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# Application of the Coastal Hazard Wheel methodology for coastal multi-hazard assessment and management in the state of Djibouti

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ABSTRACT

This paper presents the application of a new methodology for coastal multi-hazard assessment and management in a changing global climate on the state of Djibouti. The methodology termed the Coastal Hazard Wheel (CHW) is developed for worldwide application and is based on a specially designed coastal classification system that incorporates the main static and dynamic parameters determining the characteristics of a coastal environment. The methodology provides information on the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding and can be used to support management decisions at local, regional and national level, in areas with limited access to geophysical data. The assessment for Djibouti applies a geographic information system (GIS) to develop a range of national hazard maps along with relevant hazard statistics and is showcasing the procedure for applying the CHW methodology for national hazard assessments. The assessment shows that the coastline of Djibouti is characterized by extensive stretches with high or very high hazards of ecosystem disruption, mainly related to coral reefs and mangrove forests, while large sections along the coastlines of especially northern and southern Djibouti have high hazard levels for gradual inundation. The hazard of salt water intrusion is moderate along most of Djibouti's coastline, although groundwater availability is considered to be very sensitive to human ground water extraction. High or very high erosion hazards are associated with Djibouti's sedimentary plains, estuaries and river mouths, while very high flooding hazards are associated with the dry river mouths.


## Introduction

Projected climate change will alter the environmental conditions along most of the world's coastlines and thereby the livelihoods of the local coastal populations (IPCC, 2014). According to the IPCC, the utilization of the coast has increased dramatically during the 20th century and this trend will continue during the 21st century, leading to a growth in the global coastal population from the current 1.2 billion to 1.8–5.2 billion by the 2080s depending on migration assumptions (IPCC, 2007a). Identifying climate-related hazards to coastal regions is therefore essential for managing potential hazards in due course, and this is especially a challenge in developing countries where data, expertise and economic resources are limited and coastal populations are growing rapidly.

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To date, several different methodologies and approaches have been developed to assess and manage coastal climate change vulnerability and coastal climate-related hazards. Generally, one can distinguish between index and 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). The index and indicator based methods such as the Coastal Vulnerability Index (CVI) and the Smartline system are to date the most realistic options for use in data-poor regions such as developing countries, but they cannot be directly used to identify a range of sector-specific hazards and management options and require relatively detailed input data (Ramieri et al., 2011; Thieler et al., 2000; Sharples, 2014). The GIS-based decision support systems and dynamic computer models such as the DIVA model are very complex systems that would have to be combined with larger data-collection programs or be applied at very coarse resolution and also require highly specialized expertise (Global Climate Forum, 2013; Ramieri et al., 2011; Mcleod et al., 2010).

The Coastal Hazard Wheel (CHW) framework is developed to address the gap in the current coastal vulnerability/hazard assessment methodologies and to offer a tool that can be used for combined assessment and management of the key climate-related coastal hazards in areas with limited data availability, resources and institutional capacity. The framework is especially designed to facilitate hazard screening and identification of hazard-hotpots at regional and national level but can also be applied as a first-line tool for hazard identification at local level prior to more detailed feasibility studies. The CHW framework makes use of publicly available geo-data and remote sensing information, and, depending on accuracy requirements, different levels of field verification. The system covers the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding and can be used for development of hazard maps and hazard statics and subsequent identification of management options. The system can be applied for multi-hazard-assessments at three different steps depending on the data availability and accuracy requirements, namely:

- Step 1 that 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 hazard presence in a cost-efficient manner.
- Step 2 that is designed for hazard assessments with moderate accuracy and this step generally requires additional field verification of the data obtained through remote sensing and public data sources.
- Step 3 that is designed for hazard assessments with moderate and locally focused accuracy and this step requires systematic and detailed field assessments at the local level, if possible supplemented with results from other locally focused assessment tools.

Generally, Step 1 and 2 are recommended for larger sub-regional, regional and national assessments, as it would require significant time and resources to implement Step 3 at this scale. Step 1–2 can therefore be used for broader hazard assessments, while Step 3 can be used for coastal stretches of specific interest or for detailed assessment of hazard-hotspots indentified at Step 1–2. Spot-assessments of a single coastal site can be carried out at any step depending on accuracy requirements, but it is important to be aware of the associated uncertainties at local level, unless the assessment is supplemented with more detailed results from other more locally focused assessment tools.

In this paper, the CHW framework is used to carry out a multi-hazard assessment at Step 1 (which can be thought of as a 'First Pass' assessment) for the full coastline of Djibouti and to develop a range of hazard maps along with national hazard statics. For the state of Djibouti, very little information is currently available on future climate-related hazards in coastal areas and it is therefore difficult for national planners and decision-makers to address and mitigate potential hazards. As systematic geophysical data collection until now has been limited and major challenges persist in downscaling regional climate models, this knowledge gap could potentially become a barrier for sound planning decisions. With a growing population and a possible future migration to coastal areas, the need for a robust decision-base for coastal planning becomes even more critical.

Together with developing relevant information for management of coastal climate change hazards in Djibouti, the assessment provides a good example of a CHW application in a data poor location for which the system is designed. The goal of this paper is therefore twofold, namely to showcase the practical procedure for applying the CHW methodology for national hazard assessments in a data poor location, and to provide relevant information on coastal hazards and management options for the coastline of Djibouti.

Since the assessment is carried out as a national hazard assessment at Step 1, it is designed to provide a good overview of where specific hazards are present and at what level the hazards are manifested for the full length of Djibouti's coastline. If a higher level of accuracy is needed, it might be necessary to supplement the assessment with addition field verification. At this stage, however, the assessment provides a good general picture of the coastal hazards for Djibouti. The result of the hazard assessment is presented as a series of five thematic overview maps for Djibouti, and along with this, the assessment has tested the possibility of developing detailed hazard layers for use in Google Earth. Whereas the overview maps are useful for getting a good general picture of the coastal hazards, the hazard layers can be used to support more detailed planning decisions at sub-regional level.

## The Coastal Hazard Wheel (CHW) framework

The CHW framework is a hazard assessment and management methodology that can be used in areas with limited geophysical data availability and institutional capacity. The framework is based on a specially designed coastal classification system that incorporates the main geo-biophysical parameters determining the characteristics of a coastal environment and how this environment responds to the predicted changes in the global climate (IPCC, 2007b). The framework uses the coastal geological layout as basis, on which it adds the main dynamic parameters acting in the coastal environment, and it is designed to cover all generic coastal environments worldwide.

The framework provides information on the degree to which key climate change hazards are inherent in a particular coastal environment, defined as the hazards being an integrated part of the geo-biophysical properties of a coastal system when it is exposed to future climate change. The framework covers the inherent hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding, and each hazard evaluation is graduated into four different hazard levels based on a scientific literature review. The current version of the CHW framework includes 113 generic coastal environments and a total of 565 individual hazard evaluations.

