x	x		x				x			x	x				x			x	x		x	x				x			x	x	x		x	x	x			x	x		x		x		x	
CI-9	x		x		x	x		x	x	x		x				x		x	x	x				x		x				x	x							x	x	x	x	x	x	x			x	x	x	x		x		x	x
CI-10	x		x		x	x		x	x	x		x				x		x	x	x				x		x				x	x							x	x	x	x	x	x	x			x	x		x		x		x	x
CI-11	x		x		x	x		x	x	x		x				x		x	x	x				x		x				x	x							x	x	x	x	x	x	x			x	x	x	x		x		x	x
CI-12	x		x		x	x		x	x	x		x				x		x	x	x				x		x				x	x							x	x	x	x	x	x	x			x	x		x		x		x	x
TSR	x		x	x		x	x	x	x	x	x	x	x			x	x	x	x	x		x		x	x		x	x		x	x		x		x	x		x	x	x	x	x	x	x		x	x	x	x	x		x	x	x	x

Fig. 31. *Matrix of hazard management options for the different coastal environments. It is used by entering with the CHW coastal classification codes in the far left column and moving horizontally to identify relevant management options. Reference to the Catalogue of hazard management options is provided in the second row from the top (modified from Rosendahl Appelquist and Halsnæs 2015).*

If any of the hazard management options listed in the matrix have been implemented at a coastal location, it can be assumed that the hazards they primarily address are reduced. However, as the hazard reduction effect of the different management options strongly depends on their specific design, quality and implementation, it is not possible to determine the exact level of hazard reduction. The intention of the management sections is therefore mainly to give an overview of the relevant management measures for a particular coastal site and their technical characteristics and not to provide information of the exact level of hazard reduction of a particular management option.

When deciding on the hazard management options to implement at a specific coastal site, it is important to make use of the broader coastal planning approaches available. This is to ensure that the interests of all coastal stakeholders are taken into account and the interaction between societal activities and natural processes takes place with a minimum of negative effects.

The concept of Integrated Coastal Zone Management (ICZM) and the related concept of Integrated Water Resource Management (IWRM) are well-tested approaches to tackle these challenges and can be used to decide on the optimal use of the coastal resources and management measures. In many cases it can be beneficial to apply the two concepts together, as the coastal and riverine resources and processes are closely linked.

The core component of ICZM is to ensure a structured coordination of coastal activities and resource demands in order to achieve economically, environmentally and socially sustainable development in compliance with local, regional and international goals (Mangor 2004). The core aims of ICZM are described further in Box 1 below.

- To manage coastal zones in a sustainable and informed fashion which accounts for the wide range of important factors in coastal decision-making
- To promote compatibility and balance of coastal uses
- To promote cooperation between departments, ministries or agencies which have control over specific aspects of the coast. Also, to promote cooperation with other formal institutions such as universities and user groups
- To apply preventative and precautionary approaches in respect to coastal development. I.e. attempt to limit coastal development in unsustainable areas
- To account for both the economic and environmental costs and benefits of coastal management strategies in order to ensure the most beneficial use of the coastal zone
- To facilitate communication with all interested parties on coastal planning and decision-making processes to ensure that all viewpoints are considered
- To ensure the scope and complexity of the climate change issues selected as priorities for adaptation measures are appropriate to the capacity of the institutions involved

Box 1. *Aims of ICZM (Zhu et al. 2010).*

The ICZM and IWRM can be easily combined with more traditional spatial and sector planning approaches to ensure proper integration of spatial and sector interests and appropriate coordination between all involved authorities and stakeholders. The holistic thinking of ICZM and IWRM can thus be a valuable addition to traditional planning approaches.

For implementation of an appropriate hazard management strategy, it will in many cases be relevant with a portfolio of hazard management measures. Furthermore, it is critical to establish a process for monitoring and revising the strategy over time as coastal management is an ongoing process. This includes considering the flexibility of the strategy over years to decades and the possibility of future adjustments. If this is done in the context ICZM, the interrelation between societal and natural conditions, the interests from different coastal users and the short and long term perspectives will be taken properly into account.

