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Regional coastal erosion assessment based on global open access data: a case study for Colombia

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Abstract

Many coastlines throughout the world are retreating, as a result of erosion and sea level rise. The damage incurred to property, infrastructure, coastal flood defence, and the loss of ecosystem services and agricultural land have substantial economic repercussions. For many coastal regions located in developing countries, the assessment of the spatial extent of coastal erosion is very time-consuming and is often hampered by lack of data. To investigate the suitability of global open access data for coastal erosion assessments at regional scale six biogeophysical variables (geological layout, waves, sediment balance, tides, storms, and vegetation) were integrated using the Coastal Hazard Wheel approach (CHW). Original datasets with global coverage were retrieved from the internet and from various research institutes. The data were processed and assigned to the CHW classes, so that the CHW method could be applied to assess coastal erosion hazard levels. The data can be viewed in the Coastal Hazard Wheel App (www.coastalhazardwheel.org) that also allows the coastal erosion hazard levels to be determined for each point at coastlines around the world. The application of the CHW with global open access data was tested for the Caribbean and Pacific coasts of Colombia and revealed a high to very high erosion hazard along 47% of the Caribbean coast and along 23% of the Pacific coast. The application provides additional information on capital stock near the coast, as a tentative indication of assets at risk. This approach provides a straightforward and uniform erosion hazard identification method that can be used for spatial planning on coastal developments at a regional scale.

Keywords Coastal erosion · Biogeophysical variables · Open access data · Hazard assessment · Coastal hazard wheel · Spatial planning

Introduction

Coastal zones are attractive for human settlement because of the opportunities they provide for, among others, agriculture, fishery, transportation, industry, and tourism (Barragan and Andréis 2015). Adger et al. (2005) indicated that 23% of the world population reside less than 100 km from the coastline and 50% is likely to do so by 2030. Since the 1950s, coastlines throughout the world have undergone rapid development,

with an annual average urban growth of 2.6% (UN-Habitat 2009) and an increase in the number of large coastal cities from 472 in the year 1950 to 2129 in the year 2015 (Barragan and Andréis 2015).

Although living close to the coastline is advantageous, coastal residents are exposed to an increasing number of hazards and their related impacts, which are aggravated by the present conditions of climatic change. Coastal zones are very dynamic systems where changes occur continuously at diverse temporal and spatial scales (Crowell and Buckley 1993); these changes are often related to erosion caused by natural and anthropogenic activities.

Coastal erosion involves the breaking down and removal of material along a coastline by wave action and currents that break up rock and remove beach or dune sediments. Although the disruption of sediment balances is a natural phenomenon, it is exacerbated by the construction of man-made structures in rivers and on coasts. For example, groynes and harbour jetties along the coast can disrupt long shore sediment transport (Van Rijn 2011), while hydroelectric power dams in

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rivers can block sediment transport to the coastline (Milliman 1997). Coastal retreat is also caused by the sea level rise that is taking place worldwide (Bruun 1962; Wong et al. 2014). Consequently, sediment deficiency along the world's coastlines has become critical (UNEP 2014). Furthermore, coastal erosion can lead to economic losses because of damage to infrastructure, buildings, houses or coastal flood defences, and can result in loss of natural habitats and agricultural land.

One of the prerequisites for sustainable coastal development, whether at national, regional or local scale, is an adequate zoning of the coastline and the implementation of optimal coastal erosion management strategies. Another is that any coastal development must be preceded by a hazard assessment of coastal erosion based on various biogeophysical variables (EU 2004; Boruff et al. 2005; Pranzini and Williams 2013; Rangel-Buitrago and Anfuso 2015). The analysis and evaluation of coastal hazards, however, is very complex, as numerous factors and variables (natural and human-related) are involved in coastal behaviour. Different authors have developed methodologies for classifying and mapping areas according to hazard criteria (De Pippo et al. 2008; Rangel-Buitrago and Anfuso 2015). An extensive review of the literature on classification procedures for assessing coastal hazard can be found in Cooper and McLaughlin (1998), Rangel-Buitrago and Anfuso (2015) and Nguyen et al. (2016). The different coastal erosion hazard approaches focus mainly on: the distribution of erosional conditions, human occupancy within vulnerable areas (Muler and Bonetti 2014), degree of loss (Cutter 1996), and bad adaptation practices (Cooper and Pilkey 2012).

The success of any coastal erosion hazard assessment depends on the accessibility and quality of the data used. Unfortunately, for many developing countries access to data related to marine biogeophysical variables is very difficult, which hinders both stakeholders' involvement and the effective spatial planning of coastal zones.

This paper provides a method for using open access global data on biogeophysical variables to develop a coastal erosion hazard assessment on a regional scale. It is illustrated by a case study on Colombia.

First, datasets on biogeophysical variables were collected from global databases and related research institutes. Second, the concept of the Coastal Hazard Wheel (Rosendahl Appelquist and Halsnaes 2015) was applied to integrate the information on the biogeophysical variables. The Coastal Hazard Wheel (CHW) is a coastal classification system supported by UNEP (Rosendahl Appelquist et al. 2016), which incorporates six biogeophysical variables to categorize coastal hazards, including erosion. Third, the use of open access data within the CHW was tested for erosion on the Caribbean and Pacific coastlines of Colombia and the results were compared with previously published assessments of coastal erosion in this country.

This paper introduces a software application that combines and visualizes the collected open access data used and allowing the determination of CHW hazard levels at any given coastal location in the world.