When using the CHW, see Fig. 1, the user starts in the centre of the wheel and then moves outwards ending up with the inherent hazard evaluations in the outermost circles. Starting from the centre, the coastal classification parameters come in the following order where each category is represented by a new circle: Geological layout, wave exposure, tidal range, flora/fauna, sediment balance and storm climate. The special TSR category constitutes a group of highly dynamic geological environments. The inherent hazards then come in the following order: Ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding.

In the practical application of the assessment framework, the user should make a new assessment every time any of the classification parameters change significantly. This can be done based on a combination of basic geo-biophysical data and remote sensing information, if possible combined with field verification. It is important that the user always is aware of human alterations of the natural environment that may have an impact on the coastal classification and thereby the hazard levels. A detailed description of the CHW methodology, assumptions and limitations can be found in Rosendahl Appelquist (2012).

The current version of the CHW operates with eight different generic coastal environments for rocky coastlines, and hence does not capture small variations and special rarities for these environments. Since the coastline of Djibouti is predominantly of rocky origin and includes some special features such as raised coral reef plains, it was decided to increase the detail of the wheel's rocky category so it spans over a total of 26 different coastal environments. In this way, the assessment for Djibouti will be able to provide relatively detailed hazard information, even when large parts of the coastline fall into the rocky coast category. The extended list of rocky coastal environments with their assigned hazard values is shown in Table 1. The list distinguishes between flat and sloping rocky coastlines, and the hazard values are derived from the rocky coast and coastal plain categories in the original CHW framework. Thus, the eight rocky types included in the original framework are not applied for this assessment.

## Characteristics of Djibouti's coastline

The coastline of Djibouti extends from the southern Red Sea and strait of Bab el Mandeb to the Somali border around the Gulf of Tadjoura (Bird, 2010). The general outline of Djibouti's coastline, along with political borders and larger cities is shown in Fig. 2. From the figure it can be seen that Djibouti shares its longest border with Ethiopia, while the coastal borders are shared with Eritrea and Somalia.

The geology of Djibouti is shaped by the tectonic trends of East Africa's Great Rift Valley which forms a complex landscape composed of high blocks and subsistence zones, mostly of volcanic and sedimentary rocks (Schlüter, 2006). The northern parts of Djibouti's coastline from the strait of Bab el Mandeb to the mouth of the Gulf of Tadjoura is characterized by raised coral reef plains interrupted by a rocky formation of basaltic lava, subordinate ignimbrites and rhyolites. Further south, a basaltic formation is located next to the city of Tadjoura, and after this, the coastline turns into alluvial deposits until ca. 10 km north of Ghoubet Bay. The coastline of Ghoubet Bay and the southern parts of the Gulf of Tadjoura is generally characterized by rocky formations of basalts, subordinate ignimbrites, rhyolites, silicic massifs and lava flows until just west of the city of Djibouti. From here to the Somali border, the coastline is composed of a mixture of eluvial and colluvial deposits, taluses, sheetfloods, dunes and beach deposits (Schlüter, 2006). Geomorphologic form elements such as barriers, spits and river mouths are found along the northern coastline facing the Gulf of Aden, the northern part of the Gulf of Tadjoura, as well as west and south of Djibouti City. In addition, Djibouti's coastline is characterized by having extensive stretches of fringing coral reefs. Generally, the Gulf of Aden basin is a young ocean formed by the rifting of Asia from Africa and is characterized by a well-defined continental margin, a small ocean basin and an active mid-ocean ridge. It is deepest in the middle with depths of 2000–2500 m and shallowest in the west with depths of less than 1000 m (Al Saafani, 2008).

The northern mountainous areas of Djibouti have an arid climate while the central and southern regions have semi-arid conditions. The country has two distinct seasons, namely the cold season spanning from October to April and the hot season spanning from June to September. Whereas the cold season is characterized by temperatures of 22–30 °C and increased humidity, the hot season has temperatures of 30–40 °C, violent dry winds, occasional sandstorms and is generally dry. The transition periods May–June and September–October have a variable wind climate and are generally dry. The precipitation pattern is very irregular with annual precipitation levels ranging from 50 to 215 mm, although 150 mm is rarely exceeded (Ministere de l'Habitat, l'Urbanisme, l'Environnement et de l'Amenagement du Territoire, 2012). Long dry periods can be followed by very intense rain, leading to catastrophic flooding events with damage to people and property.