One should be aware that some hazard management options come with a range of co-benefits while others can have negative effects on other hazard types. It is therefore important to properly weigh the pros and cons of the different management options. An example of co-benefits could be the multi-sector gains from an Ecosystem Based Management approach, while some types of hard protection measures for erosion and flood control have negative effects on the natural coastal dynamics and ecosystems.

The Catalogue of hazard management options is available as an annex to this publication and includes descriptions of the 24 hazard management options commonly used worldwide. The descriptions of management options are sorted alphabetically and include protection, accommodation and retreat options, as well as options used for more general hazard management. The descriptions follow the same format and should provide an easily accessible introduction to the main technical aspects and applications for each option. The intention is that the CHW is used as a key for identifying the relevant management options and subsequently the catalogue can be used for acquiring further technical information.

Beach nourishment with Trailing Suction Hopper Dredger (Photo: Rohde Nielsen).

6

APPLICATION AS A STANDARDIZED COASTAL LANGUAGE

The CHW system can be used as a standardized coastal language to describe the conditions at a given coastal location. This is done by combining the CHW coastal classification codes with codes for land use and implemented hazard management measures.

The codes for land use are based on the EU LUCAS categories to facilitate compatibility with international statistics. The coding is displayed in Table 8 and can either be determined based on observations in the field/Google Earth or on more complete statistical information. If relevant, the complete detailed EU LUCAS coding can be used (Eurostat 2015).

Land use	Standardized code
Agriculture	U110
Forestry	U120
Aquaculture and fishing	U130
Mining and quarrying	U140
Energy production	U210
Industry and manufacturing	U220
Transport, communication networks, storage, protective works	U310
Water and waste treatment	U320
Construction	U330
Commerce, finance, business	U340
Community services	U350
Recreational, leisure, sport	U360
Residential	U370
Unused	U400

Table 8. *Standardized land use codes based on the EU LUCAS main categories.*

The codes for implemented hazard management measures are displayed in Table 9. Since the quality of the hazard management measures is essential for their hazard mitigation function, the coding includes four quality levels that should be estimated by the user.

Hazard management measures	Standardized code
Beach nourishment	BE
Breakwater	BR
Cliff stabilisation	CL
Coastal setback	CS
Coastal zoning	CZ
Dike	DI
Dune construction/rehabilitation	DU
Ecosystem based management	EC
Floating agricultural system	FA
Flood mapping	FM
Flood proofing	FP
Flood shelter	FS
Flood warning system	FW
Fluvial sediment management	FU
Groundwater management	GM
Groyne	GR
Jetty	JE
Land claim	LA
Managed realignment	MA
Revetment	RE
Sea wall	SE
Storm surge barrier/closure dam	ST
Tsunami warning system	TS
Wetland restoration	WE
User defined	*Write full word*

Quality level of hazard management measures	
No information	0
Low	1
Moderate	2
International state of the art	3

Table 9. *Standardized codes for hazard management measures and quality level.*

The standardized language obeys the following format with the codes from Table 8 and 9:

CHW coastal classification code: Land use, Hazard management measure-Quality level

If several land use activities or hazard management measures are present at a coastal location, several codes can be added after each other, using the same format and comma-separation. This is illustrated for the coastal locations Labutta town, Lagos CBD and Miami Beach below. Since some land use categories may be of minor importance at a particular coastal site, it is up to the user to determine the main activity(s) that should be listed. In some cases it may also be relevant to include additional information in the coastal code, such as specific hydro-meteorological conditions. In that case, this information can be added after the main code.

It should be noted that the hazard values displayed in the CHW do not take possible hazard management actions into account, as their specific effect is surrounded by great uncertainty depending on design. However, if a recommended hazard management measure is implemented at “moderate” to “international state of the art” quality, one can assume that the hazards it is designed to address are reduced.