Methodology

Data collection and application of the coastal hazard wheel

In this study, version 2.0 of the CHW was applied (Rosendahl Appelquist and Halsnaes 2015). The CHW is a coastal classification and decision-support system for coastal stakeholders worldwide that can be used for 3 main purposes:

- Coastal hazard assessments from local to regional level,
- Identification of relevant management options for a specific coastal location,
- Standardized communication between scientists, policy-makers and the general public.

The CHW constitutes a key for classifying a particular coastal location, determining its hazard profile, identifying relevant management options and communicating coastal information. It is developed as a tool that can address key coastal management issues collectively and is directly accessible for decision-makers at various levels. It is therefore well-suited as a first-line adaptation support system that can be supplemented with relevant methods and models for further assessments or engineering purposes.

The CHW is based on a universal coastal classification system that is developed particularly for decision-support. It integrates the biogeophysical parameters considered most important for the character of a coastal environment. The parameters included are: geological layout, wave exposure, tidal range, flora/fauna, sediment balance and storm climate. The CHW 2.0 is an assessment technique for natural systems and does not take man-made structures into account.

In total, the CHW distinguishes between 131 generic coastal environments that each represents a unique combination of the six biogeophysical variables. As the variables can change significantly over short spatial distances, a coastal environment will according to the classification system theoretically apply to a particular spot along a coastline. For practical use, however, a single application of the CHW will apply to a coastal stretch of hundred meter coastline, so larger national assessments can consist of thousands of individual sections classified with the CHW.

For this study, global open access data on the biogeophysical variables were first retrieved from the internet and through colleagues at several universities and research institutes and

Table 1 Categorization of the six biogeophysical variables in the Coastal Hazard Wheel and the associated global open access datasets used in this study

Variable	Category	Dataset	Author(s)	Classification parameters
Geological layout	Sedimentary plain	Global Lithological Map (GLiM)	Moosdorf and Hartmann (2014)	Unconsolidated sediments and slope[a]< 0.8% over 1000 m
	Soft sloping rock	,	,	Unconsolidated sediments and slope[a] ≥ 0.8% over 1000 m
	Flat hard rock	,	,	All other lithological types and slope[a]< 0.8% over 1000 m
	Sloping hard rock	,	,	All other lithological types and slope[a] ≥ 0.8% over 1000 m
	Barrier islands	Barrier island locations	M. Stutz (pers. comm.)	Intersection with flat cap 1 km buffered line [f]
	Delta, low estuarine islands	Global Estuary Database	Alder (2003)	Intersection with area
	River mouths / Sand spits / Tidal inlets / - / -	River Discharge to the Global Oceans	Milliman and Farnsworth (2010) / - / -	river–coastline interface with buffer of 0.1 km * river length (km) / - / -
	Coral islands	Tropical Coral Reefs of the World	Burke et al. (2011)	Intersection with coral raster cells and no other types of geological layout present
Wave exposure	Protected	ERA-Interim	European Centre for Medium-Range Weather forecasts (2015)	Hs[b]< 2 m
	Moderately exposed	,	,	Hs[b] 2–4 m
	Exposed	,	,	Hs[b]> 4 m
Tidal range	Micro tidal	FES2012 tidal range charts [e]	LEGOS (2013)	Range [c]< 2 m highest tide minus lowest tide
	Meso tidal	,	,	Range [c]2–4 m
	Macro tidal	,	,	Range [c]> 4 m
Vegetation	Vegetated	MODIS global land cover	ESA (2010)	MODIS classes 11–159
	Not vegetated	,	,	MODIS classes > = 190
	Marshes	"	"	MODIS classes 170–189
	Mangroves	MODIS global land cover OR Global Distribution of Mangroves	ESA (2010) OR Giri et al. (2011)	MODIS classes 160–169 OR intersection with polygons
	Coral islands	Tropical Coral Reefs of the World	Burke et al. (2011)	Intersection with coral raster cells and no other geological types present
Sediment balance	Balance/deficit / Surplus	LANDSAT 1984–2014	NASA (2016)	- / Accretion based on seaward shift of coastline using NDWI[d] mask
	Beach/no beach	–	–	–
Storm climate	Cyclone occurrence	IBTrACS, ERA-Interim	NOAA (2016), European Centre for Medium-Range Weather Forecasts (2015)	extreme storm occurrence was assumed if IBTrACS measured windspeed is >10 m/s higher than ERA-Interim wind fields database

[a] Slope was determined by sampling the first two 500 m SRTM15PLUS (USGS 2015) raster cells above sea level and calculating mean height, then calculating the slope by using this mean height over a length of 1000 m

[b] Significant offshore wave height Hs with a return period of 1 year. Hs was calculated at DIVA line centroids (DIVA = Dynamic Interactive Vulnerability Assessment [http://www.diva-model.net])

[c] Highest tide minus lowest tide at DIVA line centroids (see note b above) calculated on the basis of data recorded in January 2015

[d] Normalized Difference Water Index (http://deltas.usgs.gov/fm/data/data_ndwi.aspx)

[e] Paid licences, as open-source data were not available or insufficient

[f] Combination results in a square buffer with no jagged edges, which represents a 1 km around the original line

subsequently categorized according to the CHW method (Table 1). In the following, the integration of the six variables is further described.

Geological layout: The CHW distinguishes eight classes on geological layout (see Table 1, 2nd column, row 2–9). To establish these classes different open access databases were used. The Global Lithological Map (GLiM) data was combined with slope estimates for cross-sections of the coast between mean sea level and 1000 m inland, using bathymetry data in SRTM15PLUS (USGS 2015). When categorizing the geological layout for a given location, multiple categories may arise from geology datasets. In such cases, the following priority was used to make a final selection (from high to low priority): river mouths > barrier islands > delta and low estuarine islands > others. No global data was found on sand spits and tidal inlets. The Tropical Coral Reefs of the World dataset (Burke et al. 2011) was used to identify coral islands.