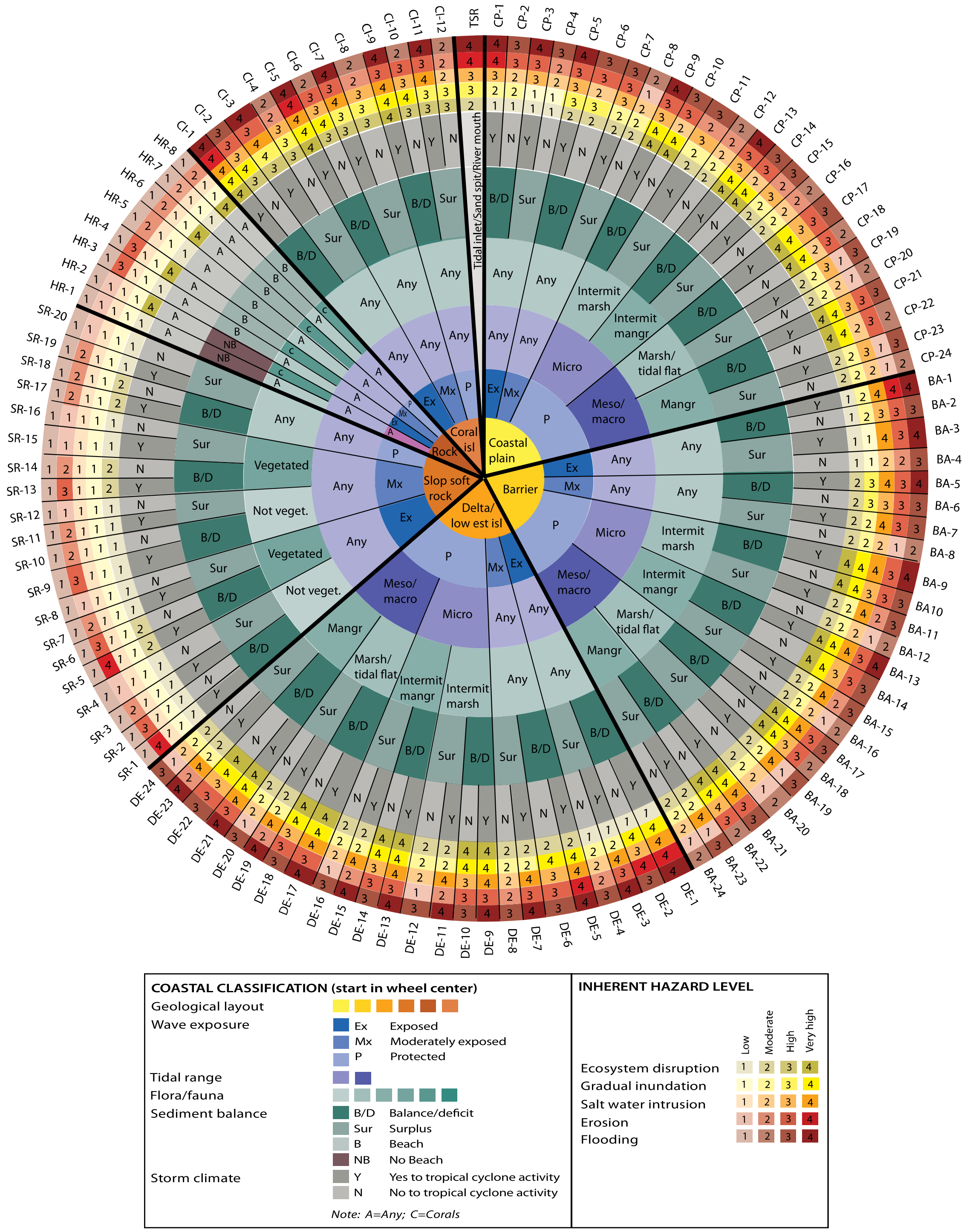


**Fig. 1.** The Coastal Hazard Wheel consisting of six geo-biophysical classification circles, five hazard circles and the coastal classification codes. In the classification code, CP stands for coastal plain, BA for barrier, DE for delta, SR for sloping soft rock, HR for sloping hard rock, CI for coral island and TSR for tidal inlet/sand spit/river mouth (Rosendahl Appelquist, 2012).

An example of this took place in 1994 where Djibouti received 360 mm rain over just two days (Ministere de l'Habitat, l'Urbanisme, l'Environnement et de l'Amenagement du Territoire, 2012). The wind regime in the Gulf of Aden is of monsoonal character with north-easterly winds during the winter months and south-westerly during the summer season (Ron Englebretson, 2002).

**Table 1**
The extended list of rocky coastal categories.

| Coastal type | Geological layout | Wave exposure | Tidal range | Flora/fauna | Sediment balance | Storm climate | Ecosystem disruption | Gradual inundation | Salt water intrusion | Erosion | Flooding |
|---|---|---|---|---|---|---|---|---|---|---|---|
| F-HR1 | Flat hard rock | Exposed | Any | Any | No beach | Yes | 1 | 3 | 2 | 1 | 3 |
| F-HR2 | | Exposed | Any | Any | No beach | No | 1 | 3 | 2 | 1 | 2 |
| F-HR3 | | Exposed | Any | Any | Beach | Yes | 1 | 3 | 2 | 2 | 3 |
| F-HR4 | | Exposed | Any | Any | Beach | No | 1 | 3 | 2 | 2 | 2 |
| F-HR5 | | Exposed | Any | Coral reef | No beach | Yes | 4 | 3 | 2 | 1 | 3 |
| F-HR6 | | Exposed | Any | Coral reef | No beach | No | 4 | 3 | 2 | 1 | 2 |
| F-HR7 | | Exposed | Any | Coral reef | Beach | Yes | 4 | 3 | 2 | 2 | 3 |
| F-HR8 | | Exposed | Any | Coral reef | Beach | No | 4 | 3 | 2 | 2 | 2 |
| F-HR9 | | Moderately exposed | Any | Any | No beach | Yes | 1 | 3 | 2 | 1 | 3 |
| F-HR10 | | Moderately exposed | Any | Any | No beach | No | 1 | 3 | 2 | 1 | 2 |
| F-HR11 | | Moderately exposed | Any | Any | Beach | Yes | 1 | 3 | 2 | 2 | 3 |
| F-HR12 | | Moderately exposed | Any | Any | Beach | No | 1 | 3 | 2 | 2 | 2 |
| F-HR13 | | Moderately exposed | Any | Coral reef | No beach | Yes | 4 | 3 | 2 | 1 | 3 |
| F-HR14 | | Moderately exposed | Any | Coral reef | No beach | No | 4 | 3 | 2 | 1 | 2 |
| F-HR15 | | Moderately exposed | Any | Coral reef | Beach | Yes | 4 | 3 | 2 | 2 | 3 |
| F-HR16 | | Moderately exposed | Any | Coral reef | Beach | No | 4 | 3 | 2 | 2 | 2 |
| F-HR17 | | Protected | Any | None | Any | Yes | 1 | 3 | 2 | 1 | 3 |
| F-HR18 | | Protected | Any | None | Any | No | 1 | 3 | 2 | 1 | 2 |
| F-HR19 | | Protected | Any | Fringing marsh/ mangr | Any | Yes | 3 | 3 | 2 | 1 | 3 |
| F-HR20 | | Protected | Any | Fringing marsh/ mangr | Any | No | 3 | 3 | 2 | 1 | 2 |
| F-HR21 | | Protected | Any | Coral reef | Any | Yes | 4 | 3 | 2 | 1 | 3 |
| F-HR22 | | Protected | Any | Coral reef | Any | No | 4 | 3 | 2 | 1 | 2 |
| S-HR1 | Sloping hard rock | Any | Any | Any | No beach | Any | 1 | 1 | 1 | 1 | 1 |
| S-HR2 | | Any | Any | Any | Beach | Any | 1 | 2 | 1 | 2 | 1 |
| S-HR3 | | Any | Any | Coral reef | No beach | Any | 4 | 1 | 1 | 1 | 1 |
| S-HR4 | | Any | Any | Coral reef | Beach | Any | 4 | 2 | 1 | 2 | 1 |

The tidal range along Djibouti's coastline is just at the transition between micro- and meso-tidal. The Red Sea has a semi-diurnal tidal regime with a tidal range of less than 1 m, while the Gulf of Aden generally has a mixed tidal regime with a tidal range exceeding 2 m (Jarosz and Murray, 2002). In the Ghoubet Bay, the tidal range is about 2 m and the tidal wave is generally one hour delayed compared to in the Gulf of Tadjoura (Salt Investment, 2008).

More than two-thirds of Djibouti's population of 865,000 live in the capital area which is located in a coastal setting facing the Gulf of Tadjoura and the Gulf of Aden (World Bank, 2011). The economy of Djibouti has been affected by political and economic instability as well as natural shocks such as droughts and floods, all damaging the country's competitiveness. Yet, recent developments in the marine and harbor industry have led to an increase in foreign direct investment. The large majority of Djibouti's rural population lives in infertile desert areas and is very susceptible to natural variations, especially water supply. Djibouti imports almost all its consumed cereal, and food aid makes up almost 10 percent of total imports (World Bank, 2011). The agricultural and industrial sectors represent the key livelihoods, although these are underdeveloped. The country is home to a large pastoralist population which lives on poor quality pasture lands and is vulnerable to climate change. Many pastoralist groups that rely on winter grazing grounds are already extremely vulnerable and are migrating to Sudan due to pasture degradation and increasing population pressure. The fishing sector constitutes a smaller source of livelihood with about one thousand people directly employed in this area (World Bank, 2011). Generally, 96.5 percent of the rural population lives below the poverty line.