Fig. 32. *Labutta town, Myanmar: DE-21: U130, U370, FW-1 (Photo: Axel Drainville 2014, CC BY NC).*

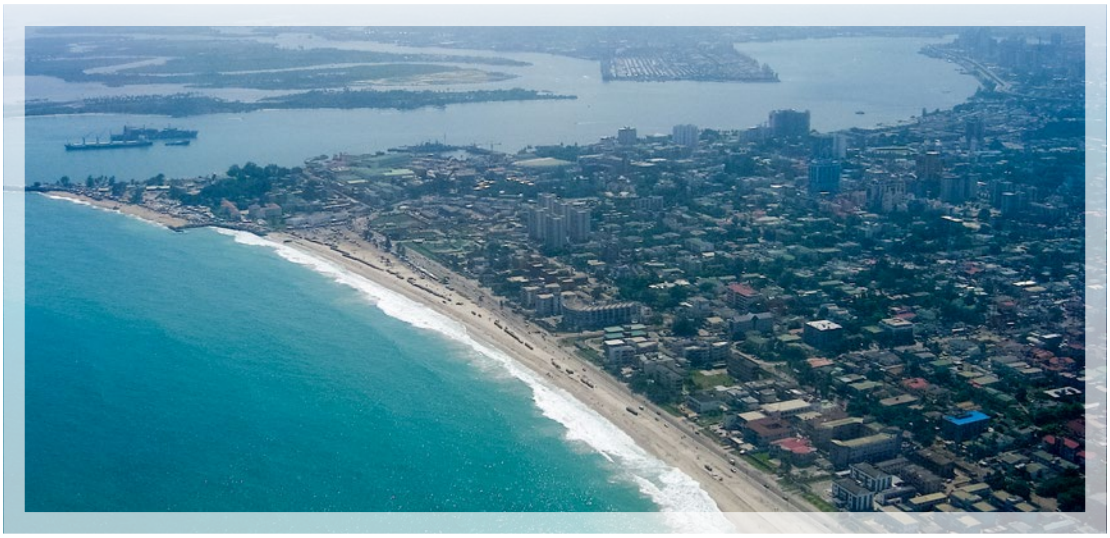

Fig. 33. *Lagos CBD, Nigeria: TSR: U310, U340, U370, FW-2, JE-3, LA-3 (Photo: Roy Luck 2005).*

Fig. 34. *Miami Beach, USA (outer coastline): BA-1: U310, U340, U360, U370, BE-3, FW-3, TS-3 (Photo: Marc Averette 2008, CC BY-SA).*

7 CONCLUSION

This publication provides guidance on how to use the CHW system for practical multi-hazard assessment, multi-hazard-management and as a standardized coastal language. The procedures outlined in the publication should be applicable on virtually all coastlines worldwide and can be used to improve the decision-base for coastal authorities and planners globally, hereunder in areas with limited data availability. If any of the hazard management options listed in chapter 5 and 6 have been implemented properly at a coastal site, it can be assumed that the hazards they primarily address are reduced. However, as the hazard reduction effect of the different management options strongly depends on their design, quality and implementation, it is not possible to determine the exact level of hazard reduction for a specific management option. The hazard profiles of the CHW should therefore be seen as the hazard profile of a specific coastal environment that can then be reduced with different hazard reduction measures. Because the overall goal of the CHW is to provide a universal decision support system that can be used in areas with limited data availability, the system involves a trade-off between simplicity and accuracy.
Hence, it is recommended to use the CHW as a coastal multi-tool that can be supplemented with more detailed data collection, modelling and engineering calculations in locations where it is considered relevant. It is the hope that the CHW will provide coastal decision-makers with a new and useful tool for tackling the challenges from climate change over the coming years and decades.

View of Table Mountain overlooking Cape Town, South Africa (Photo: Sculpies/Shutterstock).

8 REFERENCES

- Alongi DM (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. Estuarine, Coastal and Shelf Science 76, pp. 1-13.
- Brown AC, McLachlan A (2002). Sandy shore ecosystems and the threats facing them: some predictions for the year 2025. Environmental Conservation 29, pp. 62-77.
- Burkett V, Kusler J (2000). Climate change, potential impacts and interactions in wetlands of the United States. Journal of the American Water Resources Association 36, no 2.
- Davis Jr RA, Fitzgerald DM (2004). Beaches and coasts. Blackwell Publishing.
- Davies JL (1980). Geographical Variation to Coastal Development, 2nd Edition, Longman (Pearson Education Limited).
- Douglas AE (2003). Coral Bleaching - how and why. Marine Pollution Bulletin, 46, 385-392.
- Ericson JP, Vorosmarty CJ, Dingman SL, Ward LG, Meybeck M (2006). Effective sea-level rise and deltas: Causes of change and human dimension implication. Global and Planetary Changes 50, pp. 63-82.
- Essink GHPO (2001). Improving fresh groundwater supply - problems and solutions. Ocean and Coastal Management 44, pp. 429-449.
- Eurostat (2015). LUCAS - Land use and land cover survey. Accessed online 23-09-15 at http://ec.europa.eu/eurostat/statistics-explained/index.php/LUCAS_-_Land_use_and_land_cover_survey#LUCAS_.E2.80.94_the_historical_perspective.
- Galloway WE (1975). Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In Broussard ML (editor), Deltas, Models for Exploration. Houston Geological Society, Houston, 87-98.
- Gilman EL, Ellison J, Duke NC, Field C (2008). Threats to mangroves from climate change and adaptation options: A review. Aquatic Botany 89, 237-250.
- Guinotte JM, Buddemeier RW, Kleypas JA (2003). Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. Coral Reefs 22, pp. 551-558.
- Hails AJ (1997). Wetlands, biodiversity and the Ramsar convention: The role of the convention on wetlands in the conservation and wise use of biodiversity. Ramsar Convention Bureau, Gland, Switzerland.
- Hallock P (2005). Global change and modern coral reefs: New opportunities to understand shallow-water carbonate depositional processes. Sedimentary Geology 175, 19-33.
- Haslett SK (2009). Coastal systems. Routledge.
- Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias-Prieto R, Muthiga N, Bradbury RH, Dubi A, Hatziolos ME (2007). Coral reef under rapid climate change and ocean acidification. Science 318, pp. 1737.
- IPCC, 2014: Wong, P.P., I.J. Losada, J.-P. Gattuso, J. Hinkel, A. Khattabi, K.L. McInnes, Y. Saito, and A. Sallenger, 2014: Coastal systems and low-lying areas. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 361-409.
- IPCC (2013). Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IPCC (2007a). Climate Change 2007: The physical science basis. Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Eds), Cambridge University Press, Cambridge UK.
- IPCC (2007b). Climate change 2007: Impacts, adaptation and vulnerability. Contribution of the Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P.

Palutikof, P.J. van der Linden and C.E. Hanson (Eds), Cambridge University Press, Cambridge UK.

- Jennerjahn TC, Ittekkot V (2002). Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. Naturwissensschaften 89, pp. 23-30.
- Lesser MP (2004). Experimental biology of coral reef ecosystems. Journal of Experimental Marine Biology and Ecology 300, pp. 217-252.
- Mangor K (2004). Shoreline management guidelines. DHI Water & Environment, Hørsholm.
- Masselink G, Hughes MG (2003). Introduction to coastal processes and geomorphology. Oxford University Press.
- McMullen CP, Jabbour J (2009). Climate change science compendium. UNEP.
- McWillams JP, Côté IM, Gill JA, Sutherland WJ, Watkinson AR (2005). Accelerating impacts of temperature-induced coral bleaching in the Caribbean. Ecology 86:2055–2060.
- Morris JT, Sundareshwar PV, Nietch CT, Kjerfve B, Cahoon DR (2002). Responses of coastal wetlands to rising sea level. Ecology, 83(10), 2002, pp. 2869-2877.
- Nicholls RJ (2004). Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. Global Environmental Change 14, pp. 69-86.
- Press F, Siever R (2001). Understanding earth. Freeman and Company.
- Ramieri E, Hartley A, Barbanti A, Santos FD, Gomes A, Hilden M, Laihonen P, Marinova N, Santini M (2011). Methods for assessing coastal vulnerability to climate change, European Environment Agency, European topic centre on climate change impacts, vulnerability and adaptation.
- Reinson GE (1984). Barrier island and associated strand-plain systems. In RG Walker (editor), Facies Models (2nd Edition), Geoscience Canada Reprint Series 1, Geological Association of Canada, 119-140.
- Richards JA, Mokrech M, Berry PM, Nicholls RJ (2008). Regional assessment of climate change impacts on coastal and fluvial ecosystems and the scope for adaptation. Climate Change 90, pp. 141-167.
- Rosendahl Appelquist L and Halsnæs K (2015). The Coastal Hazard Wheel system for coastal multi-hazard assessment & management in a changing climate. Journal of Coastal Conservation 19, 2, 157-179.
- Rosendahl Appelquist L and Balstrøm T (2015). Application of a new methodology for coastal multi-hazard-assessment & management on the state of Karnataka, India. Journal of Environmental Management 152, 1-10.
- Rosendahl Appelquist L and Balstrøm T (2014). Application of the Coastal Hazard Wheel methodology for coastal multi-hazard assessment and management in the state of Djibouti. Climate Risk Management 3, 79-95.
- Rosendahl Appelquist L (2013). Generic framework for meso-scale assessment of climate change hazards in coastal environments, Journal of Coastal Conservation 17, 1, 59-74.
- Schwartz ML (2005). Encyclopaedia of coastal science. Springer.
- Sheppard C, Dixon DJ, Gourlay M, Sheppard A, Payet R (2005). Coral mortality increases wave energy reaching shores protected by reef flats: Examples from the Seychelles. Estuarine, Coastal and Shelf Science 64, 223-234.
- Sheppard CRC (2003). Predicted recurrences of mass coral mortality in the Indian Ocean. Nature 425, September 2003.
- Simas T, Nunes JP, Ferreira JG (2001). Effects of global change on coastal salt marshes. Ecological Modelling 139, pp. 1-15.
- Small C, Nicholls RJ (2003). A global analysis of human settlement in coastal zones. Journal of Coastal Research 19, 3, 584-599.
- Smithson P, Addison K, Atkinson K (2002). Fundamentals of the Physical Environment 3ed, Routledge.
- Spencer T (1994). Tropical coral islands – an uncertain future?, In Roberts N (ed), The Changing Global Environment, Blackwell, Oxford.
- Sun G, McNulty SG, Amatya DM, Skaggs RW, Swift Jr LW, Shepard JP, Riekerk H (2002). A comparison of watershed hydrology of coastal forested wetlands and the mountainous uplands in the Southern US. Journal of Hydrology 263, pp. 92-104.
- Thieler ER, Willams J, Hammer-Klose E (2000). National assessment of coastal vulnerability to future sea-level rise. Accessed online 20-10-15 at http://woodshole.er.usgs.gov/project-pages/cvi/
- UNEP (2015). Great East Japan Earthquake and tsunami. Accessed online 20-10-15 at http://www.unep.org/tsunami/.
- UNEP-WCMC (2015). Ocean Data viewer. Accessed online 20-10-15 at http://data.unep-wcmc.org/datasets/1.
- UNISDR (2016). Sendai Framework for Disaster Risk Reduction, Accessed online 28-04-16 at http://www.unisdr.org/we/coordinate/sendai-framework.
- Van Goor MA, Zitman TJ, Wang ZB, Stive MJF (2003). Impact of sea-level rise on the morphological equilibrium state of tidal inlets. Marine Geology 202, pp. 211-227.
- Woodroffe CD, Nicholls RJ, Saito Y, Chen Z, Goodbred, SL (2006). Landscape variability and the response of Asian megadeltas to environmental change. In: Harvey N (ed) Global change and integrated coastal management: The Asia-Pacific region. Springer, New York, pp 277–314.
- Zhu, X, Linham MM, Nicholls RJ (2010). Technologies for climate change adaptation - Coastal erosion and flooding, UNEP.

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