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Decision-support for climate change adaptation

– applications for coastal regions

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Lars Rosendahl Appelquist

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Ph.D. Thesis

Decision-support for climate change adaptation – applications for coastal regions

by

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Submitted: January 2014

Preface

The intention of this Ph.D. project is to develop a methodological framework for assessing and managing coastal climate change at local, regional and national level, and especially address the needs of developing countries. The methodological framework has been developed as a tool for coastal decision-makers and has been tested for application in developing country settings. The work on the project has been a very interesting, challenging and educational journey into the functioning of the world's coastal systems and has given me a deep respect for the scientific tradition and the earlier research in earth systems science that made my work possible. In the following, I would like to thank a number of people who have helped me during the process.

I would like to express my sincere gratitude to my supervisor Kirsten Halsnæs at DTU Climate Centre and to John Christensen, Anne Olhoff and my other colleagues at UNEP Risoe Centre for continuous advice, support and guidance throughout the project. My thanks are extended to my external supervisor Troels Aagaard at University of Copenhagen for some very valuable discussions in the early stages of the project and to Thomas Balstrøm at Aalborg University for very fruitful and good collaboration. A great gratitude is also owed to David Thomas and Andrew Goudie at University of Oxford who gave me the possibility of a very inspiring and rewarding time at the School of Geography and the Environment and St Cross College. Finally, I would like to express a great gratitude to my family for their invaluable support and to my good friends for inspiring discussions.

Abstract

This Ph.D. project aims at developing a new decision-support framework for managing climate change in coastal areas. The framework is developed in order to facilitate screening of climate change impacts in all coastal areas worldwide and is designed as a complete system for combined multi-hazard-assessment and multi-hazard-management. The framework addresses the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding and can be used for hazard management at local, regional and national level. It is developed as a simple system that can be applied in areas with limited data availability and institutional capacity and is especially targeted the needs of developing countries. In order to make the framework easily accessible to coastal managers, it is designed as a graphical tool – the Coastal Hazard Wheel – that functions as a key for determining the characteristics of a coastline, its hazard profile and possible management options, and can be used for screening purposes prior to more detailed feasibility studies.

The project has applied the framework for multi-hazard-assessments for the state of Karnataka, India and for the state of Djibouti to showcase its application in two very different coastal settings. The assessments are carried out in a GIS using basic and publicly available data, and a range of thematic hazard maps and hazard management recommendations have been developed for the two areas. Along with this, the assessments include discussions of practical challenges, uncertainties and limitations. Based on the applications on Karnataka and Djibouti, feedback from coastal experts and a range of selected spot-assessments, a slightly revised version of the Coastal Hazard Wheel has been developed. This is presented in an overview paper together with general guidelines for applying the framework for coastal hazard assessment and management.

Dansk Resumé

Dette Ph.D. projekt har som mål at udvikle et nyt beslutnings-støtte system til takling af klimaforandringer i kystområder. Systemet er udviklet til screening for klima-relaterede risici i alle verdens kystområder og er designet som et samlet system til vurdering og forvaltning and klimatiske risici. Systemet adresserer risici relateret til økosystem forstyrrelser, gradvis oversvømmelse, saltvandsindtrængning, erosion og stormflod and kan bruges til risiko-forvaltning på lokalt, regionalt og nationalt plan. Systemet er udviklet som et simpelt værktøj der kan anvendes i områder med begrænset datatilgængelighed og institutionel kapacitet og er særligt målrettet ulande. For at gøre systemet direkte anvendeligt for kystplanlæggere er det designet som et grafisk værktøj - Kysthjulet - der fungerer som en nøgle til at identificere en kysts særlige karakteristika, risiko-profil samt forvaltningsmuligheder, og kan bruges til risiko screening før mere detaljerede studier iværksættes.

Projektet har anvendt systemet til risiko-undersøgelser for den indiske stat Karnataka og for staten Djibouti for at teste det under forskellige kystforhold. Risiko-undersøgelserne er gennemført ved hjælp af GIS og ved brug af simpel og offentligt tilgængeligt data, og har resulteret i udviklingen af en række risiko-kort og anbefalinger for de to områder. Derudover inkluderer undersøgelserne en diskussion af praktiske udfordringer, begrænsninger og usikkerheder. Baseret på undersøgelserne i Karnataka og Djibouti, kommentarer fra kysteksperter og en række lokal-studier er en let revideret version af Kysthjulet udviklet. Denne version er præsenteret i en oversigtsartikel som også indeholder en samlet vejledning i brug af systemet til risiko-undersøgelser og risiko-forvaltning.

Contents

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 lead to high population densities and high levels of development in many coastal areas and this trend is continuing into the 21st century. At present, 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 2007). Along with this increase follows major investments in infrastructure and the build environment.

The characteristics of coastal environments, however, pose 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 lead to major disasters and societal disruption to various degrees. 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, expertise and economic resources are limited and coastal populations are growing rapidly.

The predicted climate change is adding an extra risk factor to human settlement in coastal areas. Whereas the natural dynamics that shape our coastlines 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 and 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 take the expected future hazards into account in the coastal planning processes.

This Ph.D. project aims at developing a decision-support framework for assisting coastal planners and authorities with management of coastal areas under a changing global climate. The project has its theoretical basis in coastal morphology and coastal systems analysis but spans the wider fields of natural sciences, engineering and economics. The project does not try to stay within some predefined disciplinary boundaries but rather embraces an interdisciplinary and broad theoretical approach in order to capture the complexities of the world's coastal systems and to develop a decision-support framework that is well-suited for addressing the challenges facing coastal societies.

The decision-support framework is methodologically developed to address a key gap in coastal climate change adaptation, namely the need for a strengthened decision-base in developing countries where data, domain expertise and economic resources are limited. The framework is therefore specially designed for use in areas with limited data availability and institutional capacity, but can be applied for management of coastlines worldwide. Hence, the framework is meant to complement existing methodologies for coastal climate change vulnerability and risk assessment and to offer a new tool for combined assessment and management of coastal hazards.

Scientific state of the art

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 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. 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 directly used to indentify management strategies. Indicator based methods allow for a greater sector-specific detail while remaining relatively simple, but still require a significant level of data input and domain 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 to indentify appropriate management strategies. However, these systems require significant amounts of data, expertise and resources to be applied, which is generally not available in developing countries. The following sections describe the main characteristics and examples of the different methodologies currently available.

Index based methods are developed to express coastal vulnerability through a one-dimensional and generally unitless risk/vulnerability index, which is calculated based on a quantitative or semi-quantitative combination of different variables. These methods are not immediately transparent as the index does not allow for an understanding of the assumptions that lead to its calculation, and the index should therefore be supplemented by a clear explanation of how it is calculated. The main index used for coastal vulnerability assessment is the Coastal Vulnerability Index (CVI) that has been used in different versions (Rimieri et al. 2011; Thieler et al. 2000). The CVI provides a simple numerical basis for ranking sections of the coastline in terms of their potential for change, which can be used by coastal planners to indentify high-risk areas and develop coastal vulnerability maps. The CVI contains 6-7 different variables that are combined into an index and the calculation of the CVI generally requires relatively detailed data on geomorphology, coastal slope, relative sea level change, shoreline erosion/accretion rates, mean tidal range and mean wave height (Thieler et al. 2000). Other index based methods include the Composite Vulnerability Index that combines a range of natural and socio-economic variables into a combined vulnerability index through a GIS overlay approach (Szlafsztein and Sterr 2007), and the Multi-scale Coastal Vulnerability Index that specifically integrates erosion impacts (McLaughlin and Cooper 2010). Generally, index based methods require relative detailed data input and only provides information on the overall vulnerability of a coastal stretch or the vulnerability related to one hazard type. No information on the presence of the range of different hazards is provided.

Indicator based methods express the coastal vulnerability as a set of independent indicators that characterise key coastal issues such as drivers, pressures, states, impacts, responses, exposure, sensitivity, risk and damage. These indicators can then be combined into a final indicator. This approach makes it possible to evaluate the different components of coastal vulnerability in a consistent assessment context. Examples of these methods include the European Eurosion assessment that used thirteen different indicators, each given a semi-quantitative score according to expected future erosion risk (Eurosion 2004), and the Deduce project that defined a core set of 27 different indicators, composed of 45 measurements to monitor sustainable development of the coastal zone at different scales (Deduce Consortium 2007). Indicator based methods can be useful for assessment of coastal vulnerability at more detailed scale and for specific coastal systems, but still provides a combined or sector specific vulnerability indicator and requires relatively detailed input data.

GIS based decision-support systems consist of more complex models that address vulnerability and risk assessment of coastal areas. DESYCO is an example of such a model that allows for regional assessment and management of multiple climate change impacts in coastal areas and related ecosystems. It is based on a multi-criteria analysis in order to prioritize risk areas and its implementation is based on a scenario construction followed by an integrated risk assessment and impact management. The system is integrated in a GIS framework and requires a diverse set of input data and modelling preparation for application in new locations (Torresan et al. 2010). DITTY-DSS constitutes another example of a GIS based decision-support system which consists of a location specific mathematical and analytical model that is used to simulate alternative scenarios and combine this with multi-criteria analyses to evaluate and rank decision-options. It is generally designed to Mediterranean lagoons and requires modification to apply to other areas (Mocenni et al. 2009). GIS based decision-support systems can be used to support broader management decisions related to several different coastal hazards but requires a significant level of data input and domain expertise.

Dynamic computer models are designed for analysing and mapping vulnerability and risks of coastal systems to climate change. Generally, dynamic computer models can be divided into sector models and integrated assessment models. Sector models focus on one particular coastal hazard or risk, such as erosion or salt water intrusion and therefore do not address multiple climate change impacts. Examples of sector models include the UK RACE model that has been used to evaluate erosion hazards and risks in England and Wales (Halcrow Group 2007), and the BTELSS and SLAMM models that have been used for coastal wetland assessments (Rimieri et al. 2011). Integrated assessment models aim at evaluating the vulnerability of coastal systems to multiple climate change impacts, including cross sector analysis of the interaction between different impacts, and often include socioeconomic components. Examples of these include the DIVA model that can be used for global assessment of biophysical and socioeconomic effects of sea level rise and cost calculations for different management strategies (Global Climate Forum 2013), and the SimCLIM model, that can be used to combine complex data in order to simulate biophysical impacts and socioeconomic effects of climate change (SimCLIM 2013). In addition, a number of two and three dimensional models have been developed for engineering purposes for application at local to regional scale. These models are not directly designed to assess climate change impacts but can be applied for both sector and integrated assessments, and examples include the Delft3D model developed by Deltares (2013) and the MIKE 2D and 3D developed by DHI (2013). Generally, dynamic computer models are advanced systems that require detailed data input and domain expertise.

Aim and objective

The aim of this project has been to develop a new decision-support framework that can be used for combined multi-hazard-assessment and multi-hazard-management in areas with limited data availability and resources. It thereby tries to address the gap in the current coastal vulnerability/hazard assessment methodologies, which do not offer a viable system for detailed multi-hazard-management in areas with limited data availability. The index and indicator based methods are to date the most realistic options for use in data-poor regions such as developing countries, but they cannot be used to identify a range of sector-specific hazards and management options and require relatively detailed input data. The other existing approaches are very complex systems that would have to be combined with larger data-collection programs or be applied at very coarse resolution, and would in any case require highly specialized expertise.

The decision-support framework developed in this project therefore aims at addressing the challenges faced by developing countries in managing coastal climate change, and to provide a tool that can be used for combined assessment and management of the main coastal climate change hazards. The framework is designed to be used with little input data and only requires limited coastal expertise, and it has been attempted to maintain an appropriate balance between method simplicity and accurately reflecting natural conditions. The framework is developed as a transparent conceptual system that allows the user to follow the causality between key coastal parameters and associated hazards, and this also makes the system useful for communication purposes. Furthermore, the framework considers each hazard type separately, which allows for identification of management options for each particular hazard type.

The framework is developed to be applied at local, regional and national level at three different steps depending on data availability and accuracy requirements. It can therefore be used for multi-hazard-screening of larger areas or for more detailed and locally focused assessments. The framework is developed to be used in combination with a GIS to allow for production of high-resolution hazard maps and to facilitate communication of results. Although the main objective of the project has been to develop a framework that can be used successfully in developing countries, the system should be equally suited for applications in developed and developing countries. The framework is global in its scope and can be applied in any coastal area using the same standard data inputs and methodology. Along with applications in data-poor regions, it can therefore be used as a first-line, cost-efficient tool in locations with good data availability and institutional capacity. To make the framework easily accessible to coastal managers, it is designed as a graphical tool – the Coastal Hazard Wheel – that functions as a key for determining the characteristics of a coastline, its hazard profile and possible management options.

Project framework

The project is carried out at the UNEP Risoe Centre at the Department of Management Engineering, Technical University of Denmark, and has included two half-year periods of work at the School of Geography and the Environment, University of Oxford. Because of its close ties to UNEP's climate change programme, the project has placed a strong emphasis on the practical challenges faced by governments and public institutions worldwide and is therefore applied in its nature. The setup with combined work at UNEP Risoe Centre and University of Oxford proved to be very valuable, as it offered a possibility for maintaining close links to UN priorities and country needs, along with a connection to a strong research environment. The project is carried out as a Ph.D. in Management Engineering where the Management Engineering components mainly relate to the fields of decision-support, coastal management and coastal systems analysis. The essential Management Engineering objective of the project is to develop an applied management methodology based on a foundation of natural sciences, engineering and economics.

Research methodology

The project has its foundation in the current scientific knowledge of coastal systems and processes, earth systems science, methods for assessing coastal vulnerability and applied coastal engineering. The decision-support framework is developed based on the existing knowledge of the functioning of the world's coastal systems and how they respond to the projected climate change, and the author has supplemented this with a large number of random site-verifications to ensure the conceptual framework is well-aligned with actual coastal conditions. The general applicability of the framework has been tested through two multi-hazard-assessments for the Indian state of Karnataka and the state of Djibouti, and based on these assessments a standardized approach for the practical application of the framework has been developed. The methodological framework does not place a strong emphasis on the different climate change projections, as the uncertainties at local level greatly outweigh the uncertainty span of the global projections. The framework therefore primarily considers how the different conceptual coastal environments will respond to the acknowledged range of climate change projections over the coming decades (IPCC 2013). It has not been possible to directly test the assessment results by comparing them to other assessments, as the results of different assessments are not directly comparable. This is because e.g. the index based methods only provide a combined vulnerability index or information on one hazard type and methods as the DIVA model operates with a much coarser resolution. However, as the framework is based on a conceptual system grounded in the scientific literature, the results of the different assessment methodologies should lead to qualitatively comparable results.

Building on the two case assessments, feedback from coastal experts and additional conceptual work, a slightly revised version of the framework, the CHW 2.0, has been developed. This is presented together with the standardized assessment procedure and management perspectives in a final overview paper. Generally, the project can be divided into three main parts namely, 1) The conceptual development of the decision-support framework, 2) The application of the framework on Karnataka and Djibouti and 3) The revision of the framework together with development of the complete hazard management system.

Structure of thesis

The Ph.D. project is presented as a paper based thesis according to the guidelines of the Technical University of Denmark. This means that the papers are used directly as chapters in the thesis. The thesis consists of four scientific papers, which cover the different components of the development, application and refinement of the decision-support framework. Paper 1 covers the conceptual development of the decision-support framework, hereunder the coastal classification system, the background for the hazard evaluation system, practical application perspectives and uncertainties and limitations. Paper 2 covers the application of the framework on the Indian state of Karnataka, including preparatory data collection and analysis, practical assessment procedure, results, uncertainties, limitations and management perspectives. Paper 3 covers the application of the framework on the state of Djibouti and further refines the assessment procedure developed for the Karnataka assessment. Along with describing the practical assessment procedure, it presents some revisions to the assessment framework and discusses results, uncertainties, limitations and management perspectives. Paper 4 presents the revised decision-support framework and the complete hazard management system drawing on the research from the previous papers. Besides from describing the revised framework, it presents a standardized assessment procedure for global application of the system and technical and economic management perspectives. Since paper 4 is intended as an overview paper that can be read in isolation it includes some revised components from paper 1. The four papers are listed in full below.

Appelquist LR (2013). Generic framework for meso-scale assessment of climate change hazards in coastal environments. Journal of Coastal Conservation.

Appelquist LR, Balstrøm T. Application of a new methodology for coastal multi-hazard assessment on the state of Karnataka, India, submitted to Natural Hazards.

Appelquist LR, Balstrøm T. Application of a new methodology for coastal multi-hazard assessment & management on the state of Djibouti, submitted to Climate Risk Management.

Appelquist LR, Halsnæs K. The Coastal Hazard Wheel system for coastal multi-hazard assessment & management in a changing climate, submitted to Journal of Coastal Conservation.

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Torresan S, Zabeo A, Rizzi J, Critto A, Pizzol L, Giove S, Marcomini A (2010). Risk assessment and decision support tools for the integrated evaluation of climate change on coastal zones. In Swayne DA, Wanhong Yang, Voinov AA, Rizzoli A, Filatova T (eds.), 2010. Proceedings of the International Congress on Environmental Modelling and Software Modelling for Environment's Sake, Fifth Biennial Meeting, Ottawa, Canada.

Joint author statement

If a thesis contains articles* made in collaboration with other researchers, a joint author statement about the PhD-student's part of the article shall be made by each of the co-authors, cf. article 12, section 4 of the Ministerial Order No. 18 February 2008 about the PhD degree. We refer to the Vancouver protocol's definition of authorship.

Titel of the article:	Application of a new methodology for coastal multi-hazard-assessment on the state of Karnataka, India
Author(s):	Lars Rosendahl Appelquist and Thomas Balstrøm
Journal/conference (if applicable):	Submitted to Natural Hazards
Name of PhD student:	Lars Rosendahl Appelquist
Date of birth:	08-02-1982

* by article is meant: published journal and conference articles, unpublished manuscripts, chapters etc.

Description of the PhD students contribution to the above-mentioned article:

Lars Rosendahl Appelquist has undertaken above 90% of the work related to this article, and has specifically:

- Formulated the focus, problem, and conceptual basis for the article
- Prepared and performed the empirical data collection
- Carried out the full analysis
- Drafted all sections of the article

Thomas Balstrøm has contributed with under 10% of the work related to this article, and has specifically:

- Contributed to formulating the focus, problem, and conceptual basis for the article
- Contributed to the technical GIS operations
- Contributed to proofreading the article

Signature of the PhD-student: Lars Rosendahl Appelquist   Date: 2 December 2013

As a co-author I state that the description given above to the best of my knowledge corresponds to the process and I have no further comments.

Signatures of co-authors:

Date (dd/mm/yy)	Name	Signature
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Joint author statements shall be delivered to the **PhD administration** together with the PhD thesis.

Joint author statement

If a thesis contains articles* made in collaboration with other researchers, a joint author statement about the PhD-student's part of the article shall be made by each of the co-authors, cf. article 12, section 4 of the Ministerial Order No. 18 February 2008 about the PhD degree. We refer to the Vancouver protocol's definition of authorship.

Titel of the article: Application of a new methodology for coastal multi-hazard assessment & management on the state of Djibouti

Author(s): Lars Rosendahl Appelquist and Thomas Balstrøm

Journal/conference (if applicable): Submitted to Climate Risk Management

Name of PhD student: Lars Rosendahl Appelquist   Date of birth: 08-02-1982

* by article is meant: published journal and conference articles, unpublished manuscripts, chapters etc.

Description of the PhD students contribution to the above-mentioned article:

Lars Rosendahl Appelquist has undertaken above 90% of the work related to this article, and has specifically:

- Formulated the focus, problem, and conceptual basis for the article
- Prepared and performed the empirical data collection
- Carried out the full analysis
- Drafted all sections of the article

Thomas Balstrøm has contributed with under 10% of the work related to this article, and has specifically:

- Contributed to formulating the focus, problem, and conceptual basis for the article
- Contributed to the technical GIS operations
- Contributed to proofreading the article

Signature of the PhD-student: Lars Rosendahl Appelquist   Date: 2 December 2013

As a co-author I state that the description given above to the best of my knowledge corresponds to the process and I have no further comments.

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Titel of the article:	The Coastal Hazard Wheel system for coastal multi-hazard assessment & management in a changing climate
Author(s):	Lars Rosendahl Appelquist and Kirsten Halsnæs
Journal/conference (if applicable):	Submitted to Journal of Coastal Conservation
Name of PhD student:	Lars Rosendahl Appelquist
Date of birth:	08-02-1982

* by article is meant: published journal and conference articles, unpublished manuscripts, chapters etc.

Description of the PhD students contribution to the above-mentioned article:

Lars Rosendahl Appelquist has undertaken above 90% of the work related to this article, and has specifically:

- Formulated the focus, problem, and conceptual basis for the article
- Carried out the methodological development and empirical data collection
- Carried out the full analysis
- Drafted all sections of the article

Kirsten Halsnæs has contributed with under 10% of the work related to this article, and has specifically:

- Contributed to formulating the focus, problem, and conceptual basis for the article
- Contributed to the methodological development and cost analysis
- Contributed to proofreading the article

Signature of the PhD-student: Lars Rosendahl Appelquist Date: 9 January 2014

As a co-author I state that the description given above to the best of my knowledge corresponds to the process and I have no further comments.

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Paper 1

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Generic framework for meso-scale assessment of climate change hazards in coastal environments

Lars Rosendahl Appelquist

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Abstract This paper presents a generic framework for assessing inherent climate change hazards in coastal environments through a combined coastal classification and hazard evaluation system. The framework is developed to be used at scales relevant for regional and national planning and aims to cover all coastal environments worldwide through a specially designed coastal classification system containing 113 generic coastal types. The framework provides information on the degree to which key climate change hazards are inherent in a particular coastal environment, and covers the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. The system includes a total of 565 individual hazard evaluations, each graduated into four different hazard levels based on a scientific literature review. The framework uses a simple assessment methodology with limited data and computing requirements, allowing for application in developing country settings. It is presented as a graphical tool—the Coastal Hazard Wheel—to ease its application for planning purposes.

Keywords Coastal management · Coastal classification · Climate change · Hazard assessment

Introduction

The growing concern for global climate change has spurred research into methods for assessing climate-related vulnerability of coastal environments at local, regional and national scale. Methods developed so far include various types of coastal vulnerability index and indicators, GIS systems and modelling approaches (Ramieri et al. 2011). The existing methodologies, however, have mainly been designed for developed country assessments and all of them require a significant amount of input data and computing capacity, limiting their application in developing countries. Furthermore, most approaches group the different hazards together into a combined risk or vulnerability index, thereby losing some specificity relevant for planning purposes. The available sector specific approaches tend to focus on one particular risk type (Ramieri et al. 2011).

This paper presents a generic framework for simple assessment of climate change hazards in coastal environments without the need for excessive data collection or computer processing capacity. It is especially targeted decision-makers in developing countries, where rapid changes in demography and land-use increase the need for regional and national planning along with tools supporting this effort. The framework aims at covering virtually all coastal environments worldwide through a specially designed coastal classification system building on key bio-geophysical parameters. It provides information on the climate change hazards considered most relevant for coastal management (Zhu et al. 2010). The framework is presented as a graphical tool—the Coastal Hazard Wheel (CHW)—to ease its application for regional and national planning, especially in developing countries.

The coastal classification system uses a geological categorization as basis, on which it adds the main dynamic forces and processes acting in the coastal environment and on the geological framework itself. Using this methodology, a total of 113 generic coastal environments have been defined and attempts have been made to keep the number of generic environments as low as possible while still maintaining the usefulness of the classification system seen from a decision-support perspective. The system allows the

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practical classification to be carried out through collection of on-site and remote sensing data or through primarily remote means. Whereas the first method produces the most reliable results, the latter may be appropriate for regional hazard assessments requiring less accuracy.

The inherent climate change hazards are defined as the hazards being an integral part of the bio-physical properties of a coastal environment when exposed to key climate change drivers. The climate change drivers considered in this regard are the ones defined in the IPCC Fourth Assessment Report and includes an increase in global average temperature of 1,1–6,4 °C by 2100, a global sea level rise of 0,18–0,59 m by 2100, an average rise in global sea surface temperature, an average decrease of ocean water pH, a possible intensification of tropical cyclones and an possible alteration of precipitation/run-off patterns (IPCC 2007a).

The framework covers the inherent hazards related to ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding, and the graduation of the inherent hazards is carried out based on a scientific literature review. The hazard graduation is illustrated by a four-level number/colour code system. The inherent hazards may be mitigated by human alteration of the natural environment or other human actions, but since the framework is based on bio-geophysical parameters, the presence of a given hazard will remain the same unless the bio-physical properties of a coastal environment are changed permanently by human actions. Changes in natural drivers may also change the classification parameters over time, which will then impact the inherent hazard levels.

The coastal classification system

The coastal classification system constitutes the foundation for the inherent hazard assessment. It is developed particularly for decision-support but includes many components of previously published coastal classification systems. The system tries to incorporate the main static and dynamic parameters acknowledged in the paradigm of coastal morphodynamics (Wright and Thom 1977; Cowel and Thom 1994).

The bio-geophysical components used in the classification system are selected as the ones considered most important for the characteristics of a particular generic coastal environment. The components included are geological layout, wave exposure, tidal range, flora/fauna, sediment balance and storm climate. Each generic coastal system has a specific combination of these variables. Since the 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 generic coastal environment should be considered to extend longshore until any of the included variables change significantly. In cases where a particular classification parameter is of minor importance, the system applies an *Any* phrase to avoid a disproportionate large number of categories. Variables such as local isostatic uplift/subsidence and sediment grain size have not been included as these to some extent are indirectly covered through other parameters. This is to achieve an appropriate balance between classification simplicity and correctly reflecting natural conditions. The different classification components have been clearly defined in order to differentiate the generic coastal environments and to make the classification system practical applicable. The definitions and classification assumptions are outlined in the following sections.

Geological layout

The geological layout constitutes the basis on which the dynamic processes act. It has been created by various past dynamic processes including glacial, fluvial, marine, volcanic and tectonic (Davis Jr 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 classification 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 are *coastal plain*; *barrier*; *delta/low estuary island*; *sloping soft 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 such as the Atlantic coast of North- and South America whereas the fifth category, *sloping hard rock coast*, is commonly found on leading edge coastlines such as the Pacific coast of North and South America. The *coral island* category is largely depending on tectonic and climatic conditions (Davis Jr and Fitzgerald 2004; Masselink and Hughes 2003). The final category *tidal inlet/sand spit/river mouth* constitutes a group of specially dynamic geologic environments.

The *coastal plain* category is defined as coasts with average slopes of less than 3–4 % at least 200 m inland of the MSL, and which are composed of sedimentary deposits such as clay, silt, sand, gravel, till or larger cobbles. If coastal dunes are present, the slope may locally be higher than 3–4 % where the backbeach meets the dunes, but the coast will still fall into the *coastal plain* category. *Coastal plains* are often formed by glacial and fluvial processes or through coastal progradation (Davis Jr and Fitzgerald 2004; Masselink and Hughes 2003).

The *barrier* category is defined as coasts that consist of shore parallel sedimentary bodies with cross distances ranging from less than 100 m to several kilometres, and lengths ranging from less than 100 m to over 100 km (Davis Jr 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 kind of marsh or mangrove vegetation, depending on climatic conditions and tidal range. In meso- 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 the barrier. This would e.g. be the case where a *coastal plain* or *sloping soft rock coast* is located landwards of a *barrier*. If a barrier has a slope of more than 3–4 % it will fall into the *sloping soft rock coast* category.

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, 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 Jr 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 significant sediment accumulation.

The *sloping soft rock coast* category is defined as coasts comprised of soft rock material with average slopes greater than 3–4 % at least 200 m inland of the MSL. Coastal cliffs with a steep cliff gradient combined with shore platforms or a landscape flattening landwards of the steep cliff also fall into this category. *Sloping soft rock coasts* can be comprised of a range of different sedimentary material 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. Since *sloping soft rock coasts* can exist as both coastal cliffs and gently sloping vegetated hills, it may be necessary to remove some topsoil and vegetation to determine the cementation level in the field. If the classification is done remotely, geologic and geomorphologic maps, as well as the ground elevation function in Google Earth can be used.

The *sloping hard rock coast* category is defined as coasts consisting of igneous, sedimentary or metamorphic rock with any seaward slope greater than zero. 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 coasts are considered as one uniform group. *Sloping hard rock coasts* can be present in different forms such as coastal mountain chains, headlands and archipelagos.

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 1,000 m 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 result of wave action. These islands can rise up to 3 m 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 which 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 1 km 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 Jr and Fitzgerald 2004). *Sand spits* are 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 1 km on each side of a well defined river mouth. *Tidal inlets*, *sand spits* and *river mouths* are assigned high priority in the classification system, meaning that e.g. a *coastal plain* will fall into this category if it is located less than 1 km on each side of a tidal inlet or river mouth.

Wave exposure

The wave exposure is the dominant energy source in the nearshore environment and a highly important parameter for the coastal morphodynamics. Even though 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).

For most coastal systems, gravity waves generated by wind stress on the ocean surface are the main source of energy. 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 after the wind stops and where 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). 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 Jr and Fitzgerald 2004). Since the wave energy increases as the square of the wave height, coastal environments with high wave heights have relatively high energy intensity compared to protected coasts (Thieler et al. 2000).

The classification system distinguishes between *exposed*, *moderately exposed* and *protected* coastlines. The distinction between these categories is based on the significant wave height, H_S, that represents the average wave height of the one-third highest waves in a wave record and corresponds well to the visual wave heights estimates (Masselink and Hughes 2003). To ensure consistency, the classification system uses the H_S 12 h/yr, which is the nearshore significant wave height exceeded for 12 h per year (Mangor 2004). In this way, a uniform time record will be used when the assessment framework is applied in practice.

The wave exposure level is determined based on the coastline geography and wind climate. All coastlines located in regions with swell waves are in the classification system defined as *moderately exposed* (Mangor 2004). These coastlines can be indentified based on Fig. 1, where coasts falling into "West coast swell", "East coast swell" and "Trade/monsoon influences" are categorized as *moderately exposed* coastlines.

If the coastline is located outside the swell regions, the wave exposure should ideally be determined based on the S-B-M method. This method uses a nomogram to predict H_S by input of wind speed, wind duration and the fetch length (Masselink and Hughes 2003). For use in the nomogram, the wind speed (U) in m/s has to be converted to the wind stress factor, U_A, calculated from the equation below. For the calculation of H_S 12 h/yr, the maximum average wind speed blowing on-shore for 12 h/yr has to be used in the equation as U.

$$UA = 0,71 * U^{1,23}$$

(Masselink and Hughes 2003)

When reading the nomogram, the H_S 12 h/y can be found by plotting U_A together with the 12 h of wind speed and the local fetch. Where the limiting parameter for H_S 12 h/yr is the fetch length, the fetch length becomes the determinant. The nomogram is shown in Fig. 2.

If the H_S 12 h/y is determined as more than 3 m, the coast is considered *exposed*, while it is considered *moderately exposed* with an H_S 12 h/y of 1–3 m. If the H_S 12 h/y is determined as less than 1 m, the coast is considered to be *protected*.

Since it can be difficult to obtain the necessary wind data to apply the S-B-M method, especially in developing countries, the free fetch can be used to roughly estimate the exposure levels of non-swell coastlines. Coasts can be considered *exposed* if they border waterbodies larger than 100 km, while they can be considered *moderately exposed* if they are associated with waterbodies of the size of approximately 10–100 km. *Protected* coasts are generally restricted to inner waterbodies in the order of less than 10 km, but can also be seen along larger waterbodies with shallow nearshore zones or mild on-shore wind climates (Mangor 2004). When estimating the exposure levels, either through the S-B-M method or roughly through

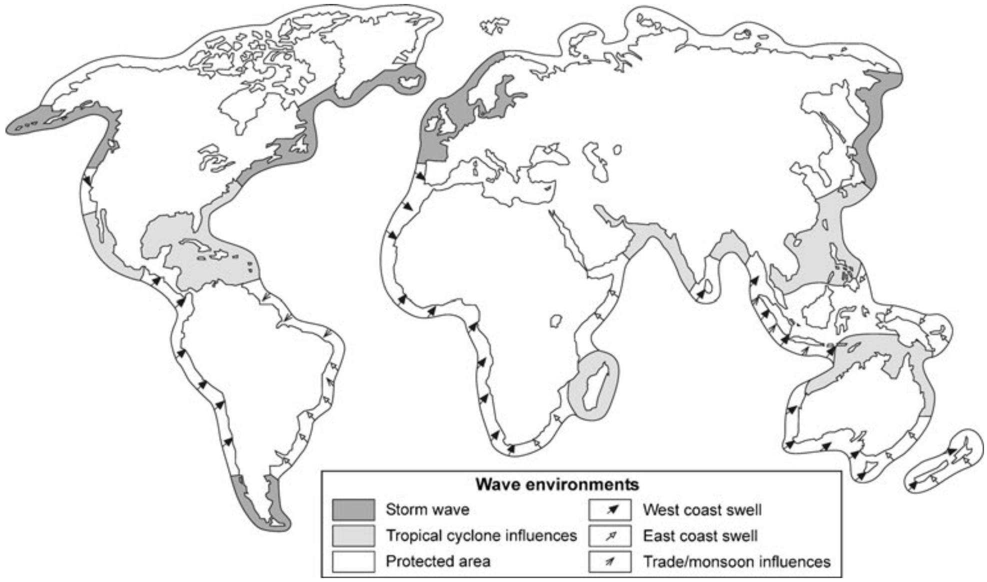

Fig. 1 Global wave climates (Davies 1980, modified by Masselink and Hughes 2003)

the free fetch, it is therefore important to be aware of physical conditions such as coastal reefs or tidal flats that cause the coast to fall into the *protected* category even when the water body is larger than 10 km. Ice affected coastlines may have seasonal fluctuating wave exposures due to presence of winter sea ice. As sea ice is expected to be highly vulnerable to climate change, however, the same approach as for ice free coasts should be applied. Only in locations where the sea ice is

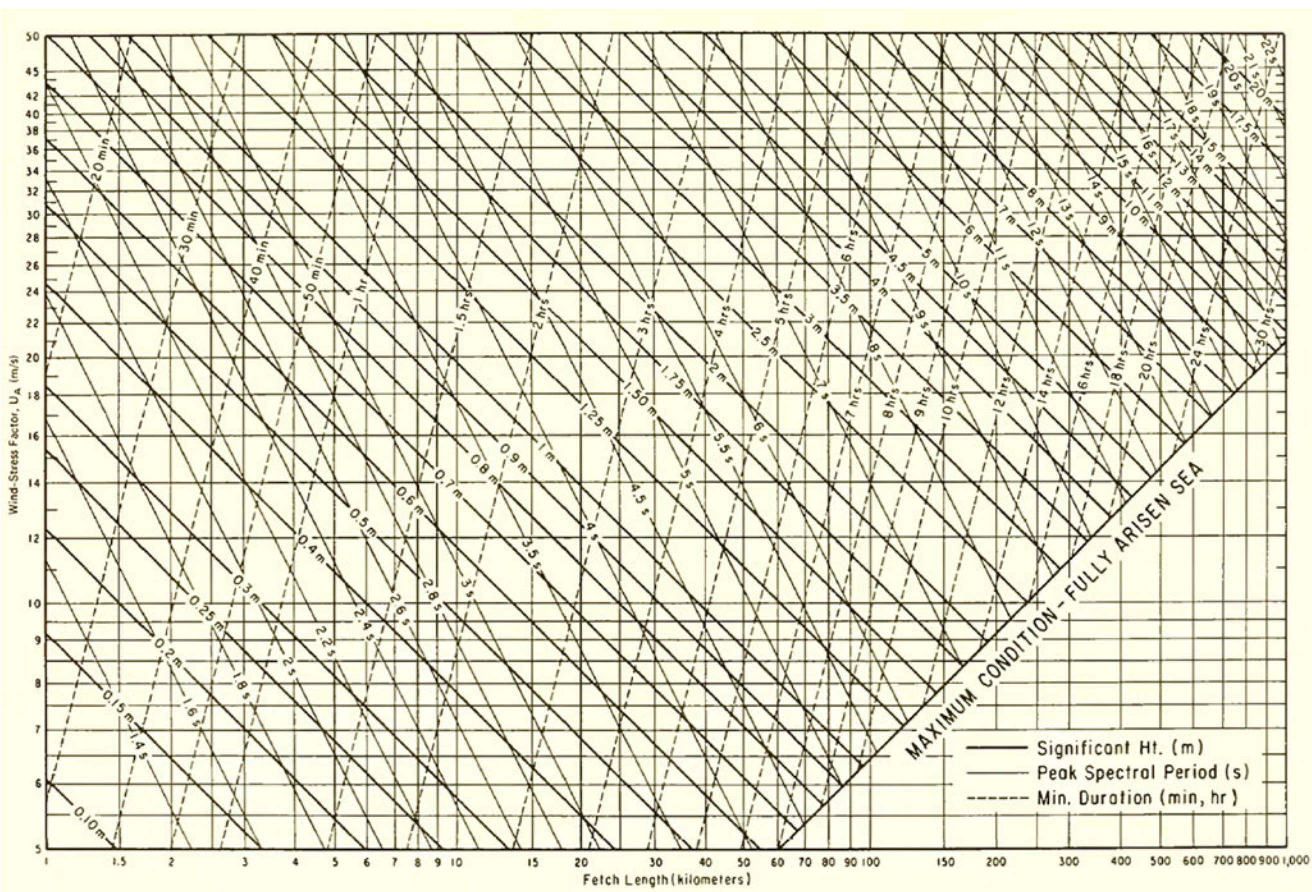

Fig. 2 Nomogram of deepwater significant wave prediction curves as function of wind speed, fetch length and wind duration (Coastal Engineering Research Center 1984)

expected to be very stable, the fetch length has to take into account the ice cover.

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 Jr and Fitzgerald 2004). Tides fluctuate on a daily basis following diurnal, semi-diurnal and mixed tidal cycles (Davis Jr 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 Jr and Fitzgerald 2004). Globally, semidiurnal and mixed tides are dominating coastal areas (Haslett 2009).

From a morphodynamic perspective, the tidal range influences coastal processes in many ways and are controlling 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, 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. Equally, a lower tidal range is present where the coast is close to an amphidromic point, does not has significant magnifying bathymetric conditions, has a narrow continental shelf and has an open coastline (Haslett 2009). The numerical value of the tidal range vary significantly between coastal locations and span from almost zero to about 16 m in funnel shaped embayments such as the Bay of Fundy, Canada (Davis Jr and Fitzgerald 2004). Tides of a particular location also fluctuate daily 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 m and can be found on open ocean coastlines such as the eastern 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 m 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 m which is the case along 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. 3.

The effect of tidal range on coastal morphodynamics is largely influenced by the local wave conditions. 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. This may lead to some inaccuracies in the hazard assessment of coastlines with a very large tidal range but is considered a reasonable simplification taking the impacts of other classification parameters into account. 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 major implications for a reliable hazard evaluation, except under extreme high tidal range conditions. Since the effect of tidal range on the inherent hazards of *sloping soft 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.

Flora/fauna

For some coastal environments, the local flora/fauna constitutes an important parameter for their morphodynamics and inherent climate change hazards. In the classification system, the flora/fauna has been included where it is considered to play an important role for the characteristics and inherent hazard profile of a coastal environment. 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

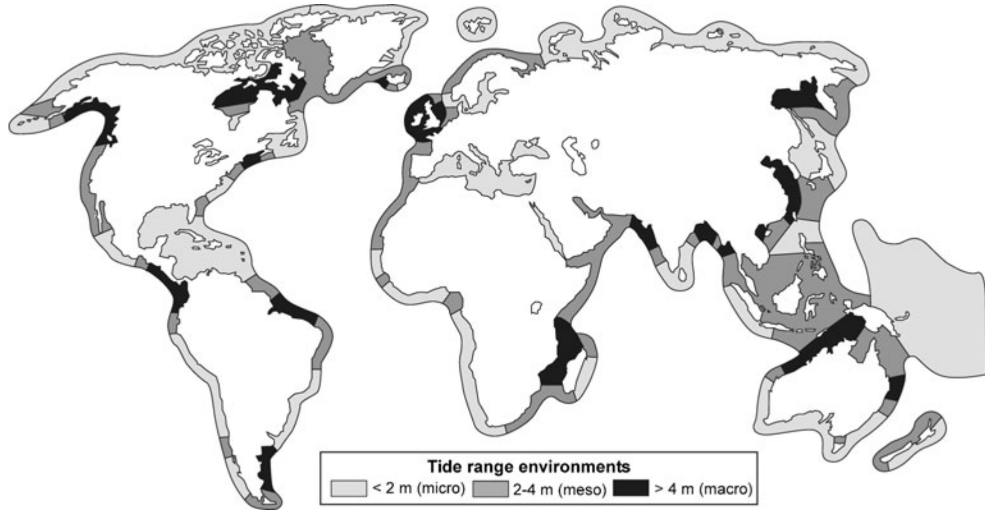

Fig. 3 Map over global variation in tidal range (Davies 1980, modified by Masselink and Hughes 2003)

the application of the flora/fauna categories. In total, the classification system operates with eight different categories namely *intermittent marsh; intermittent mangrove; marsh/tidal flat*; *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 *coastal 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*.

The *intermittent mangrove* and *mangrove* categories are applied to coastlines falling into the geological layout categories *coastal 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 providing 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* category is applied to areas with *meso/macro-tides,* as they colonise the tidal flats.

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. The *vegetated* category is applied when more than 25 % of the slope is covered with vegetation while the *not vegetated* category is used when less than 25 % 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 seen 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 an inherent hazard perspective. In cases where the fronting marsh or mangrove areas are extensive, the coastline will automatically fall into one of the non-sloping geological layout categories.

The *coral* category is applied to *sloping rocky coasts* where the corals have a firm substrate to thrive on. Corals are carnivorous suspension feeders living as polyps with an external skeleton of calcium carbonate (Masselink and Hughes 2003). They live in large colonies and reproduce by asexual polyp division or sexually during short periods of the year. As new coral larvae have limited swimming capabilities their end destination is very dependent on ocean currents and the duration of the planctonic phase and when they find a suitable substrate, they attach to it and transform into a polyp. 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 Jr and Fitzgerald 2004). Reef building corals are very light sensitive and reefs are rarely being created at depths greater than 50 m. 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. As coral reefs often are backed by carbonate beaches and not bare rock, a special beach category is available in the classification system for *sloping hard rock coasts*. The separate geological layout category for *coral island*s is assumed to be associated with coral reef environments of various kinds.

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/or inherent 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 included hazards significantly.

Sediment balance

The sediment balance is an essential morphodynamic parameter and particularly important for coastlines falling into the sedimentary layout categories. The sediment balance determines whether there is a net accumulation, removal or balance of sediment at a particular coastline over time and is largely determined by the sediment transport and availability.

The coastal sediment transport can be divided into two main categories, 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 (Mangor 2004; Davis Davis Jr and Fitzgerald 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 mud/tidal flats (Mangor 2004). Coastlines dominated by cohesive sediment can respond to 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 rocky 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 on-site or remotely. 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 dynamics. However, seen from a inherent hazard perspective, these coastlines are less likely to experience severe sediment deficits in the near future.

For achieving an optimal accuracy of the hazard assessment, temporal data on sediment transport, erosion and accumulation would be valuable for determining the sediment balance of a particular coastline. As the assessment framework is intended to be used in areas with limited data availability, however, it is designed to rely on a combination of remote sensing data and on-site assessments. Direct short-term observations are complicated by the fact that single storm and high-wave events can lead to temporal coastline erosion which is reversed during calm conditions, thus causing fluctuating erosion and accumulation patterns (Mangor 2004; Stive et al. 2002). This means that a particular coastal area may one day appear to erode while looking stable sometime later. For evaluation of the sediment balance, it is therefore recommended to make use remote sensing techniques, such as the Google Earth timeline function, to evaluate coastal changes over several years. If possible, this should be combined with local field assessments of signs of coastal stability, erosion or accretion, along with interviews of local coastal inhabitants.

In cases where there is doubt about the validity of the sediment balance evaluation, it is recommended to be guided by the precautionary principle and apply the *balance/deficit* category, as this gives the highest general hazard level. This is also recommended where there is suspicion of human alteration of the sediment balance, such as by local or nearby beach nourishment. For rocky 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.

Storm climate

In areas with tropical cyclones, coastal areas can experience extreme wind, wave, and precipitation conditions that significantly affect the coastal morphodynamics and inherent 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 inherent hazards in all areas where they occur regardless of their frequency. The classification system uses the map shown earlier in Fig. 1 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.

The inherent hazard assessment

The inherent hazard graduation for the generic coastal environments is based on a review of the scientific literature on the susceptibility of coastal systems to climate change-related hazards. 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 classification system. This approach is surrounded by some uncertainty and the hazard graduation therefore only 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 regional planning purposes, 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 environment has been assigned a specific inherent hazard level for ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding, and in the CHW, the graduation is displayed as a combined number/colour code to give the user the best possible overview of the many subsections. A total of 565 individual hazard evaluations are assigned to the 113 different coastal systems. The following sections highlight some of the key parameters determining the inherent hazard levels based on the scientific literature review.

Ecosystem disruption

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

For *exposed* and *moderately exposed* littoral coastal environments, the inherent hazard levels are generally low, as these environments represent hostile places for biota. The littoral 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/exposed coastlines, when coral coasts are disregarded (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 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 poses a risk to the diversity of coastal mangroves (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 % 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* coasts with a low tidal range generally 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 still 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 concentration decreases coral calcification rates and growth by up to 40 % (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 2007b). Furthermore, intensification of tropical cyclones could have very damaging effects on coral reefs (IPCC 2007b).

Along with the sensitive coral reef ecosystems associated with *coral island*s, freshwater dependant ecosystems on these locations often harbour rare and endemic species. These ecosystems are highly sensitive to sea level rise and the associated risk salt water intrusion (McMullen and Jabbour 2009).

Gradual inundation

The graduation of inherent hazards for gradual inundation reflects the possibility of a gradual submergence of a coastal environment due to climate change. Contrary to flooding, gradual inundation takes place over years and 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 *coastal plain*s, *barriers*, *deltas* and *coral islands* generally have a higher inherent hazard level. Coastal floodplains can be inundated due to natural levee overtopping if the sediment supply cannot keep up with the sea level rise, while inundation of delta environments depends on the balance between fluvial sediment supply and coastal emergence (IPCC 2007b). Delta environments are generally very sensitive to sea level rise (Ericson et al. 2006; Woodroffe et al. 2006) and rates of sea level rise in deltas tend to be greater than the global average due to delta subsistence (IPCC 2007b). Most deltas no longer maintain their natural sediment supply due to upstream damming activities and experience sediment deficits as they are subsiding due to the weight of the accumulated sediment (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 stated to accelerate (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 also influences inundation hazards and marsh areas with a high tidal range are generally considered to be less vulnerable to sea level rise (Simas et al. 2001).

While 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).

Mangrove coastlines are in many cases likely to migrate landwards with a rising sea level (Alongi 2008; Ross et al. 2000). Sea level rise is considered the greatest climatic threat to mangrove forests 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, together with the ability of mangroves to produce sufficient organic material to maintain their peat foundation during a rising sea level (Simas et al. 2001). In locations with a high tidal range, mangroves migrating landwards are likely to be supported by sediment eroded from the outer intertidal zone. In delta environments where delta plains of mangroves have been created following shoreline progradation, mangroves are at particular risk as they are unable to migrate landwards (Wodroffe 1995). 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 minor risk compared to the expected increase in sea surface temperature and ocean acidification (Hoegh-Guldberg et al. 2007; IPCC 2007b).

Salt water intrusion

The graduation of inherent hazards for salt water intrusion reflects the possibility of salty sea water penetrating into coastal surface waters and groundwater aquifers. 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 risk 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 salinisation of shallow aquifers as gradual inundation, erosion and higher flooding levels increases the landward reach of waves and storm surges (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 and estuaries 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 most impact on brakish and freshwater marshes due to changes in hydrological regimes (Burkett and Kusler 2000; Sun et al. 2002). 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 2007b).

Yet, the risk of saltwater intrusion is largely related to human water extraction, and the presence of this hazard therefore arises from a combination of human and natural conditions (IPCC 2007b; Essink 2001). In the assessment framework, however, the focus is solely on the natural inherent hazards.

Erosion

The graduation of inherent hazards for erosion reflects the possibility of future coastline erosion and is controlled by a range of classification parameters. The geological layout expresses the potential erodability of the coastline and thus determining if any significant erosion can happen in the first place (Davis Jr and Fitzgerald 2004). Geological layouts of sedimentary origin have a relative high erodability, while hard rock coastlines show little erosion over timescales used in coastal management (IPCC 2007b). Where beach environments are present along hard rocky 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 is also influencing the erosion rates as coastlines with a low slope generally retreat faster than steeper coastlines (Thieler et al. 2000). Yet, soft rock cliffs are still likely to retreat more rapidly in the future due to an increased erosion of the cliff profile from a rising sea level, a possible increase in precipitation intensity and higher groundwater levels. Soft rock cliff erosion often takes place in episodic intervals and the rate of erosion is controlled by a range of parameters including sea level rise, precipitation, wave exposure and sediment balance (IPCC 2007b). 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). This can cause secondary effects by gradually or abruptly transforming protected backbarrier environments into high energy coasts (Stone and McBride 1998). Infilling of estuaries and lagoons with sediment during rising sea level can lead to major sediment deficits 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 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 current conditions 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 shoreline retreat is estimated to be 50–200 times the rise in relative sea level (IPCC 2007b).

In *protected* coastal environments, a high tidal range can be important for the sedimentation processes. In these environments, a sediment surplus can lead to a gradual sediment accumulation that keeps 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 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). Erosion of the seaward margins of mangrove forests can take place as a consequence of a rising sea level, resulting in landward migration of the mangrove edge (Alongi 2008; Gilman et al. 2008). Vegetation of sloping sedimentary coasts has an important effect in reducing erosion and gully formation from heavy precipitation events and groundwater seeping, and in reducing the impact of wave action on the slope base.

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 significantly erosion and a possible reduction of island size (IPCC 2007b).

Flooding

The graduation of inherent hazards 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 *coastal plains*, *barriers*, *deltas* and *coral island*s being particularly vulnerable (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 is expected to increase flooding hazards (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. Some mangrove species seem to be more flood tolerant than others and some changes in community composition may happen as a result of climate change (Alongi 2008).

Practical application and limitations

The practical application of the assessment framework is done through the use of the CHW, which is shown in Fig. 4. The user starts in the centre of the CHW and then moves outwards, ending 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 inherent hazard circles then come in the order: Ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. Where the term “Any” is applied in the classification system, the user should simply continue with the parameter in the following circle. In the case of *sloping rocky coasts*, the user should follow the “A” (for Any) in the circle for wave exposure, for locations where no beach is present. With the presence of some kind of beach environment, the user should continue by evaluating the wave exposure levels.

The user of the assessment framework should ideally conduct a new assessment every time any of the classification parameters change significantly. For the practical application this means that a new hazard assessment is recommended every time the coastal environment changes character. Coastlines may also fall into several different categories as one move landwards. This can e.g. be the case for *deltas*, where the wave exposure decreases as one moves landwards into the delta or for *barriers* that may have a *coastal plain* or *sloping sedimentary coast* landwards of the barrier lagoon. The longshore shift from one coastal environment to another will often happen gradually over a coastal stretch, such as delta islands gradually turning into *barriers* some distance from the delta. In these cases, it may be difficult to determine when to apply the different categories. This should not lead to any significant errors, however, as the different sites will have very similar inherent hazard levels. In cases where the coastal site in question does not match any of the coastal categories in the assessment framework, the user should simply apply the category that best match the actual conditions.

The application of the assessment framework is complicated by the fact that many coastal environments have been altered by human activities to various degrees. These activities can affect the classification and inherent hazard graduation in two main ways, which should be considered by the user. Firstly, if the human alteration of the natural environment is happening outside the specific coastal site in question i.e. upstream river damming or nearby harbour construction, it may impact the classification through changes in the dynamic parameters and/or sediment balance. Examples of this can found where river damming affects the sediment balance of a delta or where the presence of a harbour affects the wave exposure and sediment balance of a nearby coast. Generally, such long term, structural alterations of neighbouring or associated environments will automatically be incorporated in the classification system unless the alteration has taken place so recently that the site in question has not yet responded to the change. When using the assessment framework, it is therefore important to be aware of recent human alterations of nearby or related environments. Secondly, human activities may have altered the specific coastal site in question with the purpose of stabilizing the coastline or changing its land-use. If this alteration affects bio-physical parameters included in the classification system, such as by increasing the vegetation of a *sloping soft rock coast* or by carrying out beach nourishment, the site may temporally or permanently shift into a new classification category. If the alteration mainly affects bio-physical parameters that are not incorporated in the classification system or they alter the coastal environment to a condition outside its natural state i.e. by completely removing a mangrove forest in an otherwise natural mangrove area, the assessment framework will not be able to take these alterations into account.

Conclusions

The framework aims at providing a methodological foundation for simple assessment of inherent hazards in coastal environments under changing climatic conditions. It is intended to complement existing frameworks and methodologies for coastal vulnerability and risk assessment, and to provide a viable alternative for developing country planners that have difficulties applying existing frameworks due to lack of sufficient data and computing capacity. The assessment framework may provide less accurate hazard estimates than more sophisticated and data-intensive methods and is therefore mainly designed for meso-scale applications relevant for regional and national planning. As is the case for most other

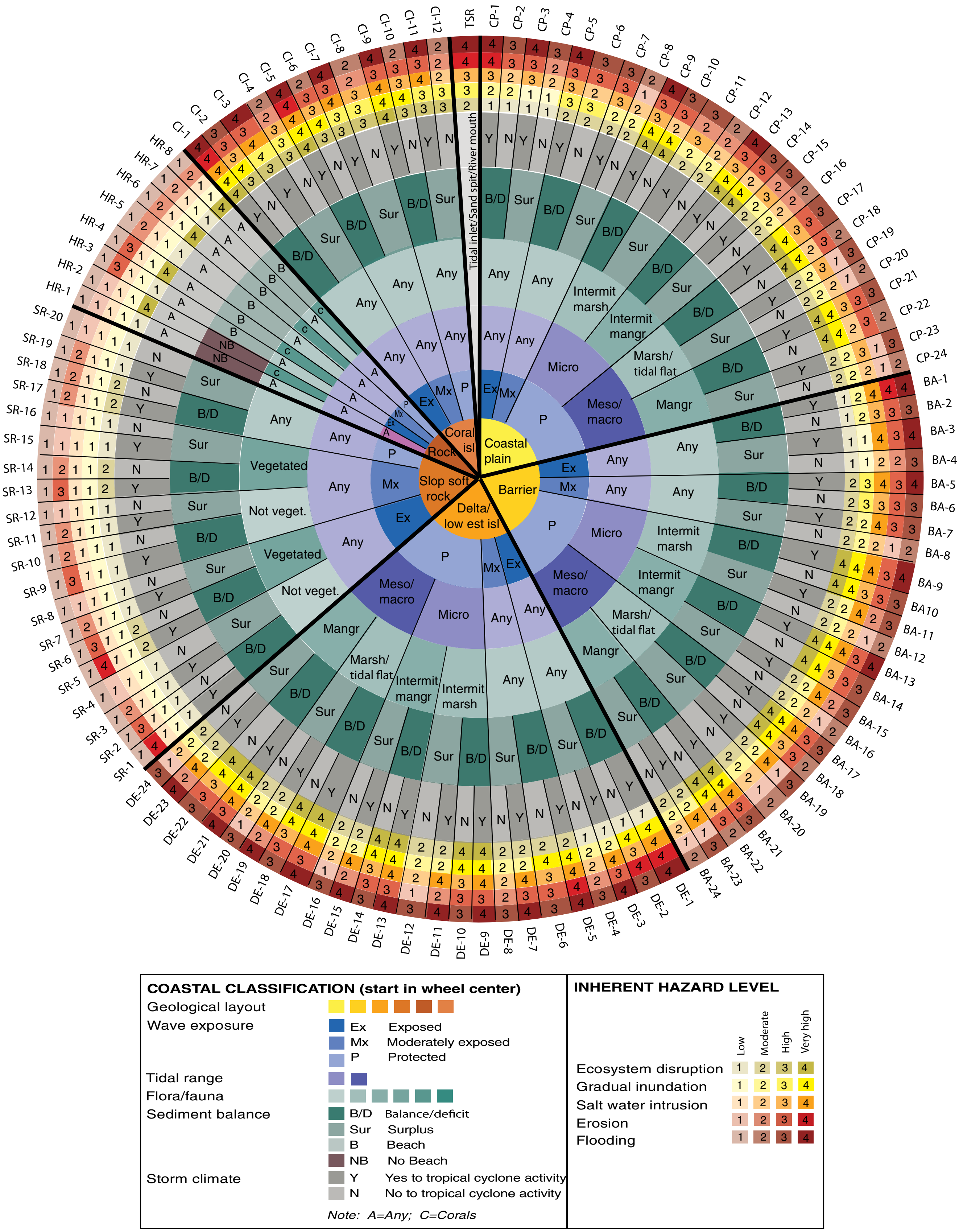

Fig. 4 The Coastal Hazard Wheel (CHW)

indicator and index based approaches, it is a useful tool for scoping assessments and to support identification of vulnerable coastal areas and systems. For local development activities, a more detailed assessment is recommended in order to obtain in-debt knowledge of the risk profile of the coastal site in question. To optimize the accuracy of the inherent hazard estimations, it is recommended to use a combination of remote sensing, on-site assessments, geophysical data and geological maps for the coastal classification. If an assessment is carried out primarily based on remote means, one should be aware of the associated uncertainties, especially related to the sediment balance estimates.

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Paper 2

Application of a new methodology for coastal multi-hazard-assessment on the state of Karnataka, India

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Abstract

This paper presents the application of a new methodology for coastal multi-hazard assessment under a changing global climate on the state of Karnataka, India. The recently published methodology termed the Coastal Hazard Wheel (CHW) is designed for local, regional and national hazard screening in areas with limited data availability, and covers the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. The application makes use of published geophysical data and remote sensing information and is showcasing how the CHW framework can be applied at a scale relevant for regional planning purposes. It uses a GIS approach to develop regional and sub-regional hazard maps as well as to produce relevant hazard risk data, and includes a discussion of uncertainties, limitations and management perspectives. The hazard assessment shows that 61 percent of Karnataka's coastline has a high or very high inherent hazard of erosion, making erosion the most prevalent coastal hazard. The hazards of flooding and salt water intrusion are also relatively widespread as 39 percent of Karnataka's coastline has a high or very high inherent hazard for both of these hazard types.

Keywords: Coastal hazard assessment; climate change; India; coastal planning

1. Introduction

The projected climate change will place significant stress on coastal regions worldwide and constitutes a particular challenge for developing countries where coastal development often happens rapidly and without prior investigation of natural dynamics. Improving the knowledge of the physical characteristics of coastal areas as well as their inherent natural hazards is therefore an important prerequisite for sustainable and safe coastal development. This paper tests the practical application of the CHW framework (Rosendahl Appelquist 2012) through a multi-hazard assessment of the coastline of Karnataka, India, under a changing global climate (IPCC 2007). The goal of the paper is both to showcase a practical procedure for applying the CHW framework for regional hazard assessments, and to develop hazard maps and hazard risk data for the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding for the state of Karnataka, India.

As the CHW framework was published in late 2012, the hazard assessment for Karnataka is intended to test its practical applicability on a diverse and largely sedimentary coastline. Whereas most existing assessment systems are designed for areas with relatively good data availability (Thieler et al. 2000; Ramieri et al. 2011), the CHW framework is developed to be used for hazard screening and assessment in areas with limited geophysical data collection systems. The state of Karnataka is therefore considered a good test case as coastal data for this region is relatively sparse but not completely absent.

The CHW framework is designed to be applied in a stepwise manner, depending on the appropriate scale and resolution of the hazard assessment. At Step 1, the framework can be applied for regional and national hazard screening, and in most cases, this can be carried out based on publicly available geophysical data and remote sensing information. For areas that are of particular interest or are indicated as hazard hotspots in the hazard screening, a more detailed assessment can be carried out as Step 2. In this step, it is recommended to supplement the data obtained in Step 1 with representative field verification. If local hazard information is needed, Step 3 can be carried out by supplementing data from step one and two with detailed local data collection. The user of the CHW framework can choose only to carry out the step relevant for their specific needs, but should be aware of the appropriate data requirements for each assessment step. The step-wise approach means that data collection can be adjusted according to the scale and resolution of the assessment and should therefore lead to an appropriate balance between data requirements and assessment detail. As this paper focuses on regional hazard screening, the assessment relies solely on published geophysical data and remote sensing information.

The regional hazard screening for Karnataka can be carried out based on relatively simple means and should therefore be replicable without major difficulties in other locations worldwide. The paper is written so it can function as a guided example for coastal planners and developers who are interested in producing hazard maps and hazard data using the CHW framework. The data used for the assessment is available at low/no cost from the internet or regional institutions and it is expected that the same will be the case for most other world regions. For the assessment, it was decided to acquire some supplementary RapidEye satellite images to cover a few low-resolution gaps in ESRI's ArcGIS image series from ArcGIS Online and this added some extra costs to the assessment. It is expected, however, that the quality of satellite images available in ArcGIS and

Google Earth will continue to improve and supplementary satellite images should therefore not be necessary for most locations in the near future.

Since the CHW framework is based on geo-biophysical properties of natural coastal systems, it gives information on the inherent hazards of the different coastal environments. Where human activities have altered a coastal area, the inherent hazards for that generic coastal system are likely to be affected. The CHW framework is able to take most human alterations into account such as changes in sediment supply from river damming and changes in wave climate due to harbour construction. However, if the human activities alter a coastline to a level outside its natural occurrences such as by completely removing a mangrove forest in an otherwise natural mangrove area or constructing a large dike in a coastal plain, the framework is unable to take these changes into account. With the data sources used for this hazard screening, it can in many cases be quite difficult to capture smaller human alternations of the natural coastline, but as a Step 1 assessment, these alterations should not have a great impact on the general hazard profile of the coastline. For more detailed hazard assessments, however, human activities such as sand mining could have a significant impact at a local level and appropriate field verification is therefore recommended if Step 2 or 3 should be implemented.

2. The Coastal Hazard Wheel framework

The CHW framework is developed as a screening and assessment tool to assist coastal planners and decision-makers in determining the hazard profile of a particular coastal area under a changing global climate. This could be relevant for regional infrastructure planning, expansion of residential areas and protection of sensitive natural sites, as well as for determining hazard mitigation strategies for coastal stretches. The CHW framework is based on a specially designed coastal classification system that contains 113 generic coastal environments. The system incorporates the main geo-biophysical parameters determining the characteristics of coastal systems and aims to cover all coastal areas worldwide. It uses the coastal geological layout as a basis on which it adds the main dynamic parameters and processes acting in the coastal environment.

The framework provides information on the degree to which key climate-related hazards are inherent in a particular coastal environment, defined as the hazards being an integral part of the geo-biophysical properties of a coastal system when exposed to future climate change. The framework covers the inherent hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding, and a total of 565 generic hazard evaluations are included in the system, each graduated into four different hazard levels based on a scientific literature review. The framework is generally designed to be applied in locations with limited data availability and computing capacity.

The CHW framework is provided as a graphical tool - the Coastal Hazard Wheel - to facilitate its application for planning purposes. The user starts in the centre of the CHW and then moves outwards, ending with the inherent hazard evaluations in the outermost circles. Starting from the centre, the coastal classification parameters comes 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 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 changes significantly. This can be done by visually assessing the coastal appearance either in the field or through remote sensing, combined with evaluating data for the individual dynamic parameters. When conducting the assessment, the user should be aware of human alterations of the natural environment and whether these alterations are of permanent character, as this would have an impact on the coastal classification and hazard levels. The CHW is shown in Fig 1 and a detailed description of the assessment methodology, assumptions and limitations can be found in Rosendahl Appelquist (2012).

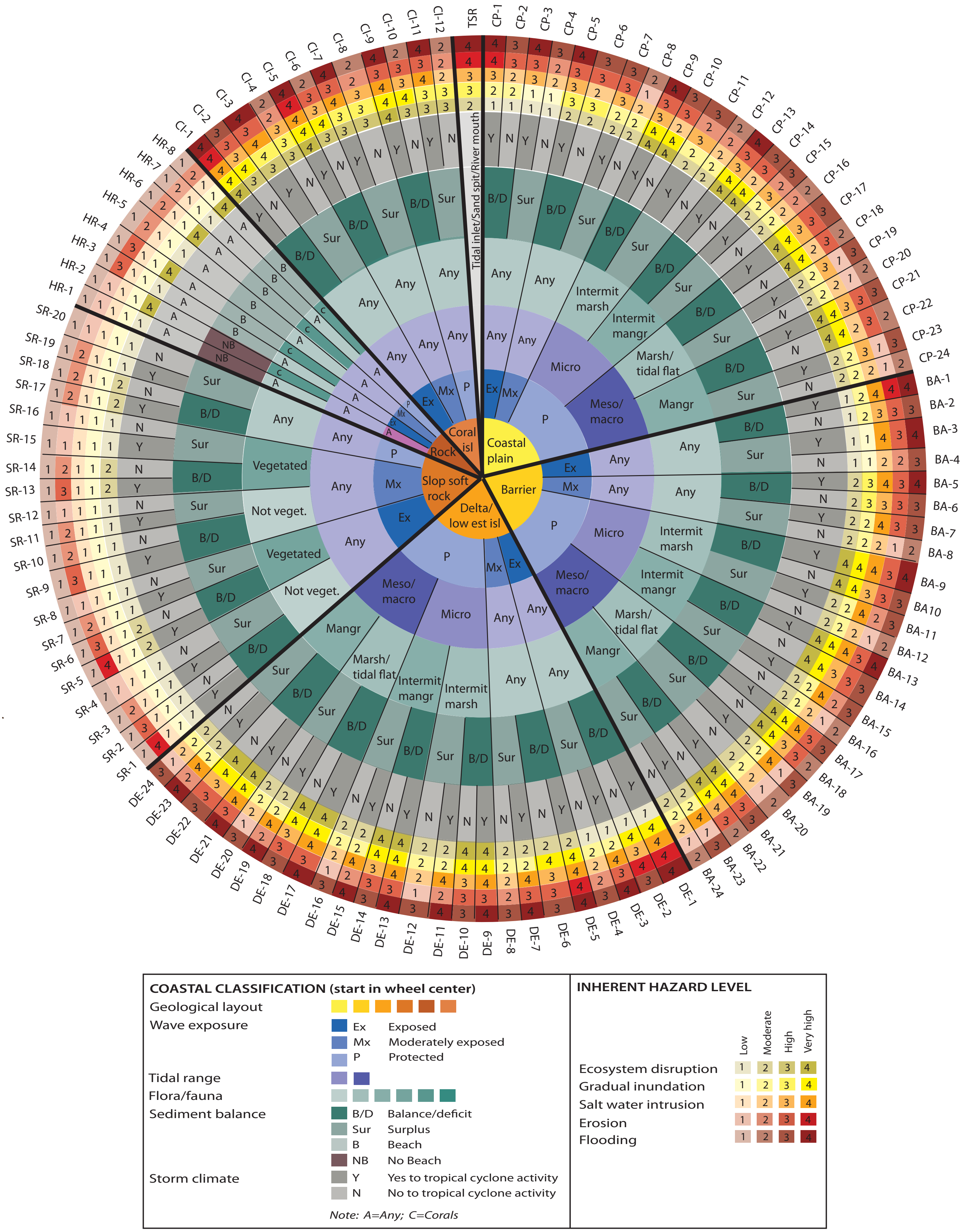
3. The coastline of Karnataka

The state of Karnataka is bordering the Arabian Sea and has a tropical monsoon climate. The months from March to May constitute the hot season with the hottest temperatures occurring in May. The state receives heavy rainfall between June and September due to the SW monsoon and the average annual rainfall is close to 4000 mm of which about 80 percent is received during the SW monsoon season (Dwarakish et al. 2009; Kumar et al. 2010). The heavy monsoon rainfall leads to increased river flows and sediment transport to the coastline (Jayappa et al. 2003). Winds are strong and mainly westerly or south-westerly during the SW monsoon months. In the remaining months, the wind generally blows from northern and eastern directions in the morning and from western and north-western directions in the evening (Jayappa et al. 2003). Deep-water waves approach the coast from south-western and north-western directions and the significant wave height, Hs, have been assessed to > 3 meter during the SW monsoon (Kumar et al. 2010). It has been observed that the long-shore currents are strongest and towards the south during the SW monsoon (Narayana et al. 2001).

The coastline of Karnataka can generally be divided into two main geomorphologic sections with somehow different characteristics. The northern part is composed of Precambrian crystalline gneiss, schist and granite rocks, fronted by a narrow coastal plain of alluvial or Tertiary deposits. In locations where the rock extends to the coastline, coastal cliffs and rocky shores are formed. The coastline displays characteristics of submergence with drowned river valleys, estuaries and many small inlets (Nayak and Hanamgond 2010). The southern part of Karnataka has extensive straight beaches backed by estuaries with low estuarine islands and mangroves. Sand spits growing northwards often border the estuaries (Nayak and Hanamgond 2010).

The northern part of Karnataka's coastlines has a relatively low level of industrial development with small fishing villages located along the coast. However, due to a growing tourist industry, increased fishing intensity and industrial aquaculture, the coastal area is under growing pressure from human activities (Equations 2000). The southern part of Karnataka's coastline close to the city of Mangalore has been used for heavy industrial development for several decades. The transformation from traditional fishing and farming activities started with the construction of the New Mangalore Port in the 1970s and today, many large-scale industries including chemical and petroleum processing plants are located along this coastline.

Fig 1. The Coastal Hazard Wheel (Rosendahl Appelquist 2012).



The port of Mangalore is India's ninth largest harbour in terms of cargo handling and handles 75 percent of India's coffee export (World Port Source 2012). The entire coastline of Karnataka has been declared special tourism area for promotion of tourism (Equations 2000).

The coastline of Karnataka generally faces severe erosion during the SW monsoon and accretion during the fair weather season (Jayappa et al. 2003). In southern Karnataka, research indicates that most of the sand lost during the SW monsoon is regained during the calmer months (Jayappa et al. 2003). However, some parts of Karnataka's coastline show continuous and significant erosion (Dwarakish et al. 2009). In some locations, beach width has been reduced to zero due to reduction in sediment supply from human activities such as construction of breakwaters and seawalls and damming of rivers (Kumar and Jayappa 2009).

Hard engineering structures including breakwaters, seawalls and revetments have been constructed along Karnataka's coastline over the past decades with varying success. Soft measures such as beach nourishment have generally not been applied due to economic reasons (Jayappa et al. 2003) although nourishment has been carried out at Thannirbhavi in January 2000 (Kumar and Jayappa 2009). Legal and illegal dredging and sand mining from beaches, estuaries and upstream rivers has resulted in sediment deficits in some locations (Jayappa et al. 2003) and a recent increase in sand mining has lead to accelerated erosion (Kumar and Jayappa 2009).

4. Data for the hazard assessment

The hazard assessment makes use of data that is available in the original CHW framework paper or that can be easily obtained from other sources. The only advanced tool used for the assessment is ESRSI's computer software, ArcGIS, which requires a license and some software-specific expertise. The complete list of data used for the assessment includes a geological map of Karnataka (Ravi Mundkur 2010), the wave, tide and storm maps included in the original CHW framework paper and published by Masselink and Hughes (2003), supplementary information on local tidal range (Nayak and Hanamgond 2010), the UNEP-WCMC World Atlas of Coral Reefs (Spalding et al. 2001), Google Earth satellite images with timeline and ground elevation functions (Google 2012), Bing Maps available in ESRI's ArcGIS (ESRI 2012; Microsoft 2012) and two sections of Rapideye satellite images covering some low resolution gaps in the Bing maps (GRAS 2012). The following sections describe how each of the coastal classification circles of the CHW has been determined based on the available data, and a thorough description of the different CHW classification categories can be found in Rosendahl Appelquist (2012).

4.1. Classification circle 1 – Geological layout

The geological layout is determined based on an ordinary geological map and Google Earth's satellite images and ground elevation function. The geological layout type is found by combining information from these three data sources and a new evaluation is made every time any of the parameters i.e. geological base material, geomorphology and coastal slope changes significantly.

For Karnataka, the determination of geological base material is relatively straightforward as the coastline is mainly composed of laterites. However, as the assessment is carried out remotely, it is not possible to assess the compaction and cementation level of the laterites in the field. In the practical classification, sloping laterite coastlines have been grouped into the sloping soft rock coast category, while flat laterites have been grouped into one of the flat coastal categories. In cases where the sloping laterites are heavily cemented, this may lead to an overestimation of the hazard levels as the coast would otherwise fall into the sloping hard rock coast category. Additional field verification of the laterite cementation would therefore be appropriate for implementing Step 2 and 3. Another challenge to the categorisation of geological layout is that smaller hard rock headlands are not visible on the geological map of Karnataka although they are visible on Google Earth's satellite images. In most cases, however, it is sufficient to rely on Google Earth as these structures are relative easily identified.

The slope of the coastline is determined using Google Earth's ruler and ground elevation functions. The elevation function is based on a digital elevation model from NASA's Shuttle Radar Topography Mission and its altitude resolution varies by country. Large parts of USA currently have a resolution of 10 meters but most other world regions including India have a lower resolution (Wikipedia 2012). When the ground elevation is assessed, the smoothing of the contours by the elevation model can be easily noticed, which may lead to some errors in flat areas adjacent to elevated regions. However, as the coastal classification system only requires input on whether the coast is sloping more or less than 3-4%, 200 meter inland of the MSL, the error is not expected to significantly affect the classification accuracy. Large sections of Karnataka's coastline are sloping to some degree and it is therefore necessary to be cautious when conducting the elevation assessment. The fact that several of the barriers along Karnataka's coastline have a slope of more than 3-4% also increases the need for a careful slope assessment.

The coastal morphology is determined based on a visual assessment of Google Earth's satellite images. Form elements presented as barriers, deltas, tidal inlets, sand spits and river mouths can be easily identified with a zoom level of 5-10 km. The remaining mainland coastline can be categorized based on geology and slope.

4.2. Classification circle 2 - The wave exposure

The wave climate is determined based on the wave maps in the original CHW paper (Rosendahl Appelquist 2012; Masselink and Hughes 2003). Since Karnataka is located outside the areas with swell/monsoon wave climates, the level of wave exposure is dependent on the free fetch and wind speeds. It was not possible to obtain detailed wind data for the region and it was therefore decided to rely solely on the free fetch to determine the exposure levels for this classification. As the wind is blowing from the open ocean during the SW monsoon season, the free fetch is likely to be an appropriate proxy for the possible wave heights. The assessment has used Google Earth to determine whether 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. Generally, the outer reaches of Karnataka's coastline are directly exposed to the waves of the Arabian Sea and categorized as exposed while the coastlines of the inner estuaries are classified as protected. As the coastline varies between estuaries and open coast, the moderately exposed category has generally not been applied.

4.3. Classification circle 3 - The tidal range

The tidal range is determined based on the tidal range maps included in the original CHW paper (Rosendahl Appelquist 2012; Masselink and Hughes 2003). However, as Karnataka is located close to the border between the micro- and meso-tidal types, supplementary data has been collected on the local tidal range. This data indicate that all of Karnataka generally stays within the micro-tidal category with tidal range increasing towards the northern part of the state (Nayak and Hanamgond 2010). It was therefore decided to apply this category for the coastal classification. Meso-tidal conditions may be present inside some of the estuaries due to the local coastal configuration but because of the limited data availability it is difficult to verify. However, the tidal range in these locations is still expected to stay close to the border between micro- and meso-tide. The micro-tide category is therefore applied consistently to the full coastline of Karnataka.

4.4. Classification circle 4 - The flora/fauna

The flora/fauna is determined based on a visual assessment of the coastline in Google Earth combined with information on its geographical location and global coral reef data. As Karnataka is situated in the tropical climate zone, flat protected coastlines such as coastal plains and barriers generally have some kind of mangrove vegetation in protected locations, but due to the relatively low tidal range, the mangrove areas are of intermittent character. Coral reefs are generally non-existent along Karnataka's coastline and it is uncertain whether past sporadic coral habitats still exists (Spalding et al. 2001). Therefore, the coral reef option has not been applied to any parts of the coastline.

4.5. Classification circle 5 - The sediment balance

The sediment balance evaluation uses remote sensing information from Google Earth's satellite images and timeline function to compare images of the coastline taken over the last decade. Generally, coastal stretches have been assumed to have a sediment balance/deficit unless it is very clear that they have a sediment surplus in order to avoid underestimating some of the hazard levels. For the exposed, littoral coastlines of Karnataka, it has to some degree been possible to get a reliable indication of the sediment balance using Google Earth's images from the last 5-10 years, as the changes in the vegetation line in most cases is clearly visible. For protected coastlines, however, it has been difficult to visually assess smaller temporal changes based on the satellite images and these coasts have therefore in many cases been placed in the balance/deficit category. In addition to the general challenge of estimating the sediment balance, Google Earth has some gaps in its timeline function meaning that some areas are only coved by one satellite image, making temporal assessments impossible. This is the case for the coastline at Kodi Bengare to Kemmannu; Kota; Marvanthe; and Ternamakki to Kasarkod and these coastlines have therefore been placed in the balance/deficit category. Sometimes only two images with a few years in between are available in Google Earth which also leads to uncertainty in the evaluations.

4.6. Classification circle 6 - The storm climate

The storm climate is determined based on the wave/storm maps included in the original CHW paper (Rosendahl Appelquist 2012; Masselink and Hughes 2003). As Karnataka is indicated to be under tropical storm influence, the complete coastline is classified to be located in a tropical cyclone area.

5. The GIS procedure

The coastal classification and hazard assessment procedure is carried out in ArcGIS based on a Hybrid Bing Map. As the resolution of the satellite images is generally better in Google Earth than in Bing Maps, is was considered to conduct the whole classification in Google Earth. However, due to the technical limitations of Google Earth, it was decided to conduct the classification in ArcGIS, using Google Earth as data source.

As a first stage a geodatabase is created in ArcGIS that will contain all coastal classification data as well as data on hazard levels. In order to have a relatively detailed and up-to-date digitized coastline of Karnataka which can be used for the coastal classification, a new line feature class is created in the geodatabase referencing the WGS1984 Web Mercator Auxiliary Sphere coordinate system. It should be noted that other coordinate systems may be more appropriate for other world locations. The line feature is then used for creating a digitized coastline of Karnataka by manually digitizing the coast at the approximate Mean Sea Level (MSL) with a zoom level of 2-4 km in the ArcGIS window. Because the satellite images are taken at different times during the tidal cycle, the line feature will most likely deviate from the actual MSL but this is considered of minor importance for the purpose of this assessment as it only requires a relatively accurate and up-to-date coastline. The digitizing is carried out with an accuracy of about 5-10 meters leaving gaps for river mouths and tidal inlets. Islands are digitized as separate units. This line feature then constitutes the foundation for the further coastal classification and the hazard maps.

To facilitate the assessment of the coastal slope and sediment balance, two supplementary line features are created in Google Earth. The line feature for facilitating the slope evaluation consists of a range of shore-parallel line sections that are drawn landwards of the coastline in all coastal areas with a slope greater than 3-4%. This enables the user to quickly determine whether a particular coastal area is sloping or not when carrying out the coastal classification. The slope of a particular coastal section is determined by manually placing the cursor over the first 200 meter landwards of the coastline in Google Earth, taking note of elevation levels given in the button of the Google Earth window. This procedure is carried out for every approximately 100-200 meters of coastline at a Google Earth zoom level of 2-4 km. The line feature for facilitating the sediment balance evaluation consists of a continuous line drawn on the approximate coastal vegetation line. When the coastal classification is carried out, the sediment balance can be assessed by comparing the satellite images taken at different times through Google Earth's timeline function, looking at how the coast has been developing compared to the digitized, most recent coastline. Since the satellite images are taken at different tide levels and time of the year, the beach width cannot be reliably used for determining the sediment balance, but the vegetation line is considered as a relatively good indicator for the general sediment balance.

The coastal classification based on the CHW is carried out on top of the digitized coastline by using a polygon feature created in the geodatabase with the same coordinate system as the line feature for the coastline. The polygons are used to split the original line feature into sections, each representing a different coastal environment defined in the CHW framework. The classification is done by manually drawing a separate polygon for each coastal classification category along the coastline, based on an evaluation of the classification parameters mentioned in the data section earlier. When drawing the polygons, it is important to enable a snapping environment to ensure that the polygons are snapped properly to each other. The name of the coastal environment in question is then typed into the attribute table for each polygon in the ID field. As the attribute table only accepts numbers, the coastal environments in the CHW framework are assigned values between 1 and 113, with 1 given to the CHW type CP-1. Because the classification of each coastal stretch is carried out based on the CHW and the listed input data, the user has to decide on an appropriate coastal type and its extension before each polygon is completed. Sometimes a coastline can maintain the same properties for longer distances, meaning that the length of a polygon can range from less than fifty meters to several kilometres.

The polygons are subsequently used to divide the initial digitized coastline into sections, each representing a specific coastal category. The hazard levels given in the CHW and further described in the original CHW paper (Rosendahl Appelquist 2012) 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 colour code. Finally, a background land polygon and a text layer with city names are created to improve the readability of the hazard maps and the relevant hazard statistics is extracted from the GIS.

6. Results

The results from the application of the CHW framework on the coastline of Karnataka are an overview table of the most common coastal types in Karnataka, an overview table of the prevalence of the different coastal hazards and a range of sub-regional and regional hazard maps. Table 1 below shows the top 10 most common costal types in Karnataka in distance as well as in percentage of the total coastline. In this assessment, the total length of Karnataka's coastline has been calculated to 647 km which is significant more than many estimates given in the literature. This is the case as the coastline in the assessment includes the open ocean coastline as well as back-barriers, estuaries and islands. From the table, it can be seen that the 10 most common coastal types make up over 90 percent of Karnataka's coastline. The most common types are the sloping soft rock coasts, SR-5 and SR-17, followed by the sloping hard rock coast HR-1. Special coastal elements such as tidal inlets, sand spits and river mouths are also relatively common, making up 13 percent of the total coastline. The flat coastal environments, coastal plain CP-13, delta DE-13 and barrier BA-13 are also quite widespread making up 9 percent, 8 percent and 3 percent respectively.

Coastal type	Length (km)	Percent of coastline
Sloping soft rock 5 (SR-5)	146	23
Sloping soft rock 17 (SR-17)	118	18
Hard rock 1 (HR-1)	100	16
Tidal inlet/Sand spit/River mouth (TSR)	84	13
Coastal plain 13 (CP-13)	58	9
Delta 13 (DE-13)	49	8
Barrier 13 (BA-13)	16	3
Coastal plain 1 (CP-1)	14	2
Delta 15 (DE-15)	13	2
Barrier 1 (BA-1)	12	2
	609	94

Table 1. The top 10 most common coastal types in Karnataka.

The hazard profile of the coastline of Karnataka is shown in Table 2. The table shows the distribution of the different hazards and hazard levels as a percentage of the total coastline's length. From the table it can be seen that erosion constitutes the most prevalent hazard type as 61 percent of Karnataka's coastline has a high or very high inherent hazard for erosion. The hazards of flooding and salt water intrusion are also relatively widespread as 39 percent of the coastline has a high or very high inherent hazard for both of these hazard types. 32 percent of the coastline has a high or very high inherent hazard of gradual inundation while 19 percent has a high or very high inherent hazard of ecosystem disruption.

Hazards/Hazard level	Low	Moderate	High	Very high
Ecosystem disruption	24	56	0	19
Gradual inundation	61	6	13	19
Salt water intrusion	61	0	25	14
Erosion	16	24	21	40
Flooding	61	0	0	39

Table 2. The distribution of hazard levels in percent for Karnataka's coastline.

Fig 2 shows the hazards of erosion and flooding for northern Karnataka and is an example of how the CHW framework can be used for sub-regional hazard mapping. The hazard class 1 is low inherent hazard, 2 is moderate inherent hazard, 3 is high inherent hazard and 4 is very high inherent hazard. The maps give a relatively good overview of areas that requires special attention and can provide a basis for sub-regional planning and management decisions.

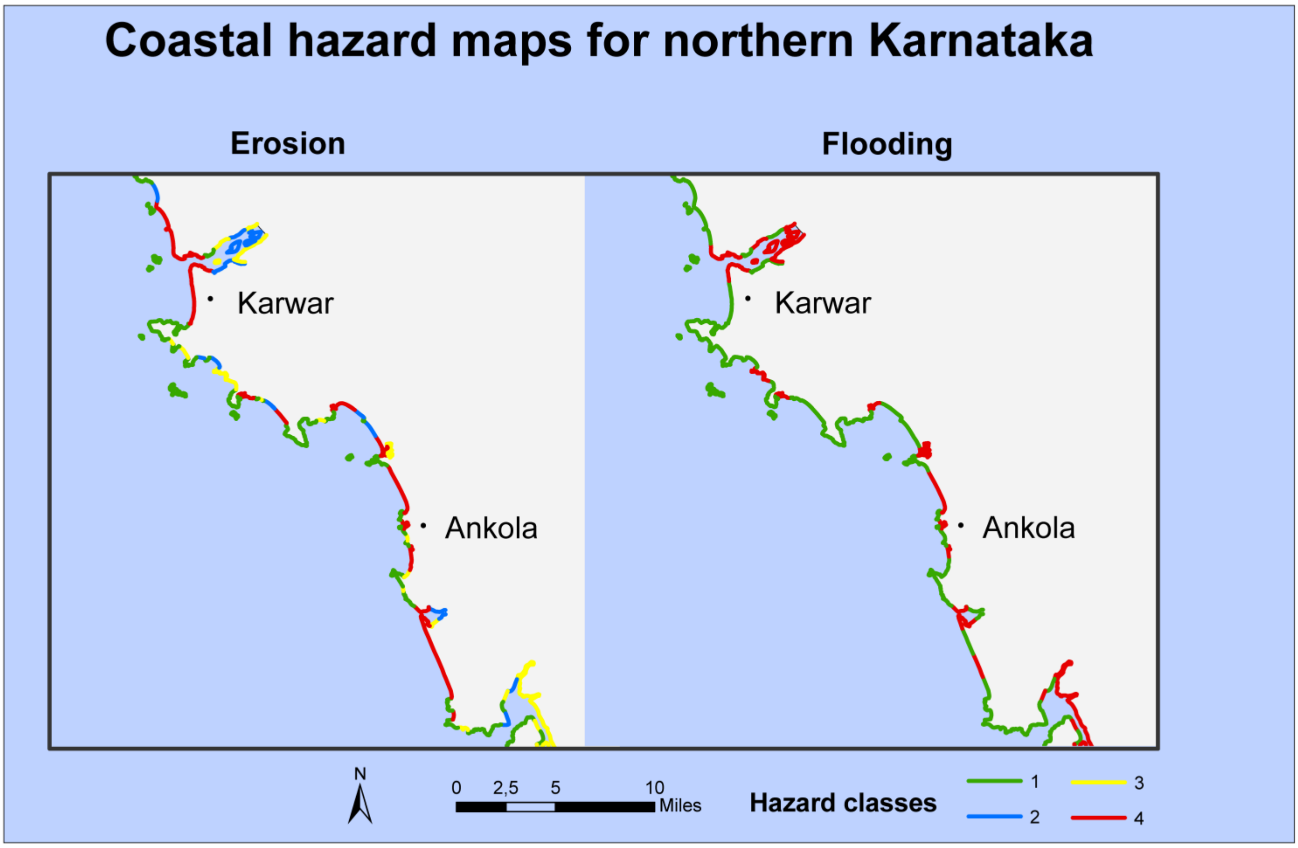


Fig 2. Coastal hazard maps for northern Karnataka.

Fig 3 shows a range of overview hazard maps for the state of Karnataka and includes the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. The hazard classes are the same as for Fig 2. Generally, the maps are not as applicable for planning and management purposes as the ones shown in Fig 2 but gives a general overview of the hazard presence along the coastline of Karnataka and can be used for identifying hazard hotspots. For the inherent hazard of ecosystem disruption, it can be seen that the outer coastline of Karnataka generally has a low or moderate hazard level, while the very high hazard levels are found in relation to the estuaries. The same pattern can be seen for gradual inundation and salt water intrusion, while large sections of Karnataka's outer coastline has a high or very high hazard level for erosion. The high and very high flooding hazards can especially be found in association with the estuaries and some of the exposed coastal plains.

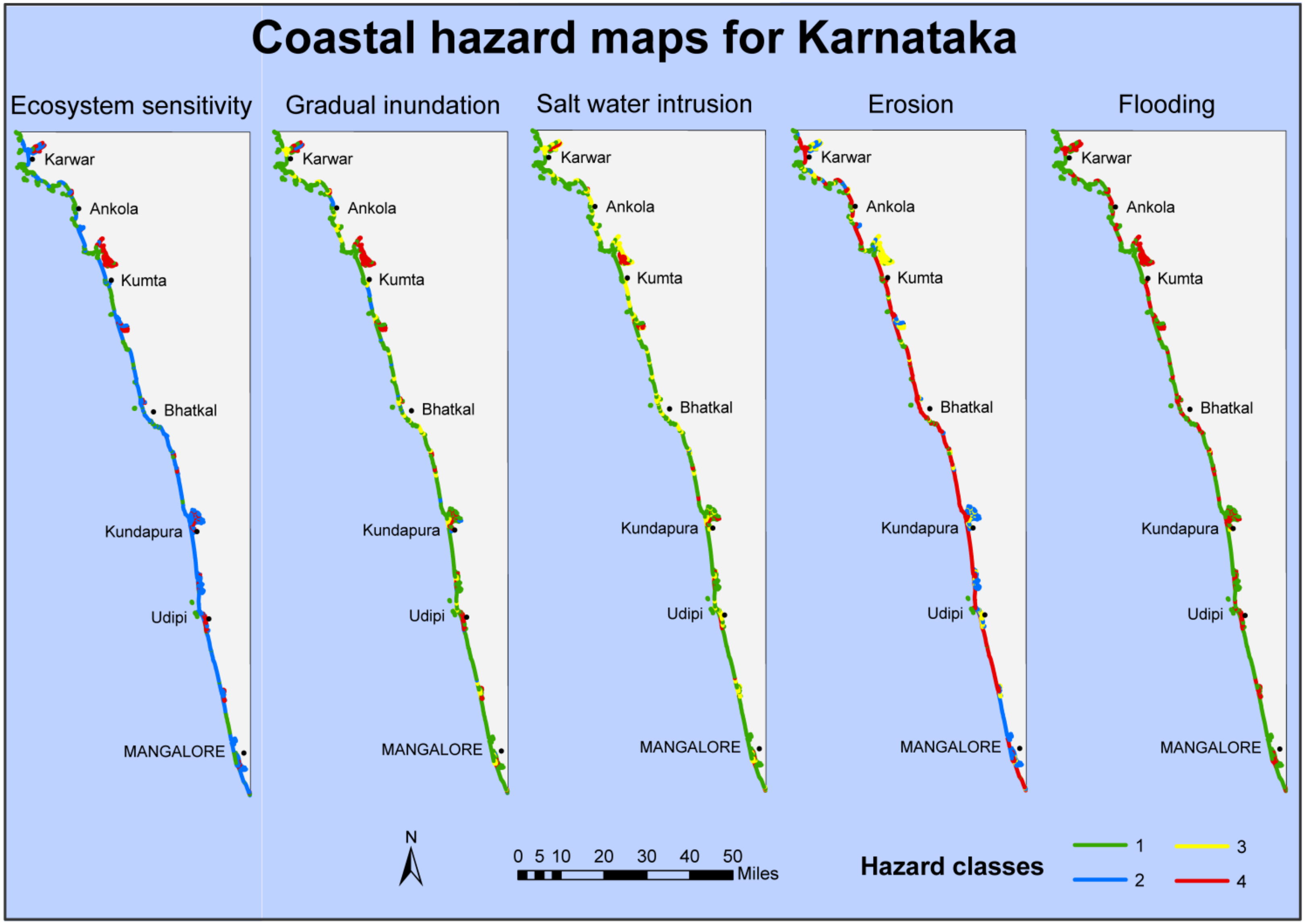


Fig 3. Overview maps of coastal hazards for Karnataka.

7. Uncertainties and limitations

The hazard assessment is carried out at sub-regional and regional scale, meaning that the hazard maps are not intended to guide local development activities but rather to assist regional planners and decision-makers in getting an overview of the hazard profile of the coastline and to indentify hazard hotspots. Whereas the maps covering the whole Karnataka are good for providing an overall picture, the more detailed maps are more appropriate for sub-regional planning purposes. Since the assessment is based on published geophysical data and remote sensing information, several uncertainties exist that should be addressed by field verification if a more detailed assessment is needed. However, as a Step 1 assessment, it is considered to provide a reasonably reliable overview of the hazard presence and the location of hazard hotspots.

An important uncertainty that could be addressed by field verification relates to the geological layout and especially the compaction and cementation level of the coastal sediment. The coastal stretches composed of laterites could be compacted and cemented to various degrees and a particular coastal stretch could therefore fall into the sloping soft rock or sloping hard rock categories depending in their cementation level. This could change for different sections of the coastline and a random field assessment of the compaction/cementation levels of the sloping laterite coastlines could therefore provide an indication of the prevalence of the different conditions. The assumption that all sloping laterite coastlines fall into the sloping soft rock category is considered reasonable as most laterites becomes relativity soft if they are made wet. However, this may overestimate the hazard levels at locations where the laterites are heavily cemented. The relatively low resolution of the geological map of Karnataka also means that it is necessary to rely on the satellite images to identify smaller sloping hard rock features such as headlands. Additional field assessments could have been useful for verifying this, although the resolution of the Google Earth images is generally sufficient to identify these structures with a relatively high accuracy.

The flora/fauna category is also associated with some classification uncertainty that could be addressed with field verification as it is almost impossible to evaluate the percentage of vegetation cover on sloping soft rock coastlines based on the satellite images available in Google Earth and Bing Maps. Because of Karnataka's favourable climatic conditions for full year vegetation growth, it is assumed that all sloping soft rock coasts are vegetated unless clear counter-indications are present. As this parameter only has a minor effect on the hazard levels of ecosystem disruption and erosion, it is considered to be an acceptable uncertainty at this step in the hazard assessment but for implementing Step 2 or 3, additional investigation would be needed.

The satellite images used for the assessment constitute another source of possible uncertainty. In areas where the resolution of Google Earth and Bing Maps images are so low that it complicates detailed assessment of the coastline, some uncertainties are related to the coastline configuration. More problematic, however, is the fact that some locations are only coved by a single satellite image in Google Earth's timeline function or only have two images with a few years in between. In the first case, temporal assessment of the sediment balance is impossible while in the second, it is associated with significant uncertainties. This problem may be addressed for most world locations in the coming years as

Google Earth continuously adds new satellite images, but for this test-assessment it constitutes a significant source of error. Furthermore, the sediment balance of protected coastal stretches is difficult to assess visually with the current resolution of the satellite images, but this may also improve in the coming years. To avoid underestimating the hazard levels, this assessment generally assumes that a coastal stretch has a sediment balance/deficit, unless it is very clear that it has a sediment surplus.

Since Google Earth and Bing Maps are comprised of a range of different images taken at different times of the day and year, one also compares images taken during different points in the tidal and sedimentary cycles. With the annual erosion/accumulation cycles of large parts of Karnataka's coastline mentioned earlier and a tidal range close to two meters, this comparison can be problematic. The possible error arising from this is partly addressed in the classification by using the vegetation line as reference when evaluating temporal developments, but it still adds some noise to the assessment. Ideally, the sediment balance should be based on satellite images captured over several years, at the same time of the year and at the same point in a tidal cycle. The current approach, however, is expected to provide acceptable results given the resolution and purpose of the assessment. If more detailed information is needed for planning purposes, aerial photos, field assessments and interviews could improve the reference data.

The human alteration of Karnataka's coastline constitutes another source of uncertainty. Coastal protection work has been carried out along Karnataka's coastline in the past decades, impacting the natural dynamics. At sub-regional and regional scale, however, these activities are not likely to have a major effect on the hazard profiles, as they are relatively locally focused and mainly based on hard engineering approaches. Legal and illegal sand mining from the beaches, however, could have some impact on the sediment balance evaluations, but the effect is unlikely to significantly affect the hazard assessment at this step. However, an implementation of Step 2 or 3 would require a further investigation of the scale and geographical focus of these activities. Heavily modified or artificial urban coastlines such as those of the city of Mangalore are likely to be surrounded by some errors in the CHW framework, since the framework only gives information on the natural inherent hazards of the coastline before it was turned into an artificial coast. But apart from this urban coastline, human alteration of Karnataka's coast is not expected to cause significant problems for the assessment at this step.

Some limitations are associated with the design of the CHW framework itself. The CHW defines a special category for tidal inlets/sand spits/river mouths as these generally are very dynamic environments with high hazard levels. However, a few tidal inlets in Karnataka have a headland next to the inlet, meaning that the hazard levels are significantly lower than for the tidal inlets defined in the CHW framework. As the hazard levels of these inlets are more in line with that of the sloping hard rock coast category, this category has been applied to these inlets, although it does not adhere to the CHW principles. Also, some of Karnataka's river mouths are so small that they could rather be considered a stream than a river mouth. The guidance given in the CHW framework to apply the river mouth category to the coastline 1 km on each side of the river mouth is therefore regarded as inappropriate. In this assessment, the river mouth category is therefore only extended 0.5 km on each side of the river if it is of stream-size.

The process of carrying out the practical classification process and drawing the polygons is also surrounded by some uncertainty as it based on a manual evaluation of the coastal data. Since the evaluation procedure for the different classification parameters are well defined in the original CHW paper (Rosendahl Appelquist 2012) and in this paper, the assessment method is not expected to lead to significant greater uncertainty than an automated assessment as that would still be based on some predefined evaluation procedures. However, the manual approach means that two parallel studies of the same area would be likely to come up with slightly different assessment results. As the CHW framework is designed as a screening tool that can be applied in developing countries and data-poor locations, it tries to strike a balance between simplicity, low-tech design, data requirements and accuracy. The magnitude of the uncertainty related to this manual procedure is therefore regarded as acceptable given the detail and purpose of the assessment but it is important to keep this uncertainty and possible source of error in mind when using the CHW framework for practical assessments.

8. Regional planning and management perspectives

The process outlined in the previous sections is intended to showcase a procedure for applying the CHW for regional hazard assessments. The hazard maps developed for Karnataka can be used for identifying hazard hotspots, getting an overview of the hazard profile of the coastline and detecting areas where human activities may be at risk from future coastal dynamics. As broader coastal hazard assessments are generally non-existent for most developing countries, the methodology provides a possibility for planners and managers to increase their knowledge base in areas with limited data availability. Likewise, it offers a simple system for initial hazard screening in areas where data is readily available.

The hazards covered in the assessment framework are of very different character and hence have very different consequences for human activities. Ecosystem disruption, gradual inundation, salt water intrusion and to some degree erosion is likely to occur gradually and worsen with climate change. Flooding, on the other hand, is an abrupt and potentially disastrous event that will become more likely with rising sea level and increasing precipitation intensity and storm activity. The different hazards are to some degree related to each others, but only a few coastlines have high inherent hazard levels for all hazard types. Coastal planners and managers therefore need to address the specific hazard combination for each coastal stretch in question.

For the state of Karnataka, all hazard types are present but apply to different stretches of the coastline. The hazard of ecosystem disruption is especially related to the mangrove areas in the extensive protected estuary and back-barrier coasts and in the short term, it will probably not be possible to distinguish the climate change hazards to these ecosystems from the major current drivers of change such as overfishing and clearing of mangroves for aquaculture. In the longer term, however, climate change is likely to pose an additional risk to these systems due to especially sea level rise. Enhancing their resilience at this point should therefore be a priority and is likely to be economically viable as these environments provide valuable services such as flood protection and breeding ground for marine fisheries (Millennium Ecosystem Assessment, 2005).

The hazard of gradual inundation is mainly related to the low-lying protected estuary coasts and the coastal barriers of Karnataka. Barriers with a sediment deficit are already at significant risk and people in these areas may face losing their land permanently to the sea, if no countermeasures are taken. Simple dikes could protect the areas to some degree, but on a longer term, a managed retreat or extensive dike systems may be necessary. If dikes are constructed, however, they should always be of a decent quality to avoid giving people a false sense of security of flood protection.

Salt water intrusion is especially a hazard to Karnataka's coastal plains and barriers. The magnitude of this hazard may increase due to human extraction of groundwater and hence it is essential to monitor the ground water reservoirs and water extraction to avoid that salt water is replacing the current freshwater resources. Simple water balance calculations can be carried out for the barriers to see if the current water extraction practices are sustainable, but gradual inundation and flooding events can completely eliminate the groundwater reservoirs in these locations. In that case, other long-term options for freshwater supply should be investigated and a managed retreat from some of the barriers may be considered.

Erosion is a major general hazard to Karnataka's coastline and many areas are already suffering from the effects of this. Although the state only has limited experience with beach nourishment, possible nourishment schemes combined with groins or breakwaters may be a viable hazard mitigation option for densely populated sections of the coastline. The challenge in this regard is likely to be offshore sand availability, as large quantities of sediment may be needed. Since the cost of sand can vary tenfold depending on dredging conditions and sediment transport distance, it can be a costly management option if sediment is not readily available. A purely hard-engineering strategy may be less costly, but will destroy the natural dynamics of the coastline and the associated natural services, and for coastal stretches used for recreational activities this may not be a viable option. A managed retreat may be relevant for areas experiencing extensive erosion, but with a densely populated coastline, some kind of hold-the line strategy is likely to be necessary in most locations.

Flooding constitutes a serious hazard for the low estuary islands, barriers and coastal plains of Karnataka, and should be addressed properly due to its potential disastrous consequences. Flood warning systems and flood shelters could provide economically viable solutions in the short term, but as repeated floods can disrupt agricultural production, freshwater supply and infrastructure, some kind of dike system may be necessary as a long term solution. As most hazard mitigation options have effects on other hazards than the ones they are primarily designed to address, it is important to consider the possible effect of a given management option on all hazard types. Dikes and hard engineering measures are good at mitigating hazards of flooding and erosion, but often increase the hazards of ecosystem disruption as they disrupt the natural coastal dynamics. For each section of the coastline, it is therefore necessary to consider which hazards are the most important to mitigate and what consequences different mitigation strategies have on all hazards. Because flooding can have dramatic consequences on human activities and be potentially life threatening, mitigating this hazard may in many cases be given higher priority than other hazards such as ecosystem disruption. Hence coastal planner should not only look at which hazards are scoring highest in the CHW framework but also consider which hazards are most problematic to the human activities taking place in a particular coastal area.

A key parameter for deciding on appropriate mitigation strategies is therefore the human activities taking place in a coastal area. Measures of this could be population density, presence of important infrastructure, cultural heritage and various economic activities. As many countries have GIS data on economic activities and global population density data is publicly available (SEDAC 2013) this information can be added to the GIS used for the coastal hazard assessment to identify areas with specific combinations of coastal hazards and human activities. In this way, the CHW framework can be used to identify areas with e.g. high flooding hazards and high population density. Combing the hazard maps with socioeconomic data could thereby provide a good base for supporting coastal management decisions.

9. Conclusion

The CHW framework has been very suitable for carrying out sub-regional and regional hazard assessments at the scale of the state of Karnataka. It has been possible to conduct the hazard assessment based on easily obtainable data and the assessment procedure outlined in this paper should be replicable in most other areas of the world yielding results of similar quality. The assessment is associated with some uncertainties as it relies solely on published geophysical data and interpretations of remote sensing information, but the uncertainties are considered acceptable given the resolution and goal of the assessment. For more detailed hazard assessments at Step 2 and 3, additional field verification is recommended to improve the assessment accuracy and reliability seen from a decision support perspective. Attempts have been made to keep the assessment procedure relatively simple, with a manual application of the coastal classification in the GIS. This makes the coastal classification process relatively straightforward but at the same time increases the possibilities for human misjudgements due to the subjectivity of the procedure. Users should therefore be aware of these risks when using the CHW framework and the assessment procedure outlined in this paper. Supplementing the physical CHW assessment with socioeconomic data may in many cases be relevant to improve the information base for coastal planners and managers. This would provide CHW users with a combined picture of physical hazards and societal activities which could be relevant for supporting long-term planning decisions.

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Paper 3

Application of a new methodology for coastal multi-hazard assessment & management on 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.

Keywords: Coastal climate change; hazard assessment; coastal management; Djibouti

1. Introduction

The projected climate change will alter the environmental conditions along most of the world's coastlines and thereby the livelihoods of the local coastal populations. According to the IPCC, the utilization of the coast has increased dramatically during the 20^{th} century and this trend will continue during the 21^{st} 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. The goal of this paper is twofold, namely to showcase the practical procedure for applying the Coastal Hazard Wheel (CHW) methodology for national hazard assessments and to provide relevant information on coastal hazards and management options for the coastline of Djibouti.

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 due to deteriorating climatic conditions further inland, the need for a robust decision-base for coastal planning becomes even more important.

The newly developed assessment methodology, the Coastal Hazard Wheel, is used to carry out a multi-hazard assessment for the full coastline of Djibouti. The CHW is designed for assessing coastal climate change hazards without the need for extensive geophysical data collection and local climate change information, and makes use of publicly available geo-data and remote sensing information (Rosendahl Appelquist, 2012). The system can be used for identifying hotspot locations, for developing sub-regional, regional and national hazard maps and for obtaining relevant hazard statistics. The assessment covers the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding, and a series of hazard maps are developed for these five hazard types. The assessment methodology can be applied at three different steps depending on the specific requirements for assessment detail and accuracy, namely:

- Step 1 that is designed for sub-regional to national hazard assessments where data availability and accuracy requirements are moderate. This step can generally be implemented based on remote sensing and publicly available data and is useful for hazard screening of larger areas.
- Step 2 that is designed for sub-regional to national hazard assessments that require a high accuracy and this step generally requires additional field verification of the data obtained though remotely sensing and public data sources.
- Step 3 that is designed for hazard assessments that require a high and locally focused accuracy and this step requires systematic and detailed field assessments at local level.

As this 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 high 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.

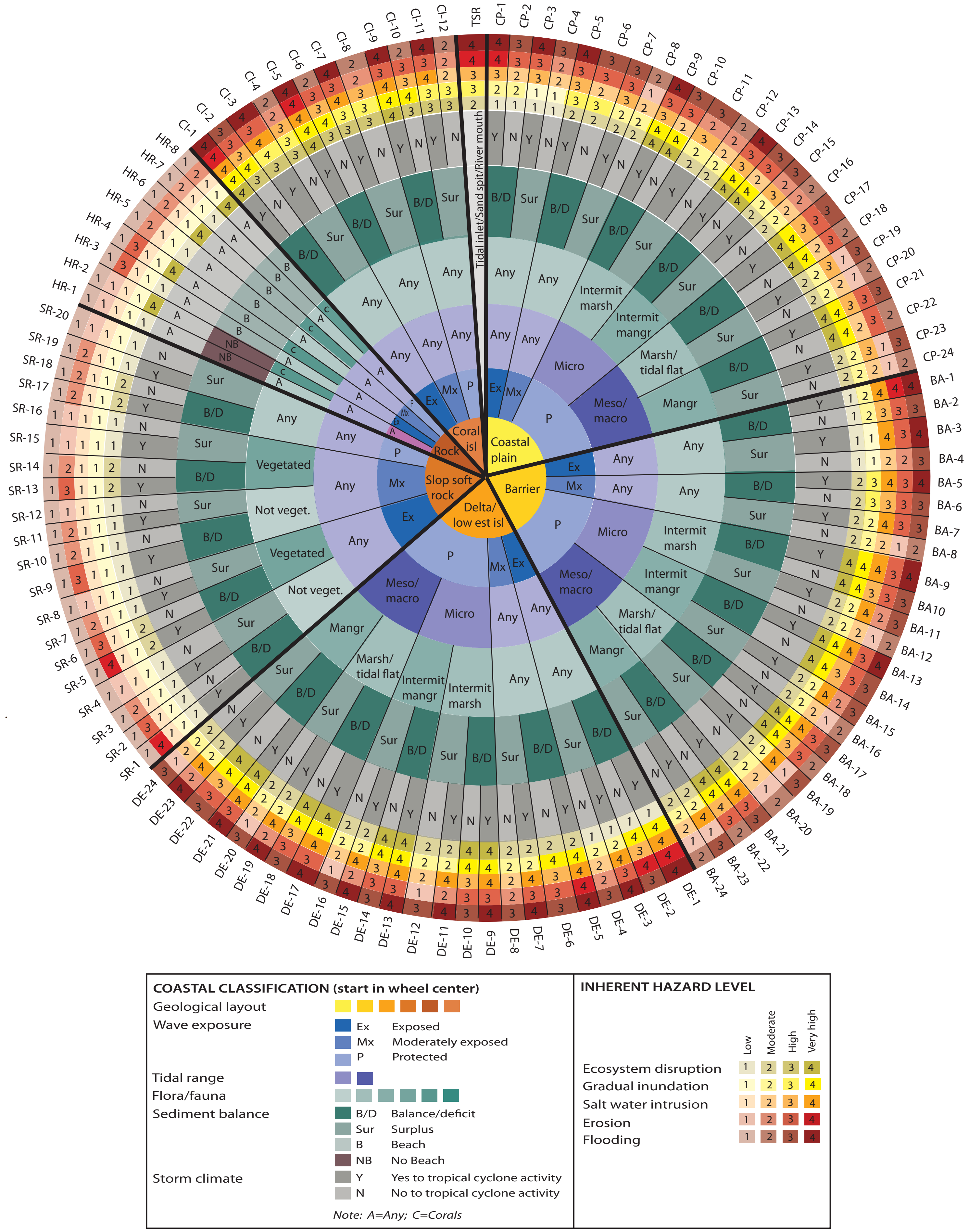
2. The Coastal Hazard Wheel (CHW) framework

The Coastal Hazard Wheel (CHW) framework is a hazard assessment and management methodology that can be used in areas with limited geophysical data availability. The framework is based on a specially designed coastal classification system that incorporates the main bio-geophysical 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 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 by visually assessing the coastal appearance either in the field or through remote sensing, combined with evaluating data for the individual dynamic parameters. 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 assessment methodology, assumptions and limitations can be found in Rosendahl Appelquist (2012).

Fig 1. The Coastal Hazard Wheel (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.

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

Table 1. The extended list of rocky coastal categories.

3. 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 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 (Schluter, 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 (Schluter, 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.

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°C-30°C and increased humidity, the hot season has temperatures of 30°C-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 mm 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. 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).

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 meter, while the Gulf of Aden generally has a mixed tidal regime with a tidal range exceeding 2 meters (Jarosz and Murray, 2002). In the Ghoubet Bay, the tidal range is about 2 meters 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-exploration 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.

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°C -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°C-2.4°C by 2050, while the sea level is expected to rise between 8 cm 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).

4. 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.

4.1 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.

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.

4.2 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. 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.

4.3 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. 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.

4.4 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).

4.5 The sediment balance

The sediment balance evaluation is carried out for all sedimentary coastal stretches based on Google Earth's temporal 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.

4.6 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.

5. The GIS procedure

The hazard assessment is carried out in ArcGIS, following the same procedure as the initial application of the CHW system in India (Rosendahl Appelquist and Balstrøm, 2013). Although the assessment makes use of the general functions available in ArcGIS, it uses the temporal satellite images and digital elevation model available in Google Earth as secondary data sources. As a first step, a geodatabase is created in ArcGIS that will contain all data on the coastal classification and subsequent hazard levels. To have a relatively detailed and up-to-date digitized coastline of Djibouti which 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 approximate Mean Sea Level (MSL), leaving gaps for river mouths and tidal inlets. The accuracy of the digitization is approximately 5-10 meters, and the final coastline is used as foundation for all the subsequent hazard maps.

To support the assessment of the coastal slope and sediment balance, two supplementary line features are created in Google Earth. The line feature supporting 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%. In this way, the user can easily determine whether a specific coastal area is sloping or not when carrying out the assessment. The line feature for supporting the sediment balance 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 satellite images captured at different times, 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/transgression/regression. Yet, it is still considered an acceptable proxy for the coastal sediment balance given that no detailed coastal survey is available.

The coastal classification is carried out on top of the digitized coastline of Djibouti, using a polygon feature created in the geodatabase using the same coordinate system as the line feature for 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 attribute table only accepts numbers, the different coastal types have been assigned a number, which in the case of this assessment spans from 1-131 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 meters, and 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 colour 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.

6. 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, relevant for supporting coastal management decisions and climate change adaptation initiatives.

The national hazard map for ecosystem disruption is shown in Fig. 2, 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, 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 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.

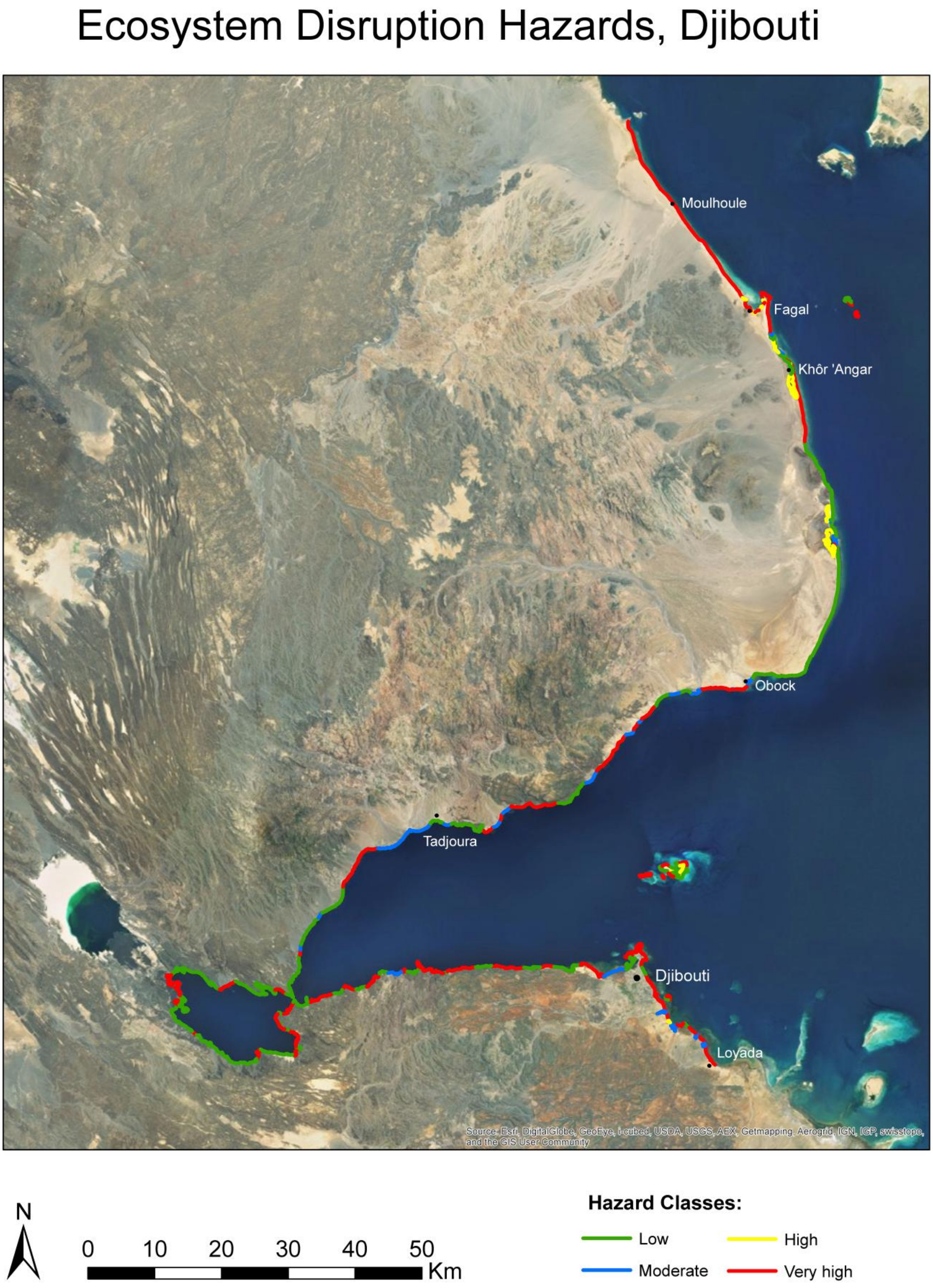


Fig 2. National hazard map for ecosystem disruption

The national hazard map for gradual inundation is shown in Fig. 3 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 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 3. National hazard map for gradual inundation

The national hazard map for salt water intrusion is shown in Fig. 4. 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.

Fig 4. National hazard map for salt water intrusion

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 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. 5 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 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.

Fig 5. National hazard map for erosion

The national hazard map for flooding is shown in Fig. 6 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.

Fig 6. National hazard map for flooding

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.

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

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

7. 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 button 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 be 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 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.

8. 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. As 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 of 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. Besides from the ethical aspects of preserving biological diversity, ecosystems are also important for maintaining important 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 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 systems have until now mainly been used in developed countries and practical approaches have to be designed so that 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.

9. 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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Paper 4

The Coastal Hazard Wheel system for coastal multi-hazard assessment & management in a changing climate

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Abstract

This paper presents the complete Coastal Hazard Wheel (CHW) system, developed for multi-hazard-assessment and multi-hazard-management of coastal areas worldwide under a changing climate. The system is designed as a low-tech tool that can be used in areas with limited data availability and institutional capacity and is therefore especially suited for applications in developing countries. The CHW constitutes a key for determining the characteristics of a particular coastline, its hazard profile and possible management options, and the system can be used for local, regional and national hazard screening and management. The system is developed to assess the main coastal hazards in a single process and covers the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. The system was initially presented in 2012 and based on a range of test-applications and feedback from coastal experts, the system has been further refined and developed into a complete hazard management tool. This paper therefore covers the coastal classification system used by the CHW, a standardized assessment procedure for implementation of multi-hazard-assessments, technical guidance on hazard management options and project cost examples. The paper thereby aims at providing an introduction to the use of the CHW system for assessing and managing coastal hazards.

Keywords: Coastal climate change; hazard assessment; coastal management; Coastal Hazard Wheel

1. Introduction

This paper presents the Coastal Hazard Wheel (CHW) system that is a tool for combined multi-hazard-assessment and multi-hazard-management of coastal areas worldwide under a changing climate. The system is developed to address a gap in the current methodologies for coastal hazard assessment and management which generally have high requirements for input data and domain expertise (Ramieri et al. 2011). The system is therefore especially suited for coastal hazard management in developing countries, where data availability and institutional capacity is limited. The system can be used for multi-hazard-assessment and multi-hazard-management at local, regional and national level and covers the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. It is based on a specially designed coastal classification system that includes 131 different generic coastal environments and a total of 655 individual hazard evaluations, each graduated into four different hazard levels. The initial version of the system was presented in 2012 in the Journal of Coastal Conservation and based on multi-hazard-assessments for the Indian state of Karnataka and the African state Djibouti, many spot assessments in locations worldwide and feedback from coastal experts, the system has been refined to a CHW 2.0 version and a standardized application procedure has been developed. This paper therefore presents the refined coastal classification system used in the CHW 2.0, the standardized assessment procedure for implementation of multi-hazard-assessments, guidance on hazard management options for the different coastal environments and cost examples for the management options. As the paper is meant as an overview article, it builds on the previous work on the CHW system and earlier references. The paper should therefore provide an introduction to the main principles and applications of the CHW system, and interested readers are referred to the related papers for a more detailed description of the theoretical basis, practical application, uncertainties and limitations (Rosendahl Appelquist, 2012; Rosendahl Appelquist and Balstrøm, 2013a; Rosendahl Appelquist and Balstrøm, 2013b).

2. The coastal classification system

The coastal classification system constitutes the foundation for the CHW methodology. It is developed particularly for decision-support but includes many components of previously published coastal classification systems. The following sections outline the revised classification system used by the CHW 2.0 and the content is based on the original description published in Rosendahl Appelquist (2012).

The coastal classification system is based on the bio-geophysical components that are considered most important for the characteristics of a particular generic coastal environment. The components included are geological layout, wave exposure, tidal range, flora/fauna, sediment balance and storm climate, and each generic coastal environment has a specific combination of these variables. As 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 generic coastal environment should be considered to extend longshore until any variables included in the system changes significantly.

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. Variables such as local isostatic uplift/subsidence and sediment grain size have not been included as these to some extent are indirectly covered through other parameters. This is to achieve an appropriate balance between classification simplicity and correctly reflecting natural conditions. The different classification components have been clearly defined in order to differentiate the generic coastal environments and to make the classification system practical applicable. The definitions and assumptions for the different classification components are outlined below.

2.1. Geological layout

The geological layout constitutes the basis on which the dynamic processes act. It 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 2.0 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 such as the Atlantic coast of North- and South America whereas the *sloping hard rock coast*, is commonly found on leading edge coastlines such as the Pacific coast of North and South America. The *flat hard rock coast* can appear in various settings e.g. 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 specially dynamic geologic environments.

The *sedimentary plain* category is defined as coasts with average slopes of less than 3-4% at least 200 meter inland of the MSL, and which are composed of sedimentary deposits such as clay, silt, sand, gravel, till or larger cobbles. If coastal dunes are present, the slope may locally be higher than 3-4% where the backbeach meets the dunes, 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 (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 kind of marsh or mangrove vegetation, depending on climatic conditions and tidal range. In meso- 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 the barrier. This would e.g. be the case where a *sedimentary plain* or *sloping soft rock coast* is located landwards of a *barrier*.

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, where large drainage basins provide a high fluvial discharge, and wide continental shelves provide a relatively shallow depositional area (Schwartz 2005). 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 significant sediment accumulation.

The *sloping soft rock coast* category is defined as coasts comprised of soft rock material with average slopes greater than 3-4% at least 200 meter inland of the MSL. Coastal cliffs with a steep cliff gradient combined with shore platforms or a landscape flattening landwards of the steep cliff also fall into this category. *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. 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, the simplest way to determine whether a coast consists of soft rock material is by using a basic geologic map. *Sloping soft rock coasts* can exist as both coastal cliffs and gently sloping vegetated hills.

The *flat hard rock coast* category is defined as coasts consisting of igneous, sedimentary and metamorphic rock with average slopes of less than 3-4% at least 200 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.

The *sloping hard rock coast* category is defined as coasts consisting of igneous, sedimentary or metamorphic rock with average slopes greater than 3-4% at least 200 meter inland of the MSL.

Sloping hard rock coasts can be present in different forms such as coastal mountain chains, headlands and archipelagos.

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. 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 result of to 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 inlet side consists of a hard rock headland, the inlet side should fall into one of the hard rock categories of the CHW classification system. *Sand spits* are 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 tidal inlet or river mouth.

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).

For most coastal systems, gravity waves generated by wind stress on the ocean surface are the main source of energy. 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 after the wind stops and where 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). 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 relatively high energy intensity compared to protected coasts (Thieler et al. 2000).

The coastal classification system distinguishes between *exposed*, *moderately exposed* and *protected* coastlines. The distinction between these categories is based on the significant wave height, H_S, that represents the average wave height of the one-third highest waves in a wave record and corresponds well to the visual wave height estimates (Masselink and Hughes 2003). To ensure consistency, the classification system uses the H_S 12h/yr, which is the nearshore significant wave height exceeded for 12 hours per year (Mangor 2004).

The wave exposure level is determined based on the coastline geography and wind climate. All coastlines located in areas with swell waves are in the classification system defined as *moderately exposed* (Mangor 2004). These coastlines can be indentified based on Fig 1, where coasts falling into "West coast swell", "East coast swell" and "Trade/monsoon influences" are categorized as *moderately exposed* coastlines.

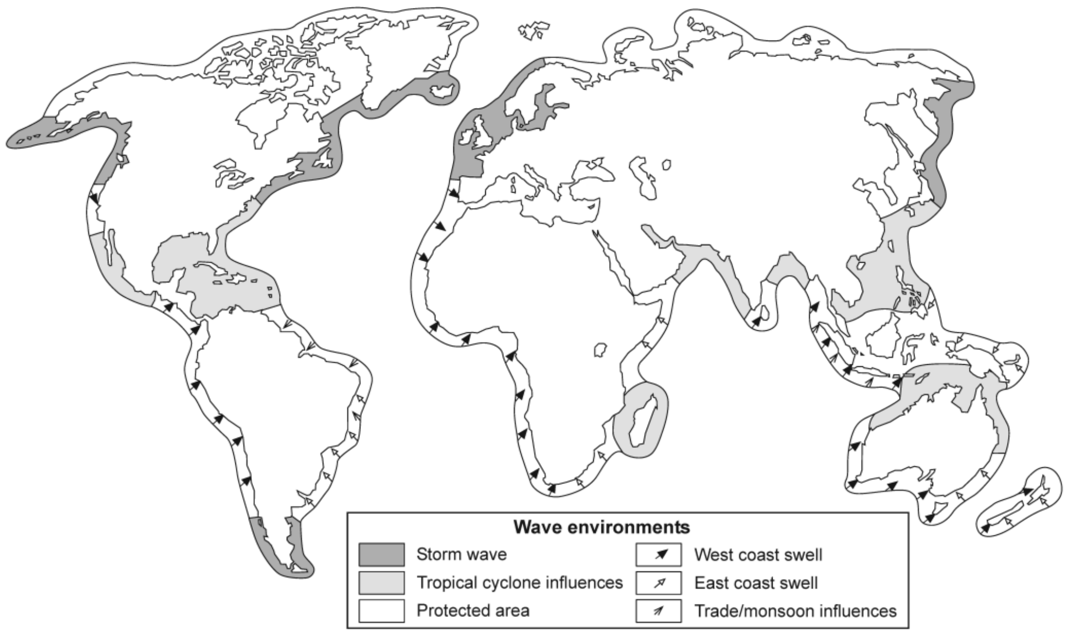


Fig 1. Global wave climates (Davies 1980, modified by Masselink and Hughes 2003).

If the coastline is located outside the swell regions, the wave exposure should ideally be determined based on the S-B-M method. This method uses a nomogram to predict H_S by input of wind speed, wind duration and fetch length and the nomogram is included in the paper for the CHW 1.0 (Rosendahl Appelquist 2012; Coastal Engineering Research Center 1984). If the H_S 12h/yr is determined as more than *3* meters, the coast is considered *exposed*, while it is considered *moderately exposed* with an H_S 12h/yr of 1-3 meter. If the H_S 12h/yr is determined as less than 1 meter, the coast is considered to be *protected*.

Since it in many cases can be difficult to obtain the necessary wind data to apply the S-B-M method, the free fetch can be used to roughly estimate the exposure levels of non-swell coastlines. This is therefore the standard methodology applied in the CHW system. Coasts can be considered *exposed* if they border waterbodies larger than 100 kilometres, while they can be considered *moderately exposed* if they are associated with waterbodies of the size of approximately 10-100 kilometres. *Protected* coasts are generally restricted to inner waterbodies in the order of less than 10 kilometres, but can also be seen along larger waterbodies with shallow nearshore zones or mild on-shore wind climates (Mangor 2004). When estimating the exposure levels, it is therefore important to be aware of physical conditions such as coastal reefs, tidal flats or wind conditions that cause the coast to fall into the *protected* category even when the water body is larger than 10 kilometres. Ice affected coastlines may have seasonal fluctuating wave exposures due to presence of winter sea ice. As sea ice is expected to be highly vulnerable to climate change, however, the same approach as for ice free coasts should be applied. Only in locations where the sea ice is expected to be very stable, the fetch length has to take into account the ice cover.

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, the tidal range influences coastal processes in many ways and is controlling 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, the local bathymetry, the width of the continental shelf and the coastal configuration (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). 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 eastern 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 which is the case along 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 2.

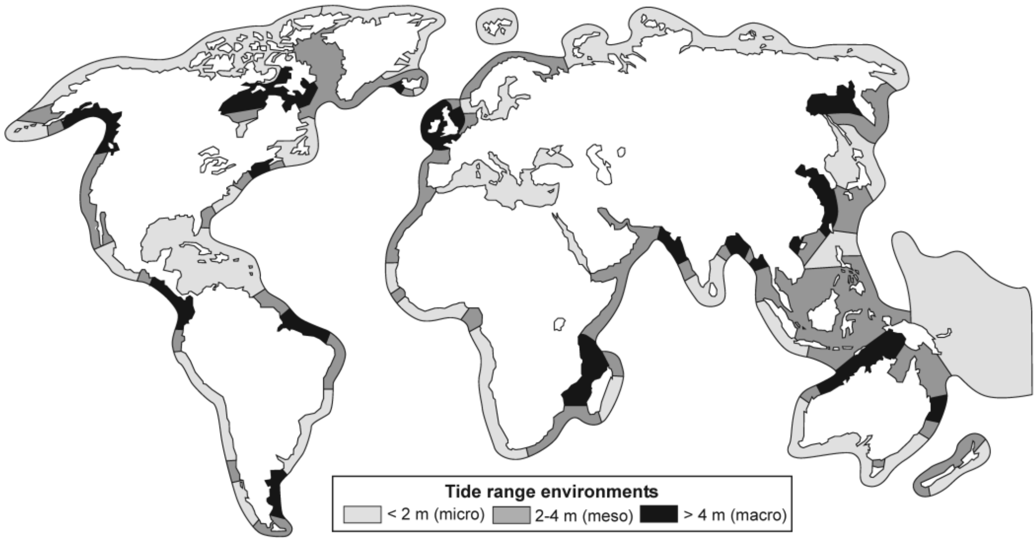


Fig 2. Map over global variation in tidal range (Davies 1980, modified by Masselink and Hughes 2003).

The effect of tidal range on coastal morphodynamics is largely influenced by the local wave conditions. 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. This may lead to some inaccuracies in the hazard assessment of coastlines with a very large tidal range but is considered a reasonable simplification taking the impacts of other classification parameters into account. 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 major implications for a reliable hazard evaluation, except under extreme high tidal range conditions. Since the effect of tidal range on the inherent hazards 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.

2.4. Flora/fauna

For some coastal environments, the local flora/fauna constitutes an important parameter for their morphodynamics and inherent climate change hazards. In the classification system, the flora/fauna has been included where it is considered to play an important role for the characteristics and inherent hazard profile of a coastal environment. 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*; *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*.

The *intermittent mangrove* and *mangrove* 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 providing 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* category is applied to areas with *meso/macro-tides,* as they colonise the tidal flats. The combined *marsh/mangrove* category is applied to *protected, flat hard rock coasts* that have a narrow band of marsh/mangrove vegetation.

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. The *vegetated* category is applied when more than 25% of the slope is covered with vegetation while the *not vegetated* category is used when less than 25% 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 seen 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 an inherent hazard 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 applied to *flat hard rock coasts* and *sloping hard coasts* where the corals have a firm 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. Since coral reefs often are backed by carbonate beaches and not bare rock, the special beach category available in the classification system for *flat hard rock coasts* and *sloping hard coasts* captures this condition. The separate geological layout category for *coral island*s is assumed to be associated with coral reef environments of various kinds.

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/or inherent 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 included hazards significantly.

2.5. Sediment balance

The sediment balance is an essential morphodynamic parameter and particularly important for coastlines falling into the sedimentary layout categories. The sediment balance determines whether there is a net accumulation, removal or balance of sediment at a particular coastline over time and is largely determined by the sediment transport and availability.

The coastal sediment transport can be divided into two main categories, 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 (Mangor 2004; Davis and Fitzgerald 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 mud/tidal flats (Mangor 2004). Coastlines dominated by cohesive sediment can respond to 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 on-site or remotely. 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 dynamics. However, seen from a hazard perspective, these coastlines are less likely to experience severe sediment deficits in the near future.

For achieving an optimal accuracy of the hazard assessment, temporal data on sediment transport, erosion and accumulation would be valuable for determining the sediment balance of a particular coastline. As the CHW system is intended to be used in areas with limited data availability, however, it is designed to rely on a combination of remote sensing data and on-site assessments. Direct short-term observations are complicated by the fact that single storm and high-wave events can lead to temporal coastline erosion which is reversed during calm conditions, thus causing fluctuating erosion and accumulation patterns (Mangor 2004; Stive et al. 2002). This means that a particular coastal area may one day appear to erode while looking stable sometime later. For evaluation of the sediment balance, it is therefore recommended to make use temporal remote sensing techniques to evaluate coastal changes over several years. In cases where there is doubt about the validity of the sediment balance evaluation, it is recommended to be guided by the precautionary principle and apply the *balance/deficit* category, as this gives the highest general hazard level. This is also recommended where there are 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.

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 inherent 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 inherent hazards in all areas where they occur regardless of their frequency. The classification system uses the map shown earlier in Fig 1 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.

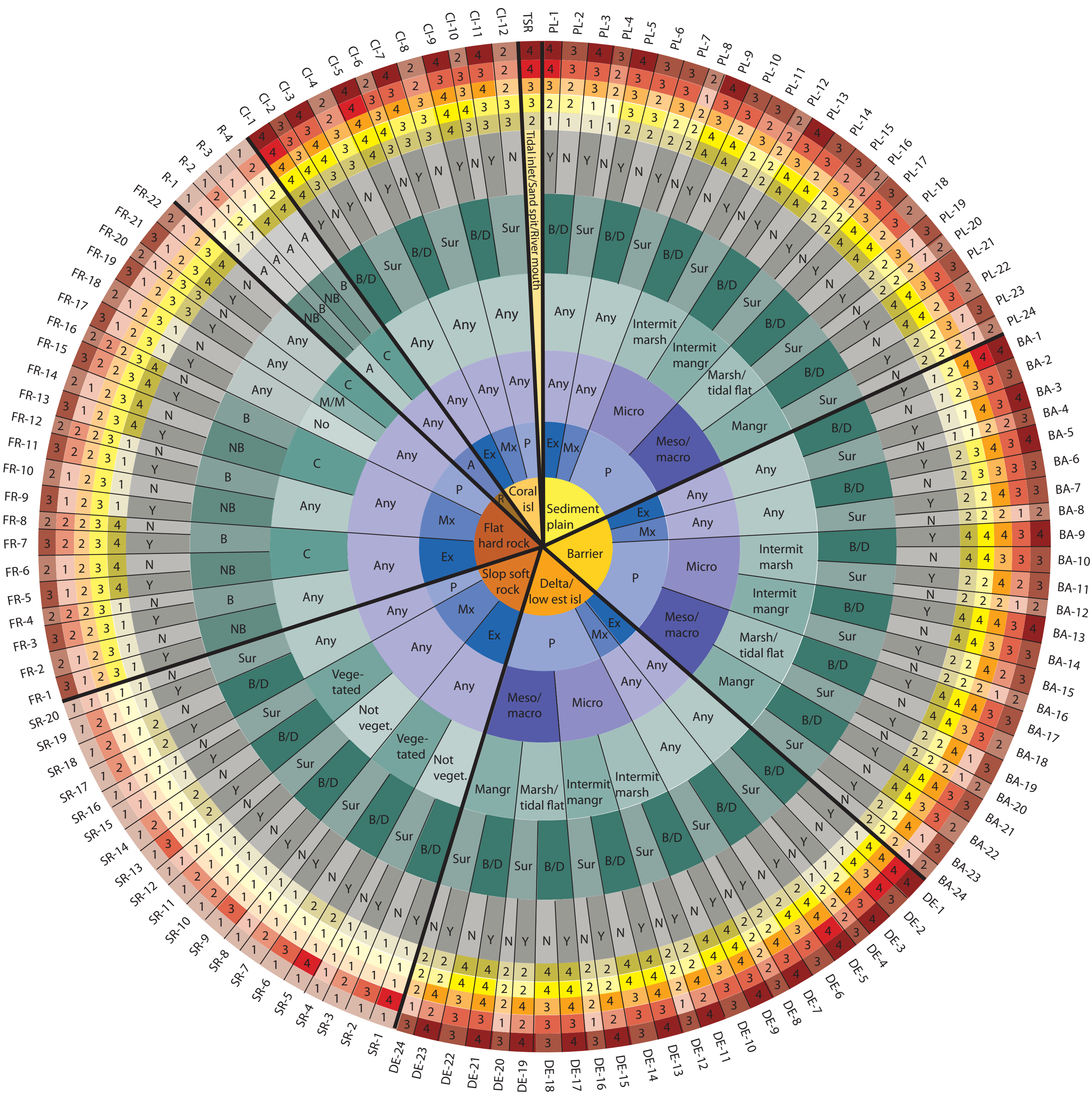
3. The inherent hazard levels

The hazards included in the CHW system are defined as the hazards being an inherent part of the bio-geophysical properties of a coastal environment when exposed to the predicted changes in global climate over the coming decades (IPCC 2013; IPCC 2007). The inherent hazards covered by the CHW system are ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding, which describe the following.

- The inherent hazard for ecosystem disruption describes the possibility of a disruption of the current state of the coastal ecosystems under a changing climate.
- The inherent hazard for gradual inundation describes the possibility of a gradual submergence of a coastal environment under a changing climate.
- The inherent hazard for salt water intrusion describes the possibility of salty sea water penetrating into coastal surface waters and groundwater aquifers under a changing climate.
- The inherent hazard for erosion describes the possibility of erosion of a coastal environment under a changing climate.
- The inherent hazard for flooding describes 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 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. 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 inherent 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 2.0 version. For an elaborate description of the basis for the assigned hazard levels, the reader is referred to the background paper for the CHW 1.0. The hazard values for the revised/new hard rock coast categories of the CHW 2.0 are based on the values for the *coastal plain* and *sloping hard rock coast* categories of the CHW 1.0 (Rosendahl Appelquist 2012). The revised CHW 2.0 is shown in Fig 3, and is used by starting in the wheel centre and moving outwards, ending with the hazard evaluation in the outermost circles.

Fig 3. The Coastal Hazard Wheel 2.0 (modified from Rosendahl Appelquist 2012)



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

4. Application for multi-hazard-assessments

The CHW system can be applied for coastal multi-hazard-assessments at local, regional and national level, and for spot-assessments to indentify the hazard profile and management options for a particular coastal site. Depending on the data availability and accuracy requirements, the CHW can be applied at three different assessment steps, 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 the 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 though remotely sensing and public data sources.
- Step 3 that is designed for hazard assessments with high and locally focused accuracy and this step requires systematic and detailed field assessments at local level.

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 if the assessment is carried out at Step 1-2. The following sections outline the data requirements and procedures for applying the CHW for multi-hazard-assessments.

4.1. Preparatory data collection and analysis

Prior to the actual assessment, it is necessary to collect and prepare appropriate input data for the different CHW classification components. Generally, the core data requirements remain the same for Step 1-3, but additional data is required for implementation of Step 2-3. The data requirements and preparatory analysis needed for each classification component are outlined in the following.

Data for geological layout

The core data requirements for classifying the geological layout at Step 1-3 are a general geologic map of the assessment area, Google Earth's satellite images and Google Earth's ground 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 indentify form-features as barriers, deltas, tidal inlets, sand spits, river mouths and islands, and Google Earth's ground elevation function is used to assess whether the coastline has a flat or sloping character.

To facilitate the assessment of the coastal slope, it is recommended to draw a supporting, shore-parallel, line-feature in Google Earth, landwards of the coastline in all areas with a slope greater than 3-4% 200 meter inland of the MSL. These coastal stretches can be identified by moving the curser in Google Earth from the approximate MSL and 200 inland (the distance can be estimated using Google Earth's ruler function) and monitoring the elevation in the button of the Google Earth window. If the elevation over this distance is more than 6-8 meters, the coastline is classified as sloping, and this procedure is repeated for every 100-300 meter coastline. The supporting line-feature is then drawn landwards of the coastline in all areas categorized as sloping, using Google Earth's New Path function. Sloping coastal sections can then easily be indentified using the line-feature when the actual CHW assessment is carried out.

For implementing assessment Step 2, this data should be supplemented by representative field verification e.g. in areas where there are doubts about the geological base material, coastal outline or slope. An implementation of Step 3 would require systematic field verification at local level of all these parameters. In situations where no geological map is available for the assessment area, systematic data collection in the field can be used as a viable alternative. However, such an assessment will only be considered as a Step 1-2 assessment due to the lack of geological background information.

Data for wave exposure

The data requirements for classifying the wave exposure is the same for all Steps 1-3, namely Fig 1 shown earlier, Google Earth's satellite images, Google Earth's ruler function and additional information on the general wind climate of the assessment area. The map shown in Fig 1 is used to determine whether the coastal stretch in question can be considered as having a swell or non-swell wave climate, as defined in section 2.2. All coastlines with a swell wave climate fall into the *moderately exposed* category, while the wave exposure of non-swell coastlines is determined through the free fetch. The free fetch is determined using Google Earth's satellite images and ruler function, assessing whether the free fetch is < 10 km; 10-100 km; > 100 km, defining *protected*, *moderately exposed* and *exposed* coastlines as mentioned in section 2.2. Generally, it is recommended to supplement this information with literature on the local/regional/national wind climate to verify that the wind is actually blowing from the direction that is used as the free fetch length.

The nomogram mentioned in section 2.2. may be used if very accurate exposure levels are considered relevant e.g. in relation to a Step 3 assessment. However, the free fetch evaluation, combined with basic information on the wind climate is regarded as the appropriate approach at all steps. The same exposure level may in some cases apply to long coastal stretches, but can also apply to very short sections in locations with a diverse coastal configuration. When the wave exposure is evaluated, it is also important to take human modifications of the coastline into account, since structures as harbours or breakwaters can change the wave exposure. If such structures are present, they should only be considered in the wave exposure evaluation if they can be regarded as permanent modifications of the coastal environment.

Data for tidal range

The data requirements for classifying the tidal range are the same for all Steps 1-3, namely Fig 2 and, in some cases, supplementary tidal data for the assessment area. The map shown in Fig 2 is used to identify whether the tidal range is of micro or meso/macro types, and in cases where the assessment area is close to any of the border areas, it is recommended to supplement the map with more detailed data on local tide conditions. Generally, such data is available on the internet, either as tidal tables from commercial harbours or in the scientific/technical literature. The same tidal range category often applies to long coastal stretches and once the tidal conditions are determined, it is relatively simple to go through this classification layer when the CHW assessment is carried out.

Data for flora/fauna

The core data requirements for classifying the flora/fauna at Step 1-3 are Google Earth's satellite images, information on the latitude of the assessment area, information on the local marsh/mangrove flora and the UNEP-WCMC global coral reef database (Reefbase 2013). The Google Earth satellite images are used to visually evaluate the extension and type of coastal vegetation, the information on latitude and the information on the local marsh/mangrove flora is used to determine whether coastal wetlands are vegetated with marsh or mangroves, and the coral reef database is used to identify stretches of coastal coral reefs. As the flora/fauna classification is strongly dependent on the previous classification parameters, it makes this classification layer a bit more complex. It is therefore important to be aware of this close relationship when the CHW assessment is carried out. It may be difficult to determine the percentage of vegetation cover for *sloping soft rock* coastlines based on Google Earth's satellite images, and to avoid underestimating the hazard levels at Step 1, it is recommended to assume that the coastline has no vegetation in cases where there are doubts about the actual percentage.

For an implementation at Step 2, the data above should be supplemented by representative field verification of vegetation cover, vegetation type and if possible coral presence. Step 3 would require systematic field verification at local level for all these parameters.

Data for sediment balance

The core data requirements for classifying the sediment balance at Step 1-3 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. This is done using Google Earth's timeline function, which allows for an evaluation of the temporal changes in coastal development.

To facilitate the sediment balance evaluation in these areas, it is recommended to draw a supporting, shore-parallel, line-feature in Google Earth, at the approximate vegetation line at all sedimentary/soft rock stretches of the assessment area. The line-feature should be based on the most recent satellite image layer in Google Earth. When the actual CHW assessment is carried out, it is then relatively simple to determine whether the coastline has been stable (sediment balance), retreating (sediment deficit) or prograding (sediment surplus) by shifting back and forth between different satellite images, and comparing the older images with the digitized, most recent coastal vegetation line. In some locations, especially at desert coastlines, the vegetation line might not be present and therefore not possible to use as reference line. Also, it may be difficult to determine a clear vegetation line at protected coastlines with a high tidal range. Under these circumstances, the user can either try to draw the supporting line-feature at the approximate vegetation line or at the approximate MSL, but the uncertainties related to this should be kept in mind. An assessment based on the approximate MSL is generally not optimal as the satellite images in Google Earth are captured at different tide conditions and at different times of the year and can therefore be captured at very different water levels. Hence, the visible water level cannot be directly compared between the different images. Also, it is important to be aware of possible human alterations of the sediment balance such as beach nourishment, sand mining or upstream river damming. A human modification of the coastal environment should only influence the sediment balance classification if it is of permanent character, and if there are any doubts it is recommend to apply the sediment balance/deficit classification to avoid underestimating the hazard levels.

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 an implementation at Step 2, the data for sedimentary/soft rock coastlines should be supplemented by representative field verification of signs of longer term erosion/accretion and human alterations. For hard rock coastlines, representative field verification should be carried out to assess the presence of beach environments. Step 3 would require systematic field verification at local level for all these parameters.

Data for storm climate

The data requirement for identifying if tropical cyclones are present in the assessment area is the same for all Steps 1-3 and is simply Fig 1 shown in section 2.2.

4.2. Assessment procedure

The actual assessment procedure can be carried out when the preparatory data collection and analysis mentioned in section 4.1. has been completed. 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 100-300 meters. For spot-assessments it may be appropriate simply to note the results of the hazard assessment for the coastal site in question. For local, regional and national assessments, however, it is recommended to conduct the analysis in ArcGIS, as this allows for a more systematic assessment procedure and subsequent development of high-quality hazard maps for ArcGIS and if relevant hazard layers for Google Earth.

When the assessment is carried out in ArcGIS, the first step is to create an ArcGIS geodatabase that will contain all data on the coastal classification and subsequent hazard levels. In order to have a relatively detailed and up-to-date coastline of the assessment area that can be used for the assessment, a new line-feature is created in the geodatabase referencing the relevant UTM Zone for the assessment area. The full coastline of the assessment area is then digitized at the approximate MSL using this line-feature, leaving gaps for river mouths and tidal inlets. The accuracy of this digitization should be approximately 10 meters, as the digitized coastline will function as basis for all subsequent coastal hazard maps.

The coastal classification is carried out on top of the digitized coastline in ArcGIS. This is done using a polygon feature created in the geodatabase, using the same UTM zone as the digitized coastline. The polygon feature is used to split the coastline into smaller sections, each being classified according to 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 assessment is done manually by drawing a new polygon every time the coastline changes to a new coastal type according to the CHW classification system, and during this process, it is important to establish a snapping environment in ArcGIS to make sure that the polygons are properly aligned with each other.

Since the classification is carried out manually based on the CHW and the data mentioned in section 4.1., the user has to decide on an appropriate coastal type when drawing each polygon. Sometimes a coastline can maintain the same properties for many kilometers, while at others, it changes every 100 meters. This means that the length of each polygon can vary significantly for the different parts of the coastline of the assessment area.

The optimal way of adding the CHW classification code to each polygon is to create an attribute domain that can contain the codes of all coastal types included in the CHW, along with the associated hazard values. The attribute table used for the polygons then includes the predefined CHW classification codes that can be selected when each polygon is drawn. Subsequently, the hazard values in the table can be used for developing the hazard maps.

When the polygons have been drawn for the full length of the coastline in question, they are used to divide the initial digitized coastline into sections, each representing a specific coastal type. This is done using the locate features along routes function in ArcGIS. Based on this, five different hazard maps are created for the respective hazards types and the different hazard levels are assigned a colour code. The hazard maps can e.g. be created on top of a hybrid Bing map to optimize the visual readability. In addition to this, separate hazard layers can be developed for use in Google Earth to allow users getting a more detailed picture of the hazard presence (Rosendahl Appelquist and Balstrøm 2013a; Rosendahl Appelquist and Balstrøm 2013b).

4.3. Application examples

The CHW has been applied for multi-hazard-assessments in selected locations using the methodology described above. Fig 4 shows an example from the application of the CHW 1.0 for a multi-hazard-assessment of the state of Karnataka, India, at Step 1. The example shows two sub-regional hazard maps for northern Karnataka, displaying the hazards of erosion and flooding (Rosendahl Appelquist and Balstrøm 2013a).

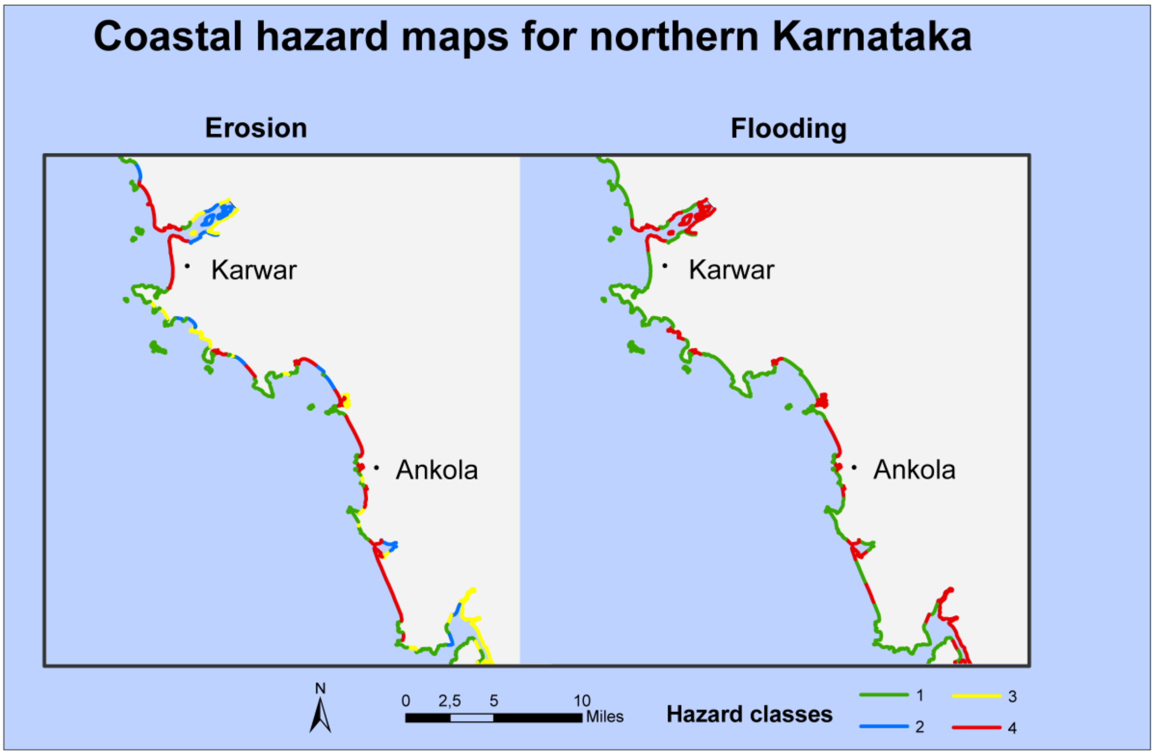


Fig 4. Sub-regional hazard maps for northern Karnataka showing the hazards of erosion and flooding (Rosendahl Appelquist and Balstrøm 2013a).

Fig 5 shows an example from the application of the preliminary version of the CHW 2.0 on the state 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, along with hazard layers for use in Google Earth.

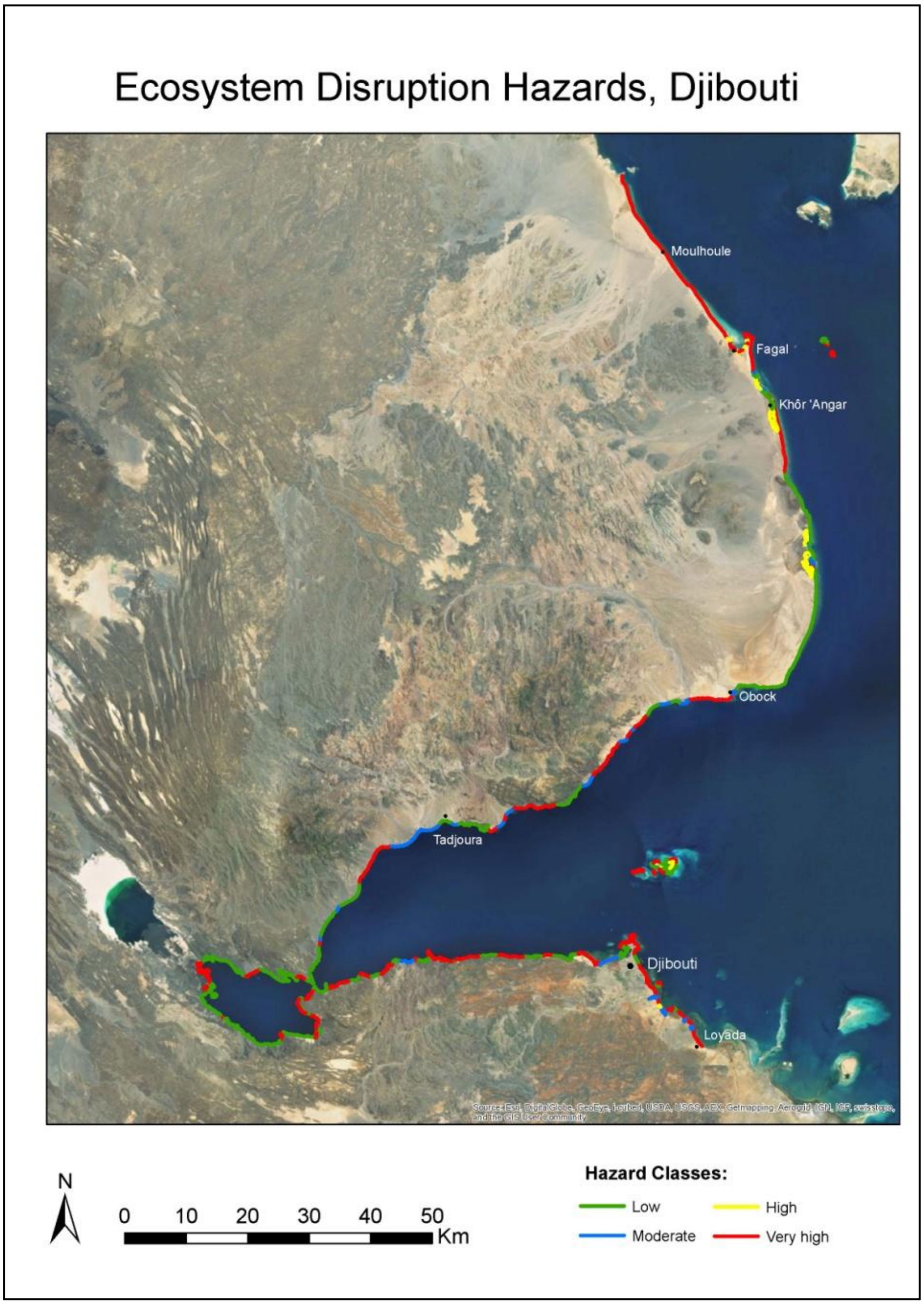


Fig 5. National hazard map for Djibouti showing the hazard of ecosystem disruption (Rosendahl Appelquist and Balstrøm 2013b).

Generally, a standard multi-hazard-assessment would result in a series of hazard maps, coving the five hazard types included in the CHW system. The hazard maps shown in Fig 4 and Fig 5 are therefore mainly for illustration, and the full range of hazard maps developed for Karnataka and Djibouti can found in the related papers (Rosendahl Appelquist and Balstrøm 2013a; Rosendahl Appelquist and Balstrøm 2013b).

5. Identification of hazard management options

Together with hazard assessments, the CHW system can be used for identifying relevant hazard management options for the different coastal environments. Fig 6 shows a matrix of how the most commonly used management options apply to the different coastal environments in the CHW, 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 purposes, as the management options available for these layouts are relatively similar. The categorization of the different management options are assigned by the authors, based on the current literature of their normal application.

The matrix covers the three main types of management options, namely hard protection measures, soft protection measures and accommodation approaches, that all can be relevant under different circumstances and have different strengths and weaknesses.

5.1. Hard protection measures

The hard protection measures are listed first in Fig 6 and include breakwaters, groynes, jetties, revetments, sea walls, dikes and storm surge barriers. They are considered the traditional approach to coastal defence and make use of hard structures to create a solid barrier between the land and sea that can resist wave and tide energy, thereby preventing land/sea interaction (Linham and Nicholls 2010). The fixation of the coastline can be beneficial for protecting specific areas of interest but creates a lot of other problems as it prevents the natural coastal dynamics from taking place. The key characteristics and applications of the different hard protection measures are outlined below.

Breakwaters, sometimes termed detached breakwaters, are shore-parallel structures situated just offshore the surf zone to intercept with incoming waves, thereby reducing incoming wave energy. They are normally built in *exposed* and *moderately exposed* sedimentary coastlines, mainly to address erosion hazards but can also have some secondary effects on flooding hazards as they protect dune fields, sea walls and dikes from wave attack. They are usually build in a series to protect longer coastal stretches and are constructed from rock armour, poured concrete, dolos or tetrapods (Davies Jr and Fitzgerald 2004). Key design parameters include the gap between the breakwaters, their length, their off-shore distance and the size of the rock armour used (Masselink and Hughes 2003; Paulsen 2013). Breakwaters provide a sheltered beach area behind them and the wave refraction/diffraction patterns lead to sediment deposition in the lee-side of the structure, sometimes resulting in salient or tombolo formation. Generally, breakwaters form a good alternative to groynes and are able to support beach formation without blocking the littoral drift if they are designed to avoid tombolo formation. However, the structures have to be very large and robust to

Ecosystem disruption	Breakwaters	Groynes	Jetties	Revetments	Sea Walls	Dikes	Storm surge barriers & closure dams	Beach nourishment	Dune construction/stabilization	Cliff stabilization	Wetland restoration	Flood warning systems	Flood proofing	Coastal zoning	Groundwater management	Fluvial sediment management
CP/BA/DE-1														X		X
CP/BA/DE-2														X		X
CP/BA/DE-3														X		X
CP/BA/DE-4														X		X
CP/BA/DE-5														X		X
CP/BA/DE-6														X		X
CP/BA/DE-7														X		X
CP/BA/DE-8														X		X
CP/BA/DE-9											X			X		X
CP/BA/DE-10											X			X		X
CP/BA/DE-11											X			X		X
CP/BA/DE-12											X			X		X
CP/BA/DE-13											X			X		X
CP/BA/DE-14											X			X		X
CP/BA/DE-15											X			X		X
CP/BA/DE-16											X			X		X
CP/BA/DE-17											X			X		X
CP/BA/DE-18											X			X		X
CP/BA/DE-19											X			X		X
CP/BA/DE-20											X			X		X
CP/BA/DE-21											X			X		X
CP/BA/DE-22											X			X		X
CP/BA/DE-23											X			X		X
CP/BA/DE-24											X			X		X
SR-1														X		
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SR-19														X		
SR-20														X		
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CI-11											X			X		
CI-12											X			X		
TSR											X			X		X

Gradual inundation	Breakwaters	Groynes	Jetties	Revetments	Sea Walls	Dikes	Storm surge barriers & closure dams	Beach nourishment	Dune construction/stabilization	Cliff stabilization	Wetland restoration	Flood warning systems	Flood proofing	Coastal zoning	Groundwater management	Fluvial sediment management
CP/BA/DE-1						X		X								X
CP/BA/DE-2						X		X								X
CP/BA/DE-3						X		X								X
CP/BA/DE-4						X		X								X
CP/BA/DE-5						X		X								X
CP/BA/DE-6						X		X								X
CP/BA/DE-7						X		X								X
CP/BA/DE-8						X		X								X
CP/BA/DE-9						X					X					X
CP/BA/DE-10						X					X					X
CP/BA/DE-11						X					X					X
CP/BA/DE-12						X					X					X
CP/BA/DE-13						X					X					X
CP/BA/DE-14						X					X					X
CP/BA/DE-15						X					X					X
CP/BA/DE-16						X					X					X
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CI-10						X					X					
CI-11						X					X					
CI-12						X					X					
TSR								X								

Salt water intrusion	Breakwaters	Groynes	Jetties	Revetments	Sea Walls	Dikes	Storm surge barriers & closure dams	Beach nourishment	Dune construction/stabilization	Cliff stabilization	Wetland restoration	Flood warning systems	Flood proofing	Coastal zoning	Groundwater management	Fluvial sediment management
CP/BA/DE-1						X			X						X	X
CP/BA/DE-2						X			X						X	X
CP/BA/DE-3						X			X						X	X
CP/BA/DE-4						X			X						X	X
CP/BA/DE-5						X			X						X	X
CP/BA/DE-6						X			X						X	X
CP/BA/DE-7						X			X						X	X
CP/BA/DE-8						X			X						X	X
CP/BA/DE-9						X					X				X	X
CP/BA/DE-10						X					X				X	X
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CI-6						X									X	
CI-7						X									X	
CI-8						X									X	
CI-9						X					X				X	
CI-10						X					X				X	
CI-11						X					X				X	
CI-12						X					X				X	
TSR							X								X	

Erosion	Breakwaters	Groynes	Jetties	Revetments	Sea Walls	Dikes	Storm surge barriers & closure dams	Beach nourishment	Dune construction/stabilization	Cliff stabilization	Wetland restoration	Flood warning systems	Flood proofing	Coastal zoning	Groundwater management	Fluvial sediment management
CP/BA/DE-1	X	X		X	X			X	X							X
CP/BA/DE-2	X	X		X	X			X	X							X
CP/BA/DE-3	X	X		X	X			X	X							X
CP/BA/DE-4	X	X		X	X			X	X							X
CP/BA/DE-5	X	X		X	X			X	X							X
CP/BA/DE-6	X	X		X	X			X	X							X
CP/BA/DE-7	X	X		X	X			X	X							X
CP/BA/DE-8	X	X		X	X			X	X							X
CP/BA/DE-9											X					X
CP/BA/DE-10											X					X
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CP/BA/DE-17											X					X
CP/BA/DE-18											X					X
CP/BA/DE-19											X					X
CP/BA/DE-20											X					X
CP/BA/DE-21											X					X
CP/BA/DE-22											X					X
CP/BA/DE-23											X					X
CP/BA/DE-24											X					X
SR-1	X	X		X	X			X		X					X	
SR-2	X	X		X	X			X		X					X	
SR-3	X	X		X	X			X		X					X	
SR-4	X	X		X	X			X		X					X	
SR-5	X	X		X	X			X		X					X	
SR-6	X	X		X	X			X		X					X	
SR-7	X	X		X	X			X		X					X	
SR-8	X	X		X	X			X		X					X	
SR-9	X	X		X	X			X		X					X	
SR-10	X	X		X	X			X		X					X	
SR-11	X	X		X	X			X		X					X	
SR-12	X	X		X	X			X		X					X	
SR-13	X	X		X	X			X		X					X	
SR-14	X	X		X	X			X		X					X	
SR-15	X	X		X	X			X		X					X	
SR-16	X	X		X	X			X		X					X	
SR-17										X					X	
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SR-19										X					X	
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R-4	X	X						X								
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CI-2	X	X		X	X			X								
CI-3	X	X		X	X			X								
CI-4	X	X		X	X			X								
CI-5	X	X		X	X			X								
CI-6	X	X		X	X			X								
CI-7	X	X		X	X			X								
CI-8	X	X		X	X			X								
CI-9				X	X						X					
CI-10				X	X						X					
CI-11				X	X						X					
CI-12				X	X						X					
TSR			X					X			X					X

Flooding	Breakwaters	Groynes	Jetties	Revetments	Sea Walls	Dikes	Storm surge barriers & closure dams	Beach nourishment	Dune construction/stabilization	Cliff stabilization	Wetland restoration	Flood warning systems	Flood proofing	Coastal zoning	Groundwater management	Fluvial sediment management
CP/BA/DE-1						X			X			X	X			X
CP/BA/DE-2						X			X			X	X			X
CP/BA/DE-3						X			X			X	X			X
CP/BA/DE-4						X			X			X	X			X
CP/BA/DE-5						X			X			X	X			X
CP/BA/DE-6						X			X			X	X			X
CP/BA/DE-7						X			X			X	X			X
CP/BA/DE-8						X			X			X	X			X
CP/BA/DE-9						X					X	X	X			X
CP/BA/DE-10						X					X	X	X			X
CP/BA/DE-11						X					X	X	X			X
CP/BA/DE-12						X					X	X	X			X
CP/BA/DE-13						X					X	X	X			X
CP/BA/DE-14						X					X	X	X			X
CP/BA/DE-15						X					X	X	X			X
CP/BA/DE-16						X					X	X	X			X
CP/BA/DE-17						X					X	X	X			X
CP/BA/DE-18						X					X	X	X			X
CP/BA/DE-19						X					X	X	X			X
CP/BA/DE-20						X					X	X	X			X
CP/BA/DE-21						X					X	X	X			X
CP/BA/DE-22						X					X	X	X			X
CP/BA/DE-23						X					X	X	X			X
CP/BA/DE-24						X					X	X	X			X
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FR-10						X						X	X			
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CI-7						X						X	X			
CI-8						X						X	X			
CI-9						X					X	X	X			
CI-10						X					X	X	X			
CI-11						X					X	X	X			
CI-12						X					X	X	X			
TSR							X				X	X				

Fig 6. Matrix of hazard management options for the different coastal environments of the CHW 2.0.

withstand the high wave exposure of deeper water and can suffer damage during storm events (Masselink and Hughes 2003; Davies Jr and Fitzgerald 2004). Problems with breakwaters are related to interference with longshore sediment transport and erosion drowndrift of the breakwaters. Also, deep holes can develop between breakwaters, which present a hazard for recreational use of the coast (Davies Jr and Fitzgerald 2004).

Groynes are hard structures constructed perpendicular to the beach to trap a portion of the longshore sediment transport and thereby build and stabilize beach environments. They are normally built in *exposed* and *moderately exposed* sedimentary coastlines to address erosion hazards. They can be constructed from rock armour, concrete, dolos, tetrapods and timber and are often constructed as a series in a groyne field. The dimensions between groyne length and groyne spacing generally varies from 1:4 on sandy beaches to 1:2 on gravel beaches, and conventional practice is that groyne length should be approximate 40-60% of the average surf zone width. This allows the groynes to trap some, but not all, of the littoral drift (Masselink and Hughes 2003). Drawbacks of groynes include the possibility of sediment starvation and erosion further downstream, especially if the structures are not designed properly and trap too much sediment. Another problem is related to formation of rip currents adjacent to groynes that can present a hazard to swimmers and lead to sediment being transported to deep water and lost from the coastal system during storm events (Masselink and Hughes 2003). The ideally designed groyne field allows sediment to accumulate and eventually bypass the buried groyne, without causing significant down-drift erosion. However, the ideal design is rarely achieved due to lack of detailed data on wave climate and long-shore sediment transport rates (Davies Jr and Fitzgerald 2004).

Jetties are much like groynes in all respects, except that they are typically larger (Davies Jr and Fitzgerald 2004). They are built to line the banks of *tidal inlets* or *river mouths* in order to stabilize one or both sides from shifting position and to preventing large volumes of sand from filling the inlet. Also, they can be used to prevent spit growth into a tidal inlet. Like groynes, they cause an interruption of the long-shore sediment transport and lead to sediment accumulation on their updrift side and sediment starvation on their down-drift side (Masselink and Hughes 2003). Since jetties can be very long, tremendous amounts of sediment can be trapped this way, leading to major setbacks of the coastline on the down-drift side (Davies Jr and Fitzgerald 2004). Impacts on long-shore sediment transport are therefore a critical design parameter.

Revetments are shore-parallel, sloping structures, constructed landwards of the beach to protect a dune area, coastal slope, dike or sea wall from wave exposure. They are mainly built on *exposed* and *moderately exposed* sedimentary coastlines to address erosion hazards, but can also have secondary effects on flooding and gradual inundation hazards depending on what they are designed to protect. They are built from rock armour, dolos or tetrapods and are designed to maximize dissipation of wave energy due to their gentle slope and loose material (Masselink and Hughes 2003). Because they are static structure they conflict with the natural coastal dynamics and may cause accelerated erosion of adjacent unprotected coastlines due to their effect on the long-shore sediment transport and dynamic processes.

Sea walls are shore-parallel, vertical or sloping structures generally constructed in backbeach environments. They are built mainly on *exposed* and *moderately exposed* coastlines to address hazards of erosion and sometimes indirectly flooding, and are constructed from rock blocks, bulkheads of wood or steel and concrete. If the sea wall is vertical, it is highly reflective and can cause scouring of the beach in front of the wall and subsequently beach loss and collapse of the wall. More concave sea walls are still reflective but introduce a dissipative element, reducing risk of beach loss and undermining (Masselink and Hughes 2003). Other problems with sea walls are related to reflection of wave energy that can cause problems elsewhere, erosion of shorelines adjacent to the sea wall due to disruption of long-shore sediment transport and a generally unsightly appearance (Davies Jr and Fitzgerald 2004). Vertical and impermeable sea walls generally cause the greatest problems while concave structures or sea walls combined with rock revetments that allow some dissipation of wave energy have less negative effects (Davies Jr and Fitzgerald 2004). Sea walls are generally expensive and only temporary and often create a long range of new problems. However, they may be an appropriate solution to protect expensive property and infrastructure. To maintain the recreational properties of the coast and address the problems of beach loss and undermining, sea walls may be combined with a beach nourishment scheme (Davies Jr and Fitzgerald 2004).

Dikes are shore-parallel features constructed in all types of low-lying coastlines. They are built for flood defence rather than erosion protection and are normally constructed between mean spring tide level and the highest astronomical tide (Masselink and Hughes 2003). They are usually build of unconsolidated material as clay and may be combined with harder erosion protection measures such as revetments if they are constructed in environments with wave exposure. The main problem with dikes is related to the process of coastal squeeze, where natural coastlines seaward of the dike gets increasingly reduced in size with rising sea level (Masselink and Hughes 2003).

Storm surge barriers and closure dams are hard structures with primary purpose of preventing coastal flooding. They are constructed in *tidal inlets*, *river mouths* and harbour areas and can be easily integrated with larger flood protection systems. Storm surge barriers are movable or fixed barriers or gates which are closed at high water levels and are generally large scale coastal defence projects (Linham and Nicholls 2010). Closure dams are a more low-tech option and consist of non-movable barriers. However, both systems generally have high construction and maintenance costs.

5.2. Soft protection measures

The soft protection measures shown in Fig 6 have largely been developed as a response to the negative effects of hard defences and represent a major shift in approach from an ad-hoc management of coastal hazards to a more holistic and proactive approach (Linham and Nicholls 2010). Soft engineering allows the natural coastal dynamics to exist and maintains the natural landscape and habitat function. The main types of soft protection measures include beach nourishment, dune construction/rehabilitation and cliff stabilization, and their application is outlined in the following.

Beach nourishment is the artificial deposition of sediment on the beach or in the nearshore zone to stabilize or advance the shoreline seaward. It is mainly used on *exposed* and *moderately exposed* sedimentary coastlines for erosion control, but some benefits in relation to flooding and gradual inundation may also occur (Linham and Nicholls 2010). Beach nourishment functions by compensating for a *sediment deficit*, either from loss of sediment or a rising sea level, while at the same time maintaining the natural coastal dynamics. As sediment often continues to be lost from the beach, beach nourishment has to be carried out with regular intervals. It may also be considered relevant to combine beach nourishment with groyne construction to limit sediment loss, although this interferes with the natural coastal dynamics. As a general rule, the size of the sand used for beach nourishment should be equal or coarser than the local sediment, to minimize rapid loss of sediment offshore (Masselink and Hughes 2003). Furthermore, it is important to take the local bathymetry and wave conditions into account in the design process, and sediment borrowing areas should be selected to cause minimal damage to the marine ecosystems. The sand used for beach nourishment should be essentially free of mud in order to avoid problems with turbidity and ecosystem damage (Davies Jr and Fitzgerald 2004). Problems with beach nourishment are often related to public perception, as the natural redistribution of sediment from the visible beach to the nearshore zone can give the impression of failure of the nourishment. However, the sediment is not lost from the system but stays in the nearshore zone, providing wave protection and a sand reservoir. Beach nourishment is increasingly becoming the preferred option for coastal protection as it is relatively cost-efficient and maintains the natural coastal environment. Also, it can be used to complement hard protection measures such as sea walls, which can then be used as a last line of defence (Linham and Nicholls 2010).

Dune construction/stabilization aims at controlling coastal erosion and flooding of adjacent lowlands and is used on *exposed* and *moderately exposed* flat, sandy coastlines. Dunes are generally fragile of nature and are easily disrupted by a footpath or a wind blowout, but can provide good coastal protection. Dune construction is normally achieved by use of fences that are placed at selected places on the backbeach. They thereby disrupt the airflow and promote sediment deposition on both sides of the fence and a well-designed fence system in an area with abundant aeolian sediment transport can lead to vertical dune growth of more than 1 meter/year (Masselink and Hughes 2003). Planting of vegetation can also be used instead of fences or for stabilizing existing dunes. Problems with dune stabilization through fences is that they prevent dune migration during washover and the result may be accelerated erosion and sediment removal on the seaward side of the dune by wave attack (Davies Jr and Fitzgerald 2004). Construction of walkovers can prevent destruction of dune vegetation when the coast is used for recreation. Dune construction/stabilization can also be carried out in association with beach nourishment, using dredged sediment (Linham and Nicholls 2010).

Cliff stabilization aims at reducing cliff erosion at *sloping soft rock coasts* due to precipitation, groundwater seeping and wave attack. Cliff stabilization is carried out through planting of vegetation, terracing and drainage of excess precipitation and groundwater. In *exposed* and *moderately exposed* coastlines, this can be combined with some kind of hard or soft wave protection measures to minimize erosion of the cliff-foot.

5.3. Accommodation approaches

The accommodation approaches listed in Fig 6 involve the continued occupancy and use of vulnerable coastal areas by increasing society's ability to cope with the effects of coastal dynamics and extreme events. These approaches should be implemented proactively and requires advanced planning and acceptance of the coastal zone as a dynamic area that undergoes continuous change (Linham and Nicholls 2010). Some of the main types of accommodation approaches include wetland restoration, flood warning systems, flood proofing and coastal zoning, that are outlined in the following.

Wetland restoration aims at reducing the hazards of ecosystem disruption, gradual inundation, erosion and flooding, along with restoring habitats and coastal ecosystems. Most commonly wetland restoration applies to *protected*, low-lying coastlines with *marsh* and *mangrove* ecosystems. These natural systems provide important environments for dissipation of wave and tidal energy and trapping of sediment, helping to stabilize the coastline (Linham and Nicholls 2010). Wetland restoration can take place in various forms and include transplantation of seedlings from other sources such as nurseries and elevation of selected areas using additional material. Generally, wetland restoration makes use of the natural protective mechanisms of coastal wetlands and thereby combines coastal protection with a conservation of the natural coastal ecosystems.

Flood warning systems aim at providing an early detection and preparation of flood events and can be relevant in all low-lying coastal environments. These systems allow the public and relevant institutions to take appropriate measures in due course, thereby reducing the general exposure of people and property to coastal flooding (Linham and Nicholls 2010). Flood warning systems can be implemented together with a range of other adaptation measures and are a necessity for the use of storm surge barriers.

Flood-proofing is used to reduce the impacts of coastal flooding on physical structure in low-lying areas and generally, one distinguishes between wet and dry approaches. Wet approaches work by allowing flood water to easily enter and exit a structure in order to minimize structural damage, by using materials that can tolerate flooding and by elevating relevant components. Dry approaches work by making structures watertight or relatively impermeable to the expected flooding height (Linham and Nicholls 2010). The advantages of flood-proofing are that it avoids the need of relocation and elevation of structures. However, it may have to be combined with evacuation schemes to limit the exposure of people to extreme events.

Coastal zoning is a relatively easy and efficient way of managing different uses of the coastal zone and depending on the local conditions, it can be relevant for coastal development, coastal wetland management and protection of fragile marine habitats. Activities in a particular zone can be allowed, allowed with permission or forbidden and can be used in relation to economic development, tourism and conservation. In Australia, the Great Barrier Marine Park uses this approach (Haslett 2009).

In addition to the hazard management options listed above, there exists a range of other coast-related management measures such as groundwater management, management of fluvial sediment supply to the coastline and delta areas (both included in Fig 6), ecosystem based management of coastal and marine ecosystems and complete human retreat from the coastline.

6. Cost examples of hazard management options

The cost of the different hazard management options is one of the essential, non-technical parameters when deciding upon appropriate management strategies. This section therefore provides a short overview of cost examples based on data collected from coastal management projects over the last two decades and recent data from international dredging companies. The cost examples are intended to provide an indication of the cost levels and cost components for the different hazard management options and can contribute to discussions of appropriate hazard management strategies for the different coastal environments.

The cost of some hazard management options, such as dike construction and wetland restoration, can vary significantly as they largely depend on local labour and material costs. Other management options, such as rock armour structures and beach nourishment have more comparable global cost levels, as they in many cases are implemented by international dredging companies using comparable materials and equipment. The following sections try to the give an indication of the cost levels for most of the management options covered in section 5, distinguishing between hard protection measures, soft protection measures and accommodation approaches.

6.1 Cost examples of hard protection measures

The cost of hard protection measures depends on local project conditions, the type of structure put in place and the material used. The cost of hard measures generally consists of a large construction cost, followed by some varying O&M costs. Fig 7 provides an overview of the construction costs of a range of different hard protection projects that are designed or implemented over the last ca. 20 years. The costs are provided in €/meter structure and have been converted to Euros using the currency conversion rates for the year the project was designed/implemented. The project examples include exposed rock breakwaters, moderately exposed rock breakwaters, exposed steel/wood/rock groynes, exposed rock/concrete revetments, moderately exposed rock revetments, exposed sea walls and moderately exposed sea walls. The examples are sorted according to the type of structure and construction costs, and the wave exposure levels for the different projects have been estimated based on the wave climate and free fetch length and of the construction site. It has not been possible to obtain the approximate O&M costs for the listed projects. Since the cost numbers have been calculated based on a range of different data sources, including research papers, project documents, company reports and personal communication with project managers, they are associated with different levels of uncertainty. Furthermore, cost variations over time affect the cost numbers. From the figure it can be seen that the construction costs of especially exposed rock breakwaters vary significantly, while the remaining measures to some degree stay within the same cost range. The high cost of some the exposed breakwaters may be explained by the need for very robust structures in some locations to avoid damage from wave attack.

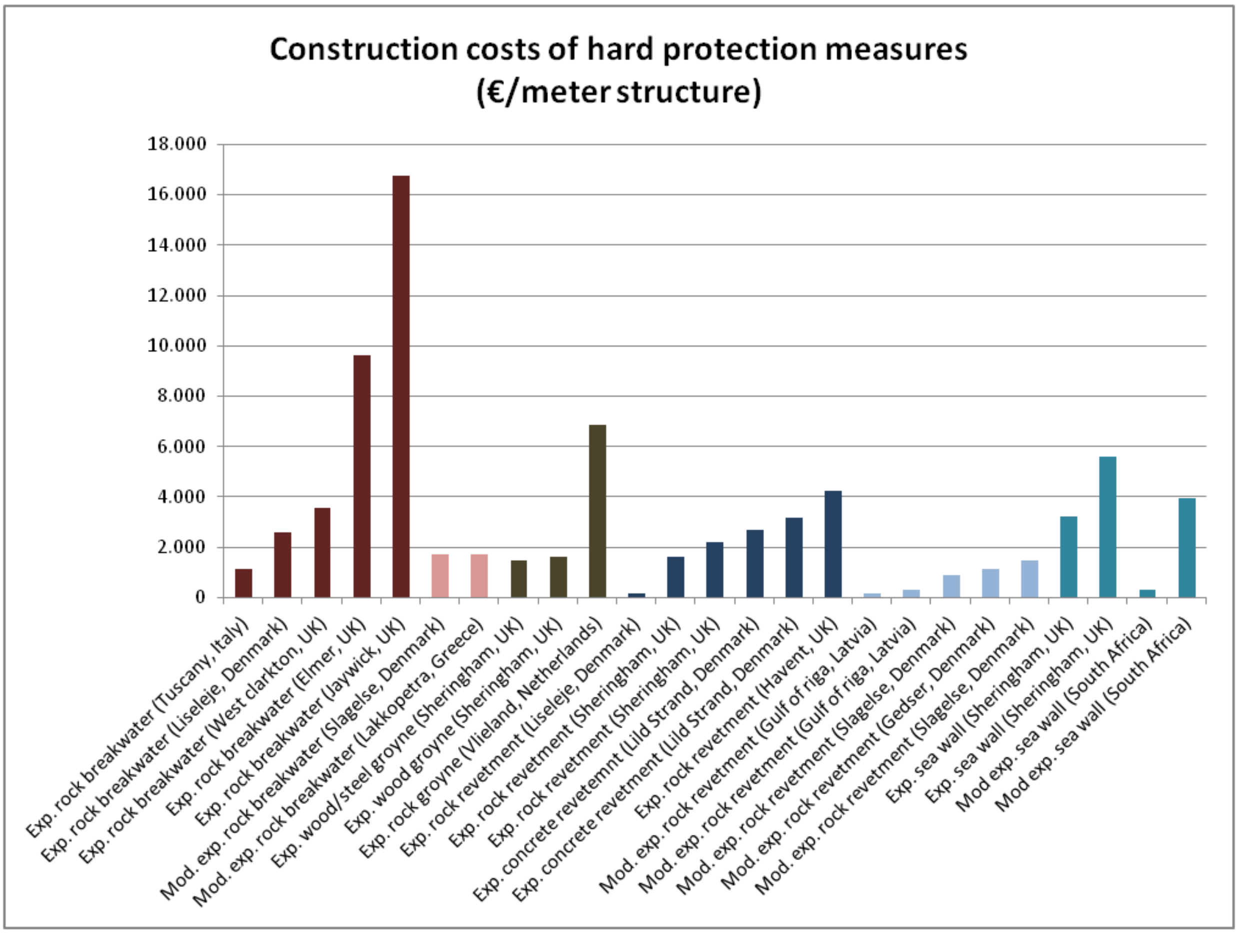

Fig 7. Construction costs for hard protection projects over the last ca. 20 years in €/meter structure. The projects types listed from left are: Exposed rock breakwaters, moderately exposed rock breakwaters, exposed groynes, exposed revetments, moderately exposed revetments, exposed sea walls and moderately exposed sea walls (Cipriani 2004; Cipriani and Pranzini 2012; COWI 2009a; El Raey et al. 1999; Environment Agency 2012; Environment Agency 2010; Evans 2012; Farrow 2012; Hillen et al. 2010; Pelliccia 2004; Povilanskas 2004b; Rosbæk 2012; Schoeman 2004; Sistermans 2004; Skaarup 2004; Slagelse Kommune 2009; Spyropoulos 2004; Thisted Kommune 2008).

The overall project costs depend on a range of different cost components that varies depending on project type and local conditions. To allow for a more detailed cost estimation for hard protection projects using rock armour, data has been collected for the different cost components. Table 1 provides an example of the magnitude of the different cost components in 2012 for rock armour structures constructed by the dredging company Boskalis. The costs are broken down into cost of rock quarrying and delivery on large pontoon at the shipment site, long distance transport by pontoon, short distance transport by pontoons at the project site and placement by grab-dredger. The numbers shown are realistic examples of the magnitude of costs for standard projects and the costs are expected to increase by 10-50 percent for projects with higher business risks such as projects in developing countries (Paulsen 2012).

Cost of rock armour structures (Boskalis example)	
Rock quarry & delivery on large pontoon at shipment site	
Large rocks bigger than 1 ton	30 Euro/ton
Mixed size rocks	20 Euro/ton
Long distance transport with large pontoon	
Cost for pontoon	10.000 Euro/day
Capacity	10.000 ton
Approximate cost for long distance rock transport	1 Euro/ton/day
Pontoon speed	5 knots
Shuttle pontoons for short distances to placement site	
Cost for pontoon loading	1 Euro/ton
Cost for pontoons (with two pontoon shift)	2 Euro/ton
Cost for tugboat	1 Euro/ton
Placement ship - grab dredger	
Operation cost	100.000 Euro/week
Capacity	100 ton/hour
Approximate weekly capacity	10.000 ton
Approximate cost for placement	10 Euro/ton

Table 1. Realistic example of cost components for rock armour structures by Boskalis in 2012 prices (Paulsen 2012).

In order to provide data from two independent sources, Table 2 shows an example of the different cost components for hard protection measures by the dredging company Van Oord in 2012. The table is less detailed than Table 1 and shows the cost of purchase and transport of rocks, assuming a transport distance of 50 km and the cost of combined dry and waterborne placing. It should be mentioned that these costs are rough examples and can vary significantly depending on the quality of the rock/quarry, transport conditions, physical conditions at the project site and other business risks. It can be seen that the cost levels for the two data sources listed in Table 1 and 2 are relatively similar although Table 2 does not provide the same level of detail.

Cost of rock armour structures (Van Oord example)	
Breakwaters/Groynes/revetments	
Purchase and transport of rocks based on transport distance of 50 km	20 Euro/ton
Placing (combination of dry and waterborne placing)	30 Euro/ton

Table 2. Realistic example of cost components for rock armour structures by Van Oord in 2012 prices (Lindo 2012).

For every specific hard protection project using rock armour, construction dimensions should be determined based on detailed engineering considerations on a case-by-case basis. Generally, breakwaters in both *exposed* and *moderately exposed* locations make use of larger rocks of the size of 1-3 ton, but smaller rocks of < 1 ton can be used for the breakwater core. Breakwaters are constructed in the form of a trapeze and can vary significantly in size depending especially on wave exposure but it is possible to provide some rough magnitude examples. An *exposed* breakwater constructed at 4 meters water depth could be 8 meters high and have top and bottom widths of 7 meters and 20 meters respectively. The rock need could be approximately 2,1 tons rock/m3 breakwater, if large rocks are used (Paulsen 2012). A breakwater constructed at a *moderately* *exposed* coastline at 2 meters water depth could be 3 meters high and have top and bottom widths of 3 meters and 8 meters respectively. The rock need could similar to an exposed breakwater be approximately 2,1 tons rock/m3 breakwater (Paulsen 2012). Geotextile is often used below breakwaters, groynes and revetments and have an approximate cost of 20 €/m^2 (Paulsen 2012). The length and space between the breakwaters depends of the specific breakwater scheme and can vary significantly, and the same applies to maintenance needs. Groynes of rock armour can be constructed using both large and small rocks depending on the wave exposure and environmental conditions of the project site, and typical groyne lengths are described in section 5. Groynes of rock armour often have the form of a trapeze, but the specific groyne dimensions depend on the local coastal profile and physical conditions and hence dimension examples are not provided here. Revetments are usually constructed of smaller rocks of < 1 ton, although lager rocks can be used under *exposed* conditions. In *exposed* locations, revetments can have a thickness in the order of 3 meters, while they tend to be 2 meters thick at *moderately exposed* locations.

The costs of hard protection measures using concrete such as sea walls are strongly dependant on local labour and material costs as well as the properties of the structure. It is therefore difficult to provide general examples of the different cost components. For the UK, the Environment Agency has estimated the cost of a standard sea wall to about €2,1 million/km and a reinforced concrete sea wall to about €7 million/km (Environment Agency 2010). For sea walls in India, the cost in 2003 was estimated to be in the order of above €30.000/km coastline (Jayappa et al. 2003).

The cost of dikes is also strongly dependent on local labour and material costs and the physical properties of the structure and it is therefore difficult to provide representative cost examples. Hillen et al. (2010) has compiled the cost of sea dikes in the Netherlands, New Orleans, USA and Vietnam and here the total engineering cost ranges from €0,75 million/km to €21,6 million/km for every 1 meter of dike height in 2009 prices. More specifically, the cost in the Netherlands ranges from €4 - €21,6 million/km for every 1 meter of dike height, in New Orleans from €5 - €8 million/km for every 1 meter of dike height and in Vietnam from €0,75 to €1,2 million/km for every 1 meter of dike height (Hillen et al. 2010). As can be seen, there is a major span in the cost numbers with dike costs in Vietnam being many times lower than in the Netherlands and USA, which is related to differences in material and labour costs and other local parameters. Estimates of maintenance costs for dikes varies significantly for different locations but are reported to range from €0,03 million/km in Vietnam to €0,15 million/km in the Netherlands in 2009 prices (Hillen et al. 2010; Linhan and Nicholls, 2010).

6.2. Cost examples of soft protection measures

The cost of soft protection measures can vary significantly depending on approach and location but the cost of beach nourishment can to some degree be compared at global level. Parameters that affect the cost is sand availability, sand quality, project size, transportation costs, physical conditions at the dredging and nourishment locations and business risks such as fuel prices, technical and security risks. Beach nourishment is generally implemented as a continuous scheme with regular nourishments of a particular coastal stretch. Fig 8 provides an overview of the cost levels in €/m^3 sand for a range of beach nourishment projects carried out predominantly in Europe over the last ca. 20 years. The costs have been converted to Euros using the currency conversion rates for the year the project was designed/implemented**.** From the figure it can be seen that the cost for most beach nourishment projects stay within the range of 1-10 €/m^3 sand, although the cost of some projects are significantly higher.

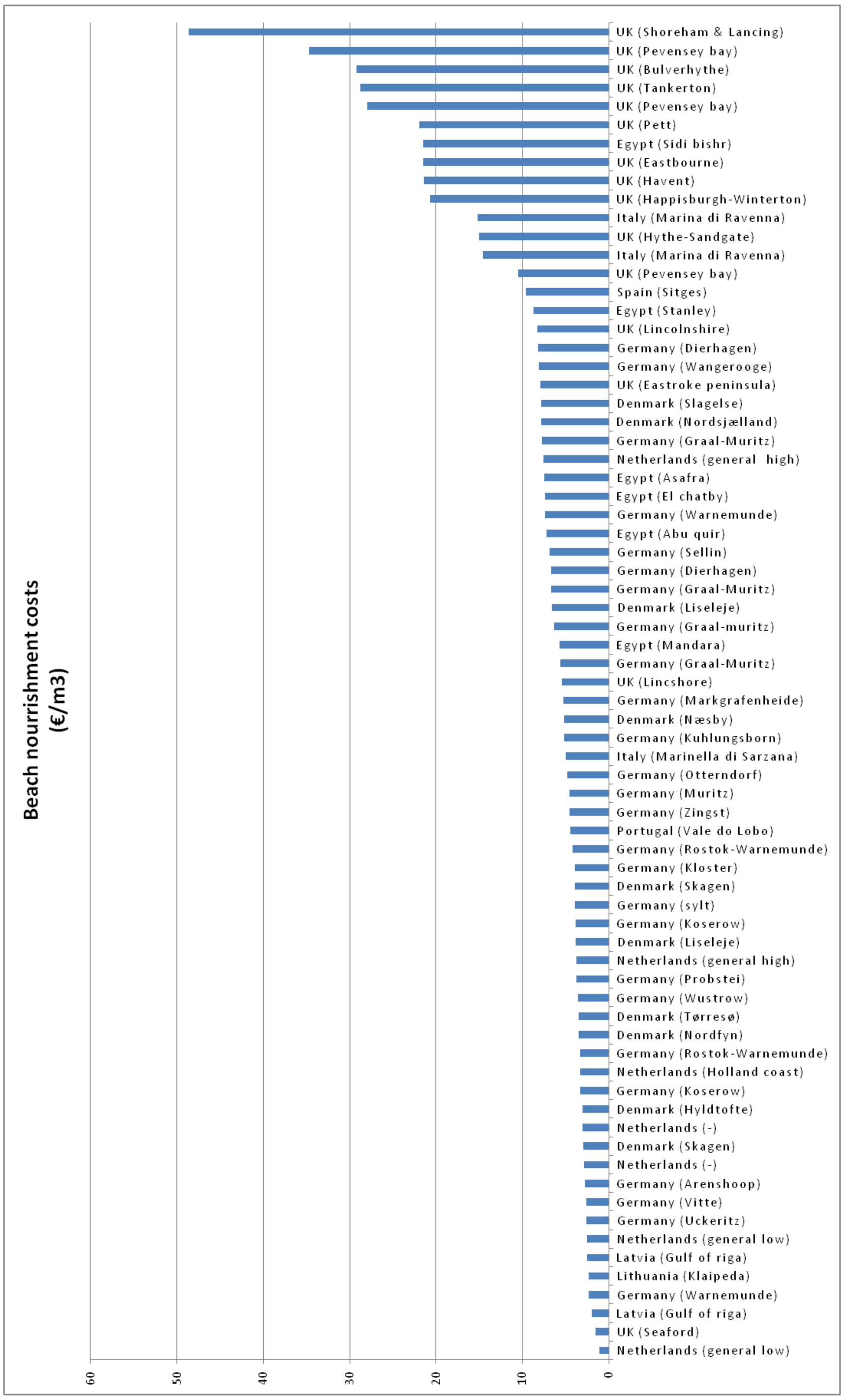

Fig 8. Overview of beach nourishment costs in €/m^3 sand for a range of global projects over the last ca. 20 years (COWI 2009b; Dornbusch 2012; Dredging International 2012; El Raey et al. 1999; Environment Agency 2012; Environment Agency 2010; Evans 2012; Gabianelli 2004; Hillen et al 2010; Kystdirektoratet 2001; Linham et al. 2010; Pelliccia 2004; Povilanskas 2004a-b; Serra Raventos 2004; Sistermans 2004; Sistermans and Nieuwenhuis 2004a-c; Slagelse Kommune 2009; Valoso Gomes and Taveira Pinto 2004).

To be able to estimate the cost of a beach nourishment scheme for a particular coastline it is necessary to have more detailed information of the cost components that make up the price levels shown in Fig 8. Therefore data has been collected of the approximate cost of the different project components from the two dredging companies Boskalis and Van Oord. Table 3 provides an overview of the magnitude of the different cost components in 2012 for projects carried out by the dredging company Boskalis. The table includes two different cost examples, where the beach nourishment is carried out by a small and large hopper dredger, and realistic numbers for mobilization costs, operation costs, sailing distance and sailing speed have been listed and used to calculate realistic examples of nourishment costs. The examples of the total cost in €/m^3 sand are shown without including the mobilisation cost, as the project size has a major influence on the mobilization cost/m^3 sand. It should be noted that these numbers only provides an indicative example of the magnitude of cost and the costs may increase by 10-50 percent for areas with high business risks such as developing countries. Also, mobilisation costs may be significantly higher for developing countries.

Cost of beach nourishment (Boskalis example)	
Beach nourrishment with small hopper dredger - 1.000 m3 vessel	
Mobilisation cost (assuming sailing distance of 1000 Nautical miles)	100.000 Euro
Operation cost	100.000 Euro/week
Assumed sailing distance between source and deposition site	15 km
Assumed vessel speed	10 knots
Daily sand transport with 4 hour cycles (both ways)	6.000 m3/day
Weekly sand transport with 7 days operation	42.000 m3/week
Approximate cost per m3 sand (without mobilisation costs)	2,4 Euro/m3
Beach nourrishment with large hopper dredger - 10.000 m3 vessel	
Mobilisation cost (assuming sailing distance of 1000 Nautical miles)	700.000 Euro
Operation cost	700.000 Euro/week
Assumed sailing distance between source and deposition site	15 km
Assumed vessel speed	10 knots
Daily sand transport with 4 hour cycles (both ways)	60.000 m3/day
Weekly sand transport with 7 days operation	420.000 m3/week
Approximate cost per m3 sand (without mobilisation costs)	1,7 Euro/m3

Table 3. Realistic example of cost components for beach nourishment by Boskalis in 2012 prices (Paulsen 2012).

Table 4 shows the magnitude of costs for beach nourishment in 2012 for projects carried out by the dredging company Van Oord. Here, different cost examples are provided depending on the geographical conditions and project size. It should be noted, however, that these cost numbers can vary significantly depending on local conditions. As can be seen from Table 3 and 4, the cost levels for the two examples are of the same magnitude if the mobilization costs are included in the Boskalis example.

Cost for beach nourishment (Van Oord example)	
Beach nourishment	
Cost in Europe based on sailing distance of ca. 15 km	5-6 Euro/m3
Cost for increasing sailing distance up to extra 25 km	0,2 Euro/m3/km
For large projects in more remote locations where dredgers are not nearby	7-8 Euro/m3
For small projects in more remote locations where dredgers are not nearby	30 Euro/m3

Table 4. Realistic example for cost of beach nourishment by Van Oord in 2012 prices (Lindo 2012).

The cost of beach nourishment for a particular coastal site also strongly depends on the amounts of sand needed and the frequency of nourishments. This depends on several factors including beach profile, wave exposure and sediment balance and the appropriate material needs should be estimated on a case-by-case basis. In order to provide a rough indication of the magnitude of sand needed for different coastal environments, however, one can generally look at coastlines with different wave exposures and sediment deficits. For an *exposed* coastline, the magnitude of sand needed for an indicative example could be 100-200 m^3/meter beach, with a possible extended span of 50-1000 m^3/meter beach. If the sediment deficit is moderate, the nourishment could be carried out every second year, while it could be carried out annually in locations with a large sediment deficit. For a *moderately exposed* coastline, the magnitude of sand needed for an indicative example could be 20-50m^3/meter beach, with nourishments carried out every third year in cases with moderate sediment deficits and every second year in cases with a large deficit (Paulsen 2012). It should be noted, however, that these amounts are purely indicative but may provide a general picture of the magnitude of material needs.

The costs of dune construction/stabilization and cliff stabilization are highly dependent on local conditions including labour costs and are therefore not described further in this section. If dune construction is carried out based on dredged sand, the cost for beach nourishment can be used to estimate the project costs.

6.3. Cost examples of accommodation approaches

The cost of accommodation approaches are highly location specific and therefore difficult to compare at global level. For restoration of coastal wetlands such as marshes and mangrove forests, Tri et al. (1998) has indentified the following parameters to determine the cost level.

- The type of wetland to be restored, expertise availability and chances of success
- The degree of wetland degradation and consequent restoration requirements
- The intended degree of restoration (e.g. depending on other land use activities such as industrial development/urbanization)
- The land cost if land purchase is required to convert the wetlands
- The labour costs
- The transportation distance between seedling source and planting site
- The seedling mortality rate between collection and planting

- The cost of raising specific species in nurseries before transplantation because they cannot be directly planted on mudflats due to strong wind and wave forces
- The scale of post-implementation monitoring operations

Tri et al. provides a cost example for a mangrove restoration project in Vietnam, where the cost of planting new mangrove trees is calculated to the order of €30/per hectare of planted mangrove in 2009 prices, including planting, capital and recurrent costs and subsequent thinning (Linham and Nicholls 2010; Tri et al. 1998). Although this can only be considered an independent example, similar cost magnitudes may apply to equivalent ecosystems and development contexts. Cost estimates for the other accommodation approaches have not been included here.

7. Conclusion

This paper has presented an overview of the CHW system that can be used for applying the system for practical multi-hazard assessment & management. The procedures outlined in the paper should be applicable on virtually all coastlines globally and can be used to improve the decision-base for coastal planners in areas with limited data availability and institutional capacity. The system faces some challenges in relation to urban or heavily modified coastlines as some components of these coastlines fall outside the coastal classification system. However, it is to some extent possible to use the system to evaluate how different human alterations affect e.g. the geological layout, wave exposure and sediment balance and thereby the inherent hazard levels. If any of the hazard management options listed in section 5 has been implemented 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 specific design, quality and implementation, it is not possible to determine the exact level of hazard reduction. For coastal multi-hazard assessments, it is therefore recommended to use the standard classification categories unless it is very clear which coastal classification parameter a specific management measure affects and that the measure is of permanent character. The intention of the management sections of this paper is therefore mainly to give an overview of the appropriate management measures for a particular coastline, their effect on the different hazard types and their approximate cost levels, and not to provide information of the exact level of hazard reduction of a particular measure. Because the overall goal of the CHW system is to provide a low-tech tool suited for hazard management in areas with limited data availability and institutional capacity, the system involves a trade-off between simplicity and accuracy. Hence, it is recommended to use the CHW system as a basic assessment and management tool that can be supplemented with more detailed data collection, modelling and engineering calculations in locations where it is considered appropriate.

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This Ph.D. project has developed a new decision-support system for managing climate change in coastal areas. The system, termed the "Coastal Hazard Wheel" is developed to facilitate screening of climate change impacts in all coastal areas worldwide and is designed as a complete system for combined multi-hazard-assessment and multi-hazard-management. The system addresses the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding and can be used for hazard management at local, regional and national level. It is developed as a simple system that can be applied in areas with limited data availability and institutional capacity and is especially targeted the needs of developing countries.

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