Excessive pumping of groundwater and over-exploitation of surface waters are already placing significant stress on the limited water resources, and challenges in this area are only expected to increase with climate change. Furthermore, human pressures on coral reefs, estuaries and mangrove forests already affect the ecosystem services these systems provide (World Bank, 2011). With the current population growth of about 2 percent, the combined pressures from increasing population density and climate change will pose significant challenges to Djibouti's coastal areas in the years to come.


**Fig. 2.** Overview map of Djibouti (CIA, 1996).

Climate change is to some degree already detectable in Djibouti. Over the past decades, the average temperature has been higher than normal and the period between 1991 and 2000 was one of the hottest decades on record. The absolute maximum monthly temperature has increased between 0.5 and 1.5 °C in the past three decades, while the minimum temperature has increased by 1.5 °C. Furthermore, there has been observed a significant decrease in rainfall in the months April–July, along with a significant increase for the months of January and October. It is projected that temperatures across Djibouti will increase by 0.6–2.4 °C by 2050, while the sea level is expected to rise between 8 and 39 cm compared to 1990 levels. Future precipitation patterns remain unclear although it is expected that critical rainfall periods are likely to be disrupted (World Bank, 2011).

## Data for the hazard assessment

The hazard assessment is carried out based on geophysical data available from relevant institutions and from the scientific literature. The complete list of data used for the assessment include the geological information and geological maps available in Schlüter (2006), the wave, tide and storm maps included in the original CHW framework paper and published by Masselink and Hughes (2003), supplementary data on wind conditions (Ron Englebretson, 2002), supplementary data on tidal range (Salt Investment, 2008; Jarosz and Murray, 2002; Jarosz, 1997), the Reefbase database of global distribution of coral reefs (Reefbase, 2013), Google Earth satellite images with timeline and ground elevation functions (Google, 2013) and Bing Maps available in Esri's ArcGIS (Esri, 2012; Microsoft, 2013). The data used for the different classification components are briefly described below.

### *The geological layout*

The geological layout is determined based on the geological map of Djibouti and Google Earth's satellite images and ground elevation function. Using these three data sources it is possible to classify the geological layout according to the CHW categories and a new classification is made every time the geological base material, geomorphology or slope changes significantly. The definitions for the different geological layouts are further described in Rosendahl Appelquist (2012) and it should be noted that several coastal types can occur at the same coastal stretch if they are located landwards of each other. This will e.g. be the case where a barrier is located landwards of a rocky or sedimentary mainland coast.

Large parts of Djibouti's coastline fall into one of the extended hard rock categories due to its volcanic, sedimentary or carbonate characteristics. Since it is not possible to determine the permeability and fractures of the carbonate rocks in the north and of the eluvial deposits in the south of Djibouti without additional field verification, it is assumed, that they have maintained most of their rocky characteristics. This assumption is also supported by the extensive presence of coral reefs shoreward of these deposits, as corals require a rocky structure to adhere to for proper habitat formation.

The slope of the coastline is determined using Google Earth's ruler and ground elevation functions. Generally, long stretches of Djibouti's coastline have a steep sloping profile, but especially the northern and southern coastal areas are characterized by extensive flat rocky coastlines. The geomorphology is determined through a visual inspection of Google Earth's satellite images, and form elements such as barriers, spits and dry river mouths can be relatively easily identified using a zoom level of about 10 km.

*The wave exposure*

Since Djibouti is located in an area outside the swell/monsoon regions according to the maps in the original CHW framework paper (Rosendahl Appelquist, 2012; Masselink and Hughes, 2003), the wave exposure is determined by the wind speeds and free fetch. As it has not been possible to acquire detailed wind data for the area, it has been decided to rely on the free fetch to determine the wave exposure. Since the wind is blowing from north-east and south-west in a monsoonal pattern, it is expected that the free fetch can be used as an acceptable proxy for the wave exposure for most of Djibouti's coastline. Google Earth is used for determining if the free fetch for a given coastal stretch is less than 10 km, 10–100 km or above 100 km, which are the defined boundaries for protected, moderately exposed and exposed coastlines in the CHW framework (Rosendahl Appelquist, 2012). As the wind is blowing from varying directions, the general maximum size of the water body in question is used as the free fetch length. Generally, the coastline facing the Gulf of Aden is classified as exposed, while the inner parts of the Gulf of Tadjoura are classified as moderately exposed, and the Ghoubet Bay is classified as protected.

*The tidal range*

Since Djibouti is situated just at the border between micro- and mesotidal regimes, supplementary data has been collected to determine the tidal conditions. The assessment therefore makes use of tidal data for the Red Sea, the Bab el Mandab Strait, the Gulf of Aden and Ghoubet Bay to determine the tidal conditions in more detail (Salt Investment, 2008; Jarosz and Murray, 2002; Jarosz, 1997). Based on this data, the northernmost coast of Djibouti is assumed to have micro-tidal conditions while the remaining coastal stretches are assumed to be meso-tidal.

*The flora/fauna*

The flora/fauna of Djibouti's coastline is mainly related to the stretches with mangrove vegetation and the extensive coral reef systems. The mangrove areas are found in relation to the estuaries and bays in northern Djibouti, on the Moucha Islands and south of Djibouti City and can be easily identified using the satellite images available in Google Earth. The coral reef systems are identified using the Reefbase database of global distribution of coral reefs that provides a relatively detailed picture of the distribution of the coastal coral reefs (Reefbase, 2013).

*The sediment balance*

The sediment balance is an indication of whether a particular coastline has a balance, deficit or surplus of sediment over a time period of e.g. 10 years, and the sediment balance evaluation is carried out for all sedimentary coastal stretches based on Google Earth's historical satellite images. The sedimentary stretches includes the barriers, spits, coastal plains and sloping sedimentary coasts, and generally the quality of the available satellite images allows for a relatively detailed assessment. Due to the desert climate of Djibouti, however, most of the coastal stretches do not have a vegetation line that can be used for assisting the evaluation. The evaluation therefore relies mainly on the land-sea interface, which is affected by the high/low water levels at the time the satellite images were taken, and this adds some uncertainty to the assessment. Where there is any doubt about the sediment balance, it is assumed that the coastline has a balance/deficit as this gives the highest general hazard levels. For rocky coastlines, the CHW simply distinguishes between whether the coastline consists of bare rock or if some kind of beach environment is present. This is reflected in the special beach/no beach categories for these coastlines, which are assigned through a visual inspection of the coastline in Google Earth.

*The storm climate*

Since Djibouti is located outside areas influenced by tropical cyclones as indicated on the map in the original CHW framework paper (Rosendahl Appelquist, 2012; Masselink and Hughes, 2003), the complete coastline is classified to be located in a non-tropical cyclone area. The extreme storm events present in Djibouti mainly relates to sand and rainstorms, sometimes associated with intense precipitation (Ministere de l'Habitat, l'Urbanisme, l'Environnement et de l'Amenagement du Territoire, 2006).

## The GIS procedure

The hazard assessment is carried out in ArcGIS, expanding on the assessment procedure suggested in the original CHW methodology paper (Rosendahl Appelquist, 2012). The assessment primarily makes use of the general functions available in ArcGIS, but uses the recent and historical satellite images and digital elevation model available in Google Earth as secondary data sources. Although other sources of historical satellite images and elevation models are available, Google Earth is selected as an easily accessible tool that is increasingly used for environmental management globally in areas ranging from marine, coastal and terrestrial assessments to wider science communication (Sawakuchi et al., 2012; Scheffers et al., 2012; Whitmeyer et al., 2012).

First step in the assessment procedure is to create a geodatabase in ArcGIS that will contain all data on the coastal classification and subsequent hazard levels. Following this, and in order to have a relatively detailed and up-to-date digitized coastline of Djibouti that can be used for the assessment, a new line feature is created in the geodatabase referencing UTM Zone 38. The full coastline of Djibouti including the coastlines of backbarriers and estuaries is then digitized at the approximate Mean Sea Level (MSL) based on ArcGIS' hybrid Bing map, leaving gaps for river mouths and tidal inlets. The accuracy of the digitization is approximately 5–10 m, and the digitized coastline will be used as foundation for all the subsequent hazard maps.

To facilitate the assessment of the coastal slope and sediment balance, two supplementary line features are created in Google Earth. The first line feature that aims to support the slope assessment consists of a range of shore-parallel line sections, drawn landwards of the coastline in areas with a slope greater than 3–4 percent. In this way, the user can easily determine whether a specific coastal area is sloping or not when carrying out the assessment. The second line feature that aims to support the sediment balance evaluation is used to compare the coastline development between different historical satellite images. The line feature consists of a continuous line drawn at the approximate coastal vegetation line for all sedimentary stretches of Djibouti's coastline. Due to Djibouti's arid climate, however, many coastal stretches are not vegetated and hence it is generally necessary to draw the line at the approximate MSL. When the coastal classification is carried out, the sediment balance can then be evaluated by comparing the different historical satellite images available in Google Earth's historical image feature, looking at how the coast has been developing compared to the digitized, most recent coastline. Because the satellite images are captured at different tide levels and times of the year, there are some significant uncertainties related to this assessment, especially as it is not possible to use the vegetation line as proxy for coastal stability/retreat/advance. In practice, the methodology therefore simply assumes a balance/deficit whenever there is any uncertainty, and a sediment surplus is only assumed in areas with a coastal advance of at least several meters per year, which generally does not occur along Djibouti's coastline. As no detailed coastal sediment surveys or a clearly visible vegetation line are available, this approach is considered an acceptable proxy for evaluating the coastal sediment balance.

The coastal classification is carried out in ArcGIS on top of the digitized coastline of Djibouti. This is done using a polygon feature created in the geodatabase with the same coordinate system as the digitized coastline. The polygons are then used to split the coastline into smaller sections, each being classified based on the CHW classification system. The sections are stored in a so called linear referencing system that keeps track of the sections based on a simple measuring system defined along the coastline (Balstrøm, 2008). The practical classification is carried out by drawing a separate polygon for each coastal classification category along the coastline, based on a subjective evaluation of the classification parameters listed in the data section earlier. It should be noted that it is important to establish a snapping environment to make sure that the polygons are properly aligned with each other. The name of the coastal type in question is then written in the attribute table for each polygon in the ID field. Because the ID field in the attribute table only accepts numbers, the different coastal types have been assigned a number, which in the case of this assessment spans from 1 to 131 due to the expansion of the category for rocky coastlines. Since the coastal classification is carried out based on the CHW and a range of different data parameters, the user has to decide on an appropriate coastal type before each polygon is completed. Sometimes a coastline can maintain the same properties for many kilometers while at others it changes for every 50 m. This means that the length of each polygon varies significantly for the different parts of Djibouti's coastline.

The polygons are subsequently used to divide the initial digitized coastline into sections, each representing a specific coastal type. The hazard levels from the CHW system are then typed into a separate attribute table that is joined to the attribute table of the coastal classification file. Based on this, five different hazard maps are created for the respective hazards types and the different hazard levels are assigned a color code. The hazard maps are created based on a hybrid Bing map to optimize the visual readability, and the smaller villages along Djibouti's coastline are added to the maps manually. In addition to this, five separate hazard layers are developed for use in Google Earth to enable users to get a more detailed picture of the hazard presence.

## Results

The assessment results presented in this paper are a series of five national overview maps and some key hazard statistics. The overview maps are designed to provide a good general picture of the hazard hotspots and hazard distribution along Djibouti's coastline and are relevant for supporting coastal management decisions and climate change adaptation initiatives.

The national hazard map for ecosystem disruption is shown in Fig. 3, and for Djibouti, this hazard is mainly associated with the extensive coral reef systems and patchy mangrove forests. Most areas indicated to have a *very high* hazard of ecosystem disruption are related to the coral reef ecosystems, and these ecosystems extend for a full 50 km stretch of the northernmost part of Djibouti and then appear in more fragmented form on the remaining parts of the coastline in locations where physical conditions allow for coral growth. As coral reefs require a hard base to adhere to and a low level of dispersed sediment, they are normally present in areas with a rocky geological layout and a low level of fluvial sediment supply.

The presence of river mouths south of Djibouti city therefore creates some gaps in an otherwise continuous coral reef system in this area. The mangrove habitats in Djibouti are generally considered to have a *high* hazard of ecosystem disruption, especially due to the limited sediment availability. These habitats are located in the bays and protected estuaries north of the Gulf of Tadjoura, but are also present on the Moucha Islands and in locations south of Djibouti City. The remaining part of the

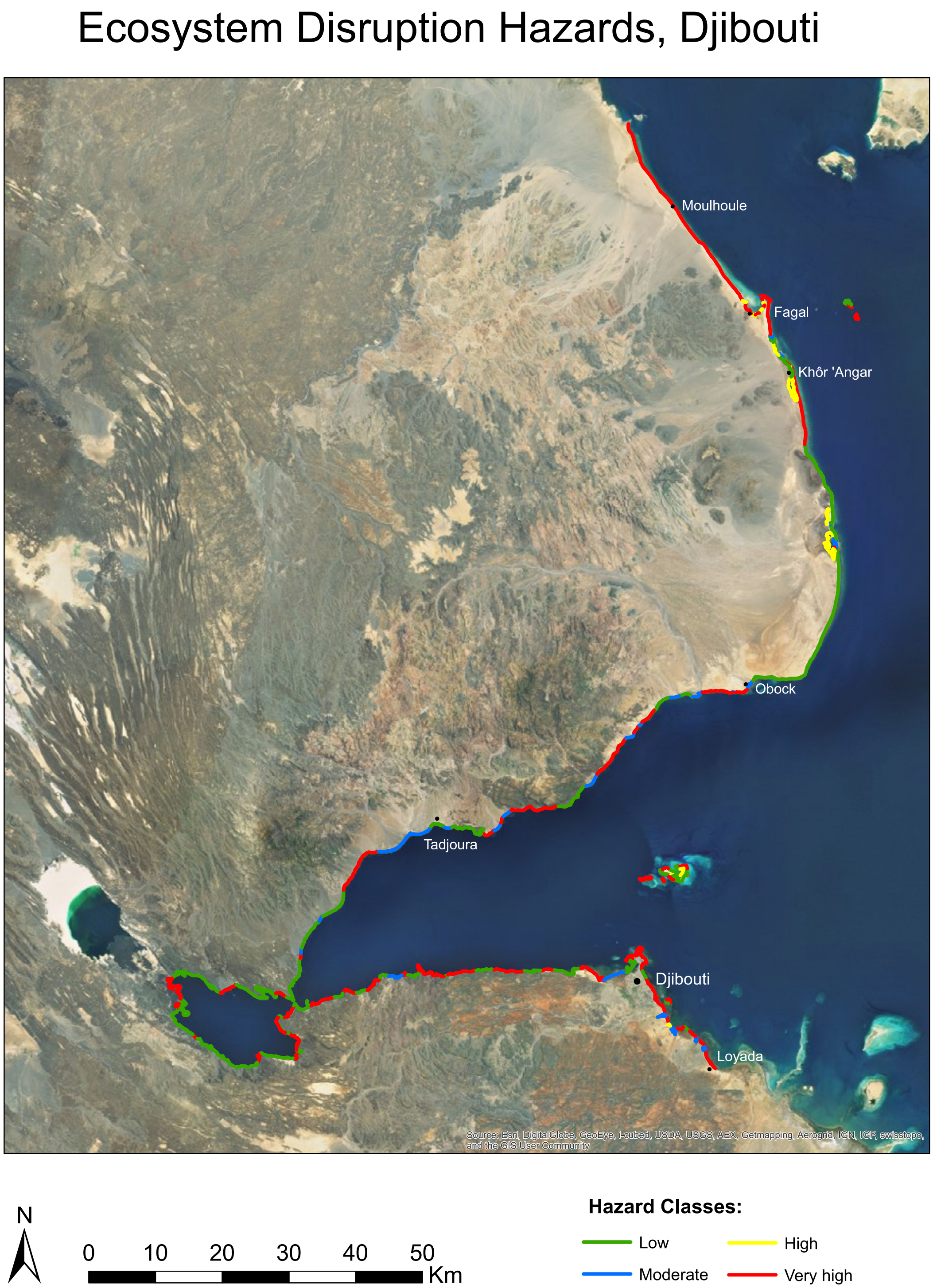


**Fig. 3.** National hazard map for ecosystem disruption.


**Fig. 4.** National hazard map for gradual inundation.

coastline is considered to have a *low* or *moderate* hazard level for ecosystem disruption and the hazards in these areas are considered minor compared to the hazards of the areas with coral reef and mangrove environments.

The national hazard map for gradual inundation is shown in Fig. 4 and this hazard is mainly related to the rocky and sedimentary plains, river mouths and barriers. The northern coastline of Djibouti from Eritrea until just north of the Gulf of Tadjoura is characterized by a low relief and several barrier systems that have a *high* and in some locations *very high* hazard of


**Fig. 5.** National hazard map for salt water intrusion.

gradual inundation. The northern part of the Gulf of Tadjoura from Obock to just south of Tadjoura also has some low-lying areas with *high* gradual inundation hazards, while the remaining part of Gulf of Tadjoura and Ghoubet Bay generally have *low* and *moderate* hazard levels. The coastline around and south of Djibouti city, however, also has a *high* hazard of gradual inundation. It should be noted, however, that gradual inundation is a slow, long-term process and is therefore mainly relevant for longer-term coastal planning.


**Fig. 6.** National hazard map for erosion.

The national hazard map for salt water intrusion is shown in Fig. 5. The hazard of salt water intrusion is generally *high* or *very high* at the low-lying barriers and river mouths along Djibouti's coastline, while it is *low* or *moderate* along most of the remaining coastline. However, due to the very dry climatic conditions, all areas indicated to have *moderate* hazard levels can very easily move to *high* or *very high* hazard levels due to human extraction of water from the very limited freshwater reservoirs. The *moderate* hazard levels should therefore be seen as relative hazard levels compared to e.g. low-lying delta areas


**Fig. 7.** National hazard map for flooding.

of Bangladesh and only applies when very little human ground water extraction takes place. One should therefore assume that coastal areas indicated to have a *moderate* hazard level will move to the *high* category as soon as any significant human ground water extraction takes place.

The national hazard map for erosion is shown in Fig. 6 and this hazard is mainly related to the barriers, tidal inlets and river mouths as well as the flat and sloping sedimentary stretches along Djibouti's coastline. The coastline of the estuaries located between the Eritrean border and Gulf of Tadjoura has some sections with *high* and *very high* erosion hazards. In the

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**Table 2**
The distribution of hazard levels in percentage for Djibouti's coastline.

| Hazard level | Ecosystem disruption | Gradual inundation | Salt water intrusion | Erosion | Flooding |
|---|---|---|---|---|---|
| Low | 41 | 35 | 50 | 44 | 50 |
| Moderate | 11 | 16 | 40 | 42 | 38 |
| High | 7 | 48 | 9 | 5 | 4 |
| Very high | 41 | 1 | 1 | 8 | 8 |

northern part of the Gulf of Tadjoura, *very high* erosion hazards are related to the dry river mouths, while *high* erosion hazards are assigned to the sedimentary coastal plain. The remaining parts of the Gulf of Tadjoura and Ghoubet Bay generally have *low* and *moderate* erosion hazards, but some of the dry river mouths east and south of Djibouti city have *high* and *very high* erosion hazard levels.

The national hazard map for flooding is shown in Fig. 7 and this hazard is especially related to the coastal stretches made of low-lying dry river mouths that are likely to be flooded during intense precipitation events. As most of these areas are completely dry during normal weather conditions, one might not be aware of the *very high* inherent flooding hazards of these locations. Some areas where these conditions are combined with human settlements are the eastern parts of Obock and west and south of Djibouti city. Other flooding hotspots include the barriers and spit systems in northern Djibouti facing the Gulf of Aden. The extensive coastal plains in northern Djibouti and the plains south of Djibouti City have a *moderate* flooding hazard which should also be kept in mind when planning human settlement.

Table 2 shows an overview of the hazard distribution in percent for the coastline of Djibouti. It can be seen that close to 50 percent of Djibouti's coastline has a *moderate*, *high* or *very high* hazard level for erosion and flooding. The hazard of gradual inundation is relatively widespread with about 65 percent of the coastline having *moderate*, *high* or *very high* hazard levels. About 50 percent of the coastline has a *moderate*, *high* or *very high* hazard level for salt water intrusion, while the hazard of ecosystem disruption is very prevalent with 60 percent of the coastline having a *moderate*, *high* or *very high* hazard level, and as much as 41 percent having a *very high* hazard level.

## Uncertainties and limitations

The assessment is considered to provide a reasonably good picture of the climate change hazards for the coastline of Djibouti. Yet, there are a number of uncertainties and limitations that should be considered when using the assessment for management and planning purposes. Generally, one should be cautious about using the assessment to support local planning decisions, as the assessment is carried out as a Step 1 analysis based solely on published geophysical data and remote sensing information. However, the available data and remote sensing information is considered to be of relatively good quality, and the assessment should be sufficiently detailed and accurate for identifying hazard hotspots and for supporting national, regional and sub-regional planning decisions.

The hazard map for ecosystem disruption is considered to give a reasonable good indication of the future hazards to Djibouti's ecosystems under a changing climate. The main uncertainties are related to the current state of the extensive coral reef systems along Djibouti's coastline, and how they will respond to the changing ocean temperature and ocean acidity. But like most tropical coral reefs, they are likely to be at significant risk. The assessment framework is unable to cover coral reefs offshore of river mouths, spits and barriers as these would normally not occur because of the increased sediment load and lack of hard bottom substrate in these locations. Therefore, the assessment may underestimate the ecosystem hazards associated with smaller reef sections associated with these features e.g. north of Khor Angar. Yet, these are only small areas and probably insignificant compared to the uncertainty of the coral reef data currently available from global coral datasets.

The hazard map for gradual inundation is generally considered as relative robust for the full coastline of Djibouti. Some uncertainties may be related to the sediment supply and availability along the rocky stretches with beach environments, but those are not expected to influence the hazard levels significantly. Uncertainties related to this hazard are therefore mainly related to the rate of sea level rise, which is an uncertainty parameter that applies to all coastal areas globally.

The hazard map for salt water intrusion is generally considered to be surrounded by significant uncertainties as this hazard is influenced by a range of parameters other than the coastal dynamics and geomorphology. Due to the very dry climatic conditions in Djibouti, the freshwater aquifers are generally considered to be limited, and just a low level of human groundwater extraction can cause severe salt water intrusion if salty sea water is replacing the extracted freshwater. If this is combined with unusual low precipitation levels, the hazard of salt water intrusion can be *high* to *very high,* even when it is indicated as *moderate* on the hazard maps. The information given in the assessment should therefore be considered as a relative hazard level compared to other coastal environments. With human water extraction, the natural aquifer replenishment can quickly become overwhelmed leading to *high* and *very high* hazards of salt water intrusion in many locations. Thoughtful water management is therefore crucial along the coastline of Djibouti.

The hazard map for erosion is mainly surrounded by uncertainty in areas where it is difficult to determine the geological base material from the available geological maps and satellite images. This is mainly the case for the outer coastline of Djibouti slightly south of Khor Angar, the outer coastline of the estuary 25 km south of Khor Angar and the coastline south

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of Djibouti City. Yet, the hazard levels for erosion in these areas are considered to be relatively accurate, but additional field verification would be needed if the assessment should support local management decisions.

When using the hazard map for flooding, it is very important to be aware of the associated uncertainties due to the sudden and often dramatic nature of flooding events. Misjudgments and bad management decisions in relation to this hazard can lead to extensive property damage and in worst case loss of lives, and additional field verification may therefore be necessary in some locations to establish a more solid decision base. Yet, the assessment is considered to provide a reasonable reliable picture of the flooding hazards on a national, regional and sub-regional level. Since coastal flooding may arise from both ocean high water and intense precipitation and run-off, different uncertainties are associated with these conditions. Generally, the CHW framework covers the ocean-caused flooding hazards relatively well, but in the case of precipitation induced flooding, some uncertainties are present. As Djibouti generally has no real rivers but only dry river valleys that are occasionally flooded during extreme precipitation events, it is necessary to rely on visual observations of the geomorphology, using satellite images to identify the dry river beds. Most dry river beds have been identified and classified as river mouths in assessment, giving them a *very high* flooding hazard, but some of the smaller dry streams are difficult to detect using this methodology. However, as a Step 1 assessment, the maps provide a generally good picture of the flooding hazards and should be sufficient to support broader planning decisions.

Since limited information on current coastal hazards is available for Djibouti, it is not possible to make broader comparisons between existing conditions and the hazards indentified in the assessment. However, in some locations it is possible to compare current hazard conditions and assessment results. For ecosystem disruption, the hazards indentified in the hazard assessment can generally not be detected at this point in time. The coral reefs along Djibouti's coastline are currently in average to good condition and have not shown major signs of degradation due to climate-related impacts. The mangrove areas are under some pressure from human exploitation combined with natural fluctuations, but no consistent climate-related impacts are detectable (PERSGA/ALECSO, 2003). As the hazard of ecosystem disruption mainly relates to changes taking place over the next decades, this picture is expected. Little information is currently available on gradual inundation, while salt water intrusion already is a significant problem for Djibouti city, with salinity levels exceeding recommended WHO levels (Ministere de l'Habitat, l'Urbanisme, l'Environnement et de l'Amenagement du Territoire, 2006). The hazard assessment indicates moderate to high hazards for salt water intrusion for most of Djibouti city, which corresponds well with these conditions. There are no broader studies available for erosion, although it is a general concern for the coastline of Djibouti (Ministere de l'Habitat, l'Urbanisme, l'Environnement et de l'Amenagement du Territoire, 2006). With regards to flooding hazards, the alluvial areas of the city of Tadjoura experience regular flooding, while Djibouti city has experienced several catastrophic flooding events in relation to the Ambouli wadi (Ministere de l'Habitat, l'Urbanisme, l'Environnement et de l'Amenagement du Territoire, 2012). This corresponds well with the assessment results, as these areas are indicated to have very high flooding hazards in the hazard assessment.

## Planning and management perspectives

The assessment procedure outlined in the previous sections provides an example of how the CHW framework can be applied for national multi-hazard assessments. The maps developed in the assessment can be used for providing an overview of the hazard profile of the national coastline and for identifying hazard hotspots and where human activities may be affected by coastal hazards. The additional hazard layers for Google Earth can be used to support more detailed management decisions and to provide a first impression of the hazard presence at local level. Since few broader hazard assessments have been carried out in developing countries such as Djibouti, the CHW framework offers national planners a possibility for obtaining a picture of the hazard profile for the coastline, even when little geophysical data is available. The assessment for Djibouti can therefore function as a guide for carrying out similar assessments in other developing countries.

Since the hazards along Djibouti's coastline are of very different character and extension, a range of different measures and approaches are required to manage the hazards appropriately. Some coastal stretches have high hazard levels for several hazard types that to some degree are interrelated. It is therefore relevant to consider which measures can be used for addressing several hazards at the same time. Also, it is important to consider human use of the coastal area and the different ecosystem services the coastal systems provide, when deciding on hazard mitigation strategies.

Since ecosystem hazards are extensive along Djibouti's coastline, nation-wide measures are likely to be relevant for addressing this hazard type. Aside from the ethical aspects of preserving biological diversity, ecosystems are important for maintaining key ecosystem services for human society (Millennium Ecosystem Assessment, 2005). The significant threat to the country's coral reefs from climate change is therefore not only problematic seen from a biological diversity perspective but also constitutes a direct risk to the sustainability of the broader marine ecosystems and Djibouti's fishing sector. Likewise, the threat to the country's mangrove ecosystems is also related to coastal fisheries. As very little data is available on the health of these ecosystems and their role in the broader marine ecosystems, it is difficult to decide on appropriate management strategies. Initially, it might be appropriate to assess the direct human threats to these systems from unsustainable fishing methods, wastewater pollution, clearing of mangroves etc. but on the longer term, it is necessary to obtain more data on the state and dynamics of these systems. One way of doing this could be through a citizen science approach where local fishermen, tourists, etc. are involved in data collection as part of their normal activities through a simple, standardized data collection system. If such system is designed properly, it can be used for collecting significant amounts of temporal data which subsequently can be analyzed by scientists and coastal managers, providing a continuous indication of the

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state of the ecosystems. Along with providing a basis for implementing dynamic adaptation measures, such data collection systems may also increase the general knowledge about the ecosystems amongst coastal residents and increase their responsibility and ownership for the sustainability of these systems. Yet, these approaches have until now mainly been used in developed countries and have to be specifically designed so they fit into the conditions on the ground in Djibouti.

Although the hazard of gradual inundation is relatively widespread in Djibouti, it does not constitute an imminent threat to the coastal activities due to its slow, gradual nature. Yet, it is very important to consider this hazard for long-term planning decisions related to infrastructure development, human settlement etc. to avoid the need for costly relocation and adaptation measures at a later stage. The hazard maps developed in this assessment can be used to support such planning decisions and may be supplemented by more detailed data on isostatic uplift/subsidence and rate of sea level rise at a later stage.

The hazard of salt water intrusion is mainly related to the human extraction of groundwater because of the low precipitation levels in Djibouti. Careful water management and water conservation is therefore a key issue for all coastal areas and more detailed assessments may provide estimates of the amount of water that can be sustainably withdrawn from the different areas. Since the changes in precipitation levels with climate change are very uncertain, it may be relevant to establish a monitoring system to assess the temporal developments in water levels in wells and the possible salt water intrusion. For this purpose, a citizen science approach may also be relevant for broader data collection that can subsequently be analyzed by ground water specialists. From such monitoring it will over time be possible to see the impact of changing precipitation patterns and adapt dynamically to these changes.

As the hazard of erosion mainly is related to the low-lying dry river mouths, barriers and tidal inlets, it does not constitute a major nation-wide hazard in Djibouti. The most cost-efficient way of addressing this hazard is likely to minimize infrastructure development and human settlements in these erosion-prone locations and then implement some technical erosion control measures at specific locations if deemed necessary. Generally, it may also be relevant to make people aware of these erosion hazards if they are settling more permanently in these hotspot locations. Technical measures for tackling erosion include hard engineering approaches such as breakwaters, groins and sea walls, and soft measures as beach nourishment, but all these options come with a cost. It is therefore wise to consider erosion hazards early in the planning process to minimize the need for technical protection measures.

The flooding hazards related to the dry river beds pose a significant threat to human settlement in these locations. The best way to mitigate this hazard is to avoid any permanent settlement in these locations and over time assist inhabitants with a permanent relocation. As larger settlements are present in these hotspot areas in parts of Djibouti City, it may be necessary to consider different technical protection measures to manage the threat to the settlements. This could include the development of a levee system that directs the water away from the most densely populated areas or dams further upstream to absorb peak flows. With regards to flooding hazards for the extensive coastal plains of Djibouti, the most cost-efficient management approach is probably to create a small buffer zone along the coastline without human settlement, so the impact of a flooding event is limited.

Because the hazard management measures are highly dependent on the interrelationship between the natural coastal systems and human actives, it is important to consider the key goals of any management activity. For some measures, such as preserving coral reef and mangrove environments, maintaining the natural state is of direct benefit to human activities due to their important ecosystem services e.g. for coastal fisheries. In other cases, technical measures that modify the natural dynamics such as erosion and flood protection may be appropriate. Generally, it is recommended to consider climate change hazards in the early stages of all coastal planning processes to avoid damage to people and property, costly protection measures and unnecessary degradation of natural systems and associated services. The concept of working with nature, which aims at combining societal interests with natural dynamics is gaining increasing attention and can in many cases reduce planning costs, while at the same time maintaining the services provided by natural coastal systems.

## Conclusion

The application of the CHW framework on the coastline of Djibouti has proved appropriate for a relatively detailed multi-hazard assessment for the full coastline. The extension of the CHW framework with additional categories for rocky coastlines has been appropriate for Djibouti's predominantly rocky coastline, and it may be considered to incorporate the extra categories in a future update of the CHW system. The national overview maps provide sufficiently detail and accuracy for supporting broader management decisions, while the hazard layers developed for Google Earth seems to be a useful supplement for supporting sub-regional and local planning. Some uncertainties are related to the geological layout and sediment balance evaluations, but the results are generally considered acceptable as a Step 1 assessment. For a more detailed assessment at Step 2 or 3, additional field verification is recommended to clarify some of these uncertainties. It may be considered to supplement the assessment with some dynamic data collection systems through a citizen science approach involving coastal residents. This would especially be relevant for the hazards of ecosystem disruption and salt water intrusion as uncertainties related to these hazards are difficult to address during a short field campaign. Generally, the assessment for Djibouti can be used as an example of a CHW application on a predominantly rocky coastline and the procedure should be replicable on other coastlines globally, yielding results of similar quality.

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