Waves: The CHW include 3 significant wave height classes (Table 1, 2nd column, row 10–12). In this study, wave climate was classified by the significant wave height (Hs) for a return period of 1 year, as determined with the ERA-Interim dataset for the years 1979–2014 (http://apps.ecmwf.int/datasets/data/interim-full-daily/in). Significant wave height was calculated for each of the (16.395) DIVA coastal segments of the world (Dynamic Interactive Vulnerability Assessment; http://www.diva-model.net/), using the nearest available point in the ERA-Interim dataset.

Tides: Three tidal range classes are included (Table 1, 2nd column, row 13–15). For each of the DIVA coastal segments (see above) tidal range data were used from the FES (Finite Element Solution) tide model developed in 2012 (LEGOS 2013).

Vegetation: The CHW makes a distinction in five vegetation classes (Table 1, 2nd column, row 16–20). The MODIS global land cover dataset (Moderate Resolution Imaging Spectroradiometer; ESA 2010) was used to identify vegated and non-vegetated coasts. The presence of mangroves was based on Giri et al. 2011 and additionally on MODIS. The Tropical Coral Reefs of the World dataset was used to identify fringing coral reefs on rocky coasts (Burke et al. 2011). When categorizing the vegetation for a given location, multiple categories may arise from the vegetation datasets. The following priority was used to make a final selection in vegetation: mangrove > marsh > others.

Sediment Balance: The CHW distinguishes two classes: sediment deficiency/balance and surplus. In this study, all coastal segments are considered to have sediment deficiency/balance by default, unless sediment accretion is observed. To identify this localized phenomenon of accretion, Landsat cloud-free satellite images in

Google's Earth Engine were used. Along the coastline the distinction between land and water was calculated according to Donchyts et al. (2016) using a normalized water difference index (water mask) and averaged for the 1980s and most recent years 2010–14 (n~35 per decade). Long-term accretion was determined as the difference in water masks between the historical (1980s) and most recent satellite images (2010–14). The spatial extent of this analysis was limited to a zone of 40 km width around the coastline, as defined in OpenStreetMap (www.osm.org; Topf and Hormann 2015). For hard rock coastlines, the CHW does not need an assessment of the sediment balance but simply requires information on the presence of beaches. However, no global data on beaches at hard rock coastlines were found and therefore beaches were ignored in the classification.

Storm Climate: The CHW makes a distinction in coastlines that do or do not experience tropical cyclones. In this study occurrence of extreme storms was determined, based on the difference between the ERA-Interim dataset and the parametric wind fields generated by the IBTrACS database. This approach was developed under the Aquaduct project (http://www.wri.org/our-work/project/aqueduct) and overcomes the problem that the ERA-Interim dataset underestimates tropical cyclones (Muis et al. 2016). For points for which wind speed is more than 10 m/s higher in the IBTrACS data than in the ERA-Interim dataset, an area within 2 degrees was taken into account, to compensate for the limited number of cyclones in some areas. Overall, the results resemble the global pattern described by Masselink and Hughes (2003).

Coastal erosion hazard levels

Each coastal environment is associated with a certain erosion hazard level, ranging from low (1), moderate (2), high (3), to very high erosion (4). High to very high inherent erosion hazards are associated with 58 out of the 131 coastal environments recognized in the CHW. From the perspective of the geological layout, they are particularly associated with deltas and river mouths, sedimentary plains, barrier islands, sloping soft rock, and coral islands (Table 2).

Data exploration and visualization

Data were explored and visualized with QGIS version 2.0.1-Dufour. The percentage of erosive coastlines was determined as the number of segments with coastal environments that are associated with a high to very high erosion hazard, divided by the effective sample size.

Table 2 Number of coastal environments per geological layout category and associated hazard level as defined in the Coastal Hazard Wheel (after Rosendahl Appelquist and Halsnæs 2015)

Geological layout category			Inherent erosion hazard			
	Abbr.	Number of coastal environments [a]	Low (level 1)	Moderate (level 2)	High (level 3)	Very high (level 4)
Delta	DE	24	4	6	11	3
Sedimentary plain	SP	24	5	5	13	1
Barrier island	BA	24	7	3	13	1
Sloping soft rock	SR	20	6	8	4	2
Coral islands	CI	12		3	7	2
River mouth	TSR	1				1
Flat hard rock	FR	22	14	8		
Sloping hard rock	R	4	2	2		
Total		131	38	35	48	10

[a] As well as depending on the geological layout, the coastal environment code (e.g. DE-1, DE-24, R-1) depends on the combination of the other variables: wave exposure, tidal range, vegetation, sediment balance, and storm climate

The CHW app

A web application was developed that allows the global open access data used in this study to be viewed. The application also permits the determination of coastal environments and associated erosion levels. For this purpose, the coastlines were devided into segments of 100 m long. It was implemented following the OpenEarth (http://openearth.eu) approach favoured by Deltares to encourage the use of open data and open standards in a transparent way in water-related applied research. The CHW application was set up following the latest standards of data exchange and interaction between end users (via a web portal) and data. These standards are used worldwide and are described and maintained by the Open Geospatial Consortium (http://opengeospatial.org).

Although the risk assessment is not part of the CHW, additional data on capital stock was considered, for the discussion on the relevance of erosion in the area adjacent to the coast. Data on capital stock were retrieved from the Global Risk Assessment (UNISDR 2015), and are expressed as the 2011 price in US dollars per 5 km^2 of land.

Accordance with observed erosion rates

To assess whether the general trend in erosion identified by the CHW is accurate a comparison was made with observed coastal erosion rates over the last 35 years estimated for the Caribbean coastline of Colombia by Rangel-Buitrago et al. (2015). These authors made a detailed erosion assessment based on aerial photography, satellite images over the period 1980–2014, and recent field observations.

The comparison was executed in GIS for the coastal segments of 100 m with CHW erosion hazard levels 3 and 4. The outcome of this comparison was expressed in percentages of segments relative to the total number of segments in the following 3 categories:

i) equivalently, i.e. segments with both high CHW erosion hazard levels of 3 and 4 and high observed erosion rates >0.5 m/year according to Rangel-Buitrago et al. (2015);

ii) false positive, i.e. the CHW predicts low to moderate erosion (levels 1 and 2) while observed erosion rates exceed 0.5 m/year and

iii) false negative, i.e. the CHW predicts high to very high erosion (levels 3 and 4) while observed erosion rates are less than 0.5 m/year.

It should be noted that this comparison is not a validation of the CHW, as the two methods are not based on the same paradigm. Instead, the comparison is meant to assess whether the CHW is able to accurately identify the general trend in erosion.

Colombia case study

Colombia (Fig. 1) is a country with 5548 km of coastline bordering the Caribbean Sea (2733 km) and Pacific Ocean (2815 km). Analysis of coastal evolution trends developed by Posada and Henao (2007) for the Pacific coastline and Rangel-Buitrago et al. (2015) for the Caribbean coast revealed that 23% of the Caribbean coastline and 49% of the Pacific coastline are experiencing severe erosion problems (Table 3). The spatial and temporal variability of coastal erosion in Colombia can be related to the heterogeneity of the coast and a diversity of factors contributing to erosion–accretion processes of differing intensity along the coastline. In general terms, the coastal erosion in Colombia seems to be strongly influenced by regional

Table 3 Coastal evolution trend categories along the coastlines of Colombia

	CARIBBEAN (Rangel-Buitrago et al. 2015)		PACIFIC (Posada and Henao 2007)	
	Length (km)	Percentage (%)	Length (km)	Percentage (%)
Erosion	1339	49	647	23
Accumulation and Stability	1394	51	2168	77
TOTAL	2733	100	2815	100

natural and human-induced processes, such as sea level rise, extreme events, sediment supply, anthropogenic induced sedimentary imbalances, and subsidence.

Pacific coastline study area

The Pacific coast of Colombia extends along the west of the Cordillera Occidental, between Punta Ardita and the Mira River Delta. Its general orientation is N–S, with some sectors oriented NE–SW. In this area the Nazca plate and the South American plate meet and therefore the Pacific coast of Colombia is an active tectonic zone with a record of high-magnitude earthquakes.

The geomorphology of the Pacific coast of Colombia comprises cliffs alternating with terrigenous sandy/shingle coves, wide sandy beaches and sandy–muddy tidal flats, barriers, barrier islands and segmented sand bars, and intertidal mudflats and mangrove swamps.

According to Correa and Morton (2010), the climate of the Pacific coastline is humid tropical, dominated by the annual migration of the Intertropical Convergence Zone (ITCZ) and by the high mountains of the Cordillera Occidental. Average annual temperatures are around 26 °C, with minimum values of 14 °C.

On the Colombian Pacific coast, high rainfall values have been recorded: the mean annual rainfall is 10 m. The high rainfall is the result of remarkable atmospheric convective activity highly influenced by latitudinal migration of the Intertropical Convergence Zone (ITCZ). The ITCZ distributes the rainfall bimodally in the northern zone, so there are two rainy seasons: from April to June, and from September to November. In the latter season, precipitation reaches values of 0.57 m/month. In the southern zone, rains have a unimodal distribution, with abundant rainfall from January to June and an average of 192 rainy days. Likewise, the occurrence of regional climatic processes such as El Niño and the Choco jet stream as well as local conditions (i.e. terrain and vegetation, latitude, altitude, and sea currents) can produce variations that disturb the response to the influence of the ITCZ.

Tides along the Pacific coast are mixed semi-diurnal, with mean amplitudes between 2 and 4 m. Spring tide amplitudes change slightly along the entire coast; they vary between 3 m at Tumaco to 4.5 m at Buenaventura city. Winds along the

Pacific coastline blow from Baudó Range (s), and from the west to southwest along the central and southern sectors of the Pacific coast. Swell waves along the Pacific coast are about 0.5–1.5 m high during calm periods, but can be as high as 2.5–3.5 m during strong winds (Correa and Morton 2010).

The Pacific coastline remains mostly uninhabited and undeveloped. It is divided into four departments including 18 municipalities with 0.9 million inhabitants. This population (1.8% of Colombia), is mainly concentrated in two port cities: Buenaventura and Tumaco (DANE 2015).

Caribbean coastline study area

The Colombian Caribbean coast extends between the eastern frontier with Venezuela and the western frontier with Panama (Fig. 1). The general coastal orientation is NE–SW, with some sectors oriented W–E, so that long linear segments alternate with bays. This coastline is a complex region, where tectonic processes have defined the actual topography and the landscape units include mountainous areas and extensive deltaic plains (Correa and Morton 2010; Rangel-Buitrago et al. 2013). Quaternary interactions among tropical climate, oceanographic processes, and tectonic activity have produced a varied unstable littoral geomorphology characterized by bars and beaches along the flat coastal plains, spits, and cliffs (Martínez et al. 2010).

Precipitation is seasonal, with two rain periods (April–May and October–November) and two dry periods (November–April and July–September). Maximum annual precipitation is approximately 2500 mm, while mean annual temperatures of <28 °C make the area attractive for the development of tourism (Rangel-Buitrago et al. 2013).

Tides are mixed semi-diurnal, with maximum amplitudes of 65 cm (Andrade 2008). Coastal dynamics are influenced by how the intensity and seasonality of the trade winds affect wave propagation in the shallow waters, and by rising sea level (Restrepo et al. 2012). The average significant wave height is 1.5 m; peak period average is 7 s. From November to July the wave system is dominated by NE swells; for the remainder of the time, waves are from the NW, WSW and even SW. This seasonal variation in wave direction corresponds with a decrease in significant wave height, with the lowest values occurring between August and October

Fig. 1 Coastline of Colombia
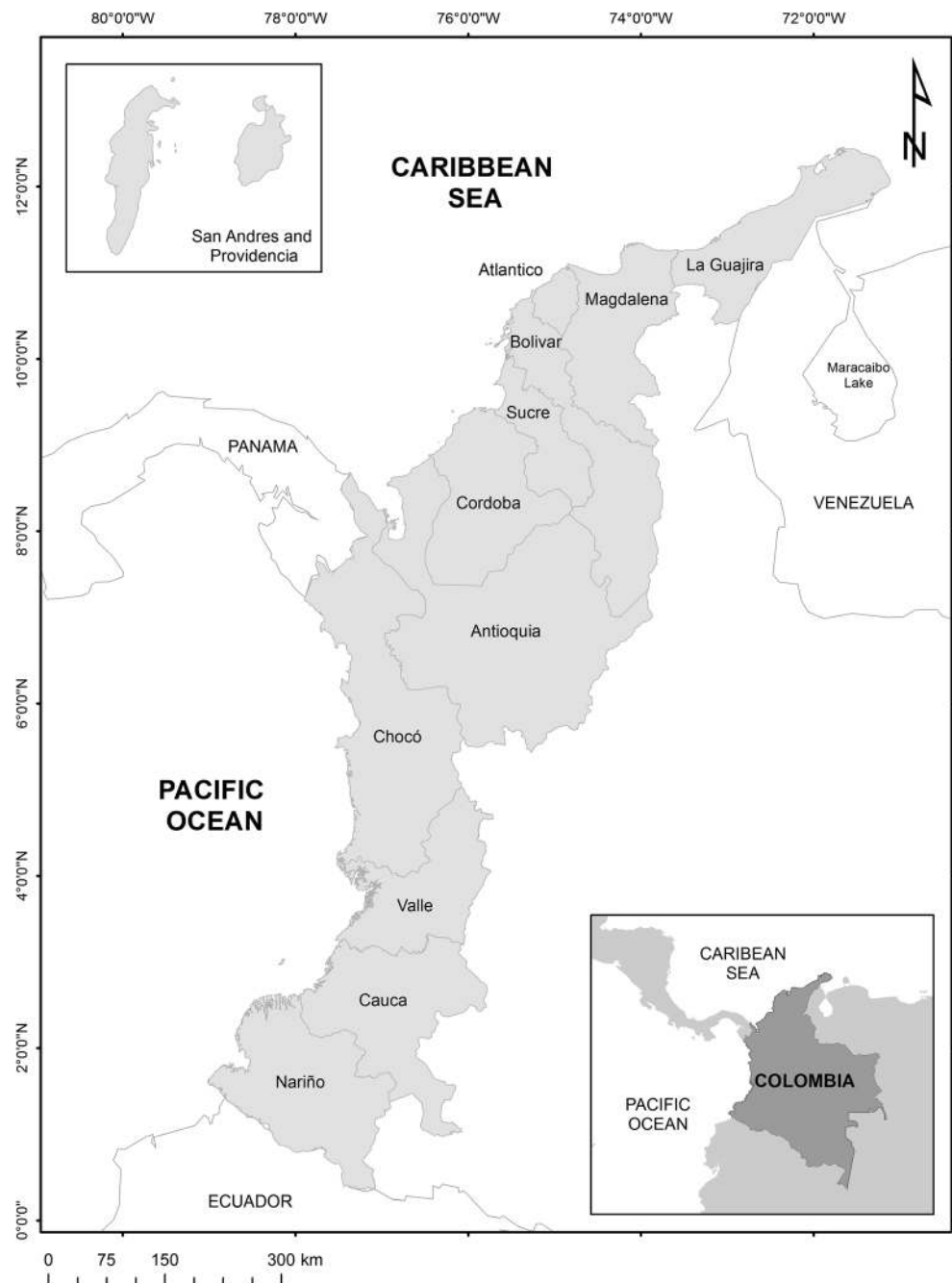
(≤1.5 m); whereas the highest energy conditions occur from November to July, when wave heights can exceed 2 m (INVEMAR 2006; Restrepo et al. 2012). Longshore sand drift has a dominant south-westward component, but minor reversals to the northeast occur during rain periods when southerly winds become dominant in some sectors and set up short, high-frequency waves able to cause significant shore erosion along cliffed and mud coastlines (Correa and Morton 2011).

The Caribbean coastline is a developing region, divided into eight departments and including 28 municipalities with over 4 million inhabitants. This population (8.5% of

Colombia), is mainly concentrated in four commercial and tourist cities: Barranquilla, Cartagena de Indias, Santa Marta, and Riohacha (DANE 2015).

Results

Open access data

Global open access data for six variables were available for approximately 90% of the segments along the Colombian

coast; the remaining 10% could not be used in the analysis due to non-conformance (Table 4). Open access data was found for all CHW biogeophysical variables, except for tidal range, for which the licensed FES2012 dataset was used. In all cases the data have global coverage. Data used in this study can be viewed at www.coastalhazardwheel.org.

Colombia case study

The dominant coastal environments of the entire Colombian coast are: flat hard rock (32%; CHW codes FR 9 and 17), sedimentary plain (22%; PL 5, 7 and 15), delta (19%; DE 5,7,11 and 15), sloping hard rock (6%; R-1) and river mouth (3%; TSR).

The wave exposure at the Pacific coast is classified as protected and on average is lower than at the Caribbean coast, which is classified as moderately exposed and protected. Conversely, the tidal range is higher at the Pacific (meso and macro tidal) than at the Caribbean coast (micro tidal). The vegetation on the Pacific coast is dominated by mangroves (59%) while the Caribbean coast shows more variation (31% mangroves and 48% other vegetation, according to MODIS). Sediment accretion takes place along 42% (934 km) of the Caribbean coast and 59% (1369 km) of the Pacific coast. As far as storm climate is concerned, cyclones occur on the Caribbean coast but not on the Pacific coast.

CHW-derived erosion hazard levels along the coastlines of Colombia

The CHW shows great spatial variability in predicted coastal erosion hazard levels on the Caribbean and Pacific coasts of Colombia, although some long coastal stretches do have a uniform hazard level (Fig. 2). The variability depends on the variation in the six underlying variables that determine the coastal environments.

Erosion hazard levels are high to very high along 47% of the Caribbean coastline and 23% of the Pacific coastline

Table 4 Number of coastal segments (each 100 m long) along the Caribbean and Pacific coasts of Colombia, and data availability for use in the Coastal Hazard Wheel

Segments	Caribbean coast		Pacific coast	
	n	%	n	%
Total	27,332	100	28,146	100
No data available	3297	12	1833	7
Non-conformance [a]	3158	12	2980	10
Effective sample size	22,311	76	23,333	83

[a] Non-conformance exists because the CHW leaves no leeway when marshes and mangroves are not found for certain protected wave exposure environments

(Table 5). Erosion hotspots occur in sedimentary plains (PL-5, −7 and − 22), deltas (DE-5, −13 and − 22) and river mouths (TSR). The common characteristic is the absence of sediment inputs. Further, except for PL-5, these environments are mangrove-dominated.

Accordance with erosion rates observed at the Caribbean coast of Colombia

The CHW approach and the observed coastline retreat at the Caribbean coast of Colombia (Rangel-Buitrago et al. 2015) do identify similar locations prone to erosion but also deviate from one another. The GIS analysis showed that for 54% of the Caribbean coastline, high CHW erosion hazard (levels 3 and 4) fits in with the erosion rate of more than 0.5 m/year observed by Rangel-Buitrago et al. (2015). False negatives and false positives occur in 21% and 25% of the coastline, respectively.

Discussion

The Colombia case study

The CHW approach reveals that the erosion hazard is high to very high along 23% of the Pacific coast and 47% of the Caribbean coast of Colombia (Table 5). These percentages match very well with those reported by Posada and Henao (2007) for the Pacific coast and by Rangel-Buitrago et al. (2015) for the Caribbean coast of Colombia, as summarized in Table 3.

For the Colombian Pacific coast, the CHW estimates erosion to take place exclusively at sediment plains, deltas and barrier islands that receive insufficient sediment inputs. This is in line with observations by Posada and Henao (2007), Correa and Morton (2010), and Restrepo and Lopez (2008).

For the Caribbean coast the accordance between locations with a high CHW erosion hazard level and locations with high observed erosion rates revealed that just over half the segments were classified equivalently, i.e. high CHW erosion hazard matched the high observed erosion rates. False negatives occurred for 25% of the coastline, i.e. erosion is not likely according to the CHW using global data, yet Rangel-Buitrago et al. (2015) reported erosion rates of 0.5 m/y or more. One example is Puerto Colombia, which has a low CHW erosion hazard level (see Fig. 3.1, location B) but experiences severe erosion of beaches and shoreline (Posada and Henao 2007, Rangel-Buitrago et al. 2015). This discrepancy might be the result of invalid data in the CHW App on, for instance, geological layout. According to the lithological data, the coast of Puerto Colombia is a flat hard rock coast. However, beaches are present, which would normally raise the CHW erosion hazard level to 'moderate', but since no dataset on beaches is available, the geological layout
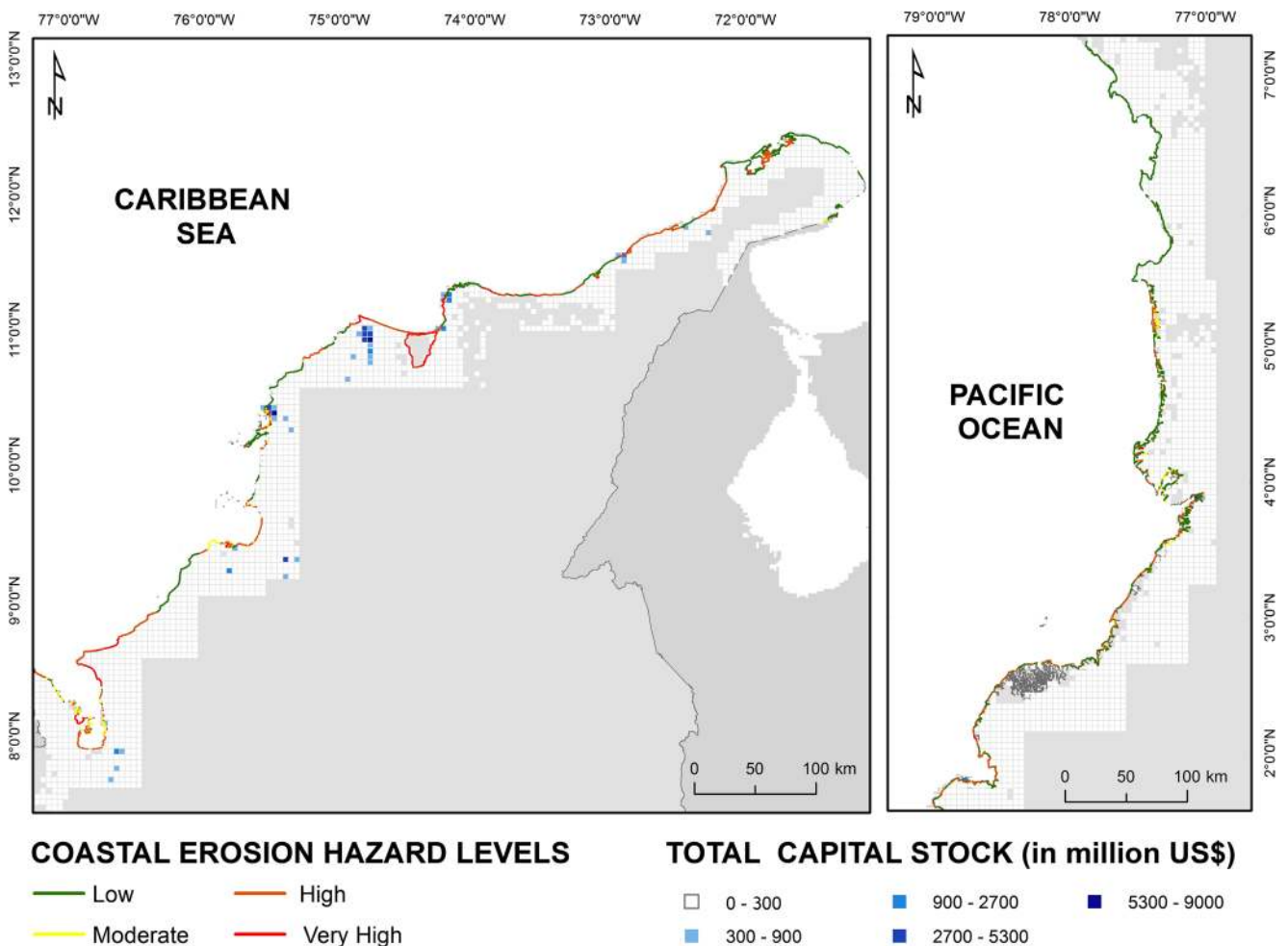
Fig. 2 Coastal erosion hazard levels at the Caribbean and Pacific coasts of Colombia according to the CHW when using global open access data. Capital stock data are also shown

classification defaults to 'no beach' and thus 'low' erosion. In addition, the erodibility of the sedimentary rock formations found along the Colombian coast depends on the rock consolidation, i.e. the rock's hardness. Thus the rock's cementation may ultimately determine whether a stretch of coastline can be classified as soft rock or hard rock. The discrepancy

Table 5 Coastal erosion hazard level distribution (% of coastal segments) along the Caribbean and Pacific coasts of Colombia and the 3 most important associated coastal environments

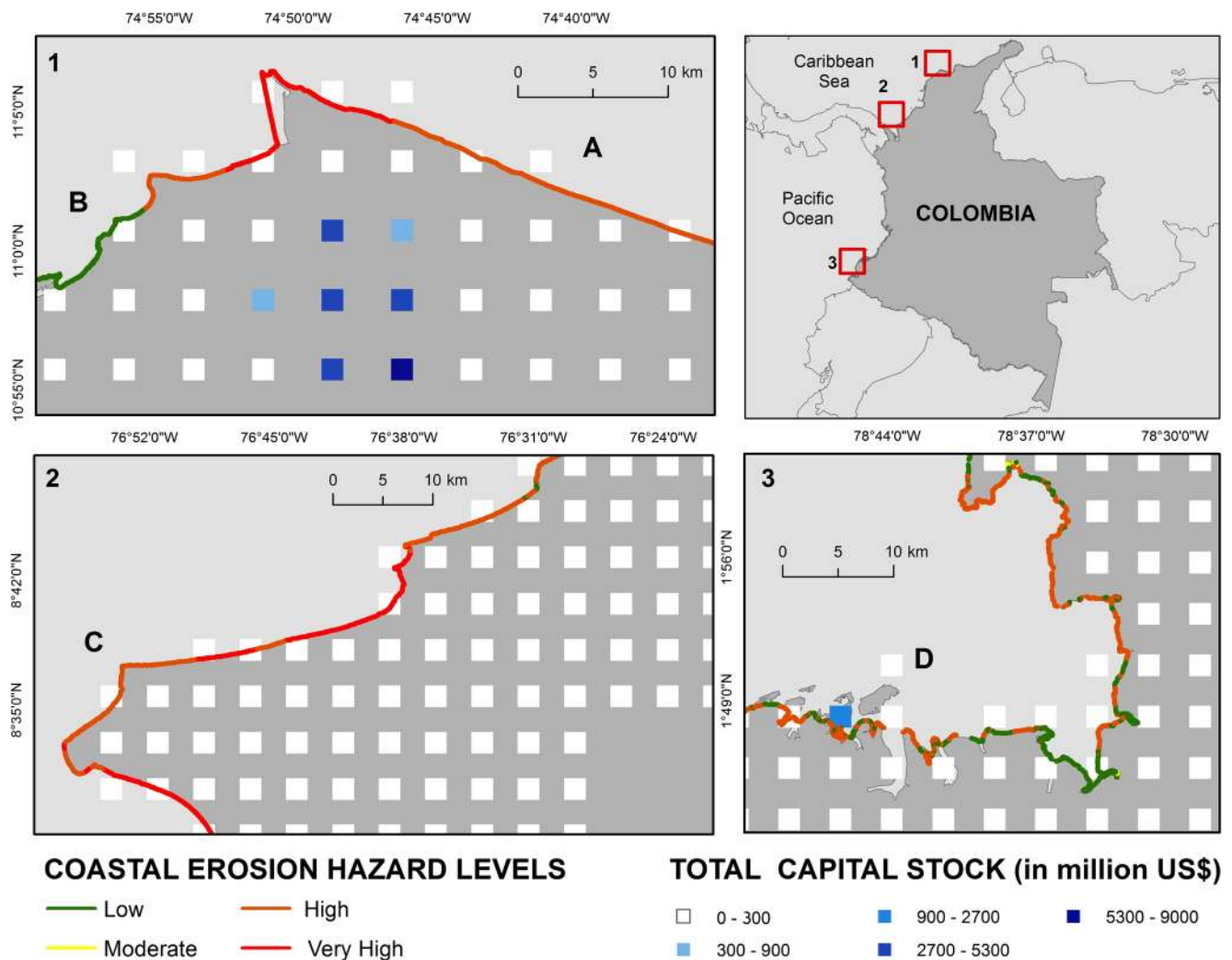| Hazard level	Caribbean coast		Pacific coast	
	%	Top 3 coastal environments	%	Top 3 coastal environments
1	44	FR-9 (26%)	70	DE-24 (17%)
		FR-17 (7%)		R-1 (15%)
		R-1 (4%)		SR-20 (10%)
2	5	DE-15 (3%)	7	SR-18 (6%)
		PL-15 (1%)		
		DE-11 (1%)		
3	36	PL-5 (13%)	22	DE-22 (10%)
		PL-7 (10%)		BA-22 (7%)
		DE-13 (5%)		PL-22 (5%)
4	11	DE-5 (7%)	1	TSR (1%)
		TSR (3%)		
		CI-5 (<1%)		

Fig. 3 Spatial variability in erosion hazard levels and capital stock for the Colombian coast of (1) Antioquia department near the city of Barranquilla, (2) the NE coast of Antioquia department and (3) the Nariño department near the city of Tumaco (3). The letters refer to locations mentioned in the Discussion

may also be the result of human interventions, such as man-made structures along shorelines. The construction of harbour jetties at the mouth of the Magdalena river in 1936 has resulted in erosion down-drift and is one of the underlying causes of coastline retreat at the village of Puerto Colombia (Restrepo and Lopez 2008). However, the CHW is an assessment technique for natural systems, it does not take man-made structures into account when estimating hazard values.

As mentioned earlier, false positives occurred for 21% of the Caribbean coastline. One example is Punta Arenas (Fig. 3.2, location C) that is regarded as erosive in the CHW because here the geology is unconsolidated sediment, but reported erosion rates are low (Rangel-Buitrago et al. 2015). Other examples are at Atrato delta and Manaure in La Guajira, locations where at present sediment accretion is taking place. Accretion, however, is not factored strongly in the CHW. High to very high erosion might occur if the sediment influx stops, which is what the CHW output implies.

From hazard to risk

The UNISDR capital stock data show that highest capital stocks rates on the Colombian coast occur near the large coastal cities of Cartagena de Indes, Barranquilla, Santa Marta, and Riohacha on the Caribbean coast, and near Buenaventura and Tumaco on the Pacific coast. The most relevant locations from a risk assessment perspective are those where high coastal erosion hazard levels coincide with high capital stock. On the Colombian coast, this occurs most often in deltaic environments (Fig. 3.3, location D) and in sedimentary plains (Fig. 3.1, location B). Other locations on the Caribbean coast of Colombia where high capital stock coincides with high erosion hazard are, for instance, Rioacha (PL-7), Santa Marta (DE-5), Ciénaga (PL-5), Arboletes (PL-5), and Necoclí (DE-5) (locations not shown on the maps).

Not only capital stock but also critical infrastructure can be affected by erosion. For example, the coastal highway

between the harbour cities Santa Marta and Barranqualla is eroding at km 19 (Fig. 3, location A), which has major economic implications.

Uncertanties

The spatial resolution of the global, open access data used in this study if often limited. When over time more accurate data become available the results of the CHW are likely to improve. In particular, high resolution data on the geological lay-out or bathymetry will strongly improve the CHW hazard assessment. Another very important source of uncertainty is the estimation of the nearshore wave class. At present, however, the data is generated at a resolution of 0.75 degree latitude/longitude and represent the general offshore wave climate. Therefore, wave climate estimations are inaccurate because near-shore bathymetry is not taken into account. Moreover, erosion also depends on the angle of the incoming waves relative to the coastline. This also requires further data processing in order to provide a good estimate of the near-shore wave exposure.

CHW version 2.0 addresses biogeophysical variables only and disregards man-made structures. This may lead to false negatives in the erosion hazard assessment. The recently published version 3.0, provides an extended scheme for inclusion of hard and soft management measures, mainly for standardized coastal communication (Rosendahl Appelquist et al. 2016). It is the aim that version 3.0 will be used for the development of hazard adjustment factors for different technical management measures. Future hazard mapping should thereby be able to factor in the effects of man-made hazard management activities.

CHW as a coastal planning tool

While the need to protect the functioning of natural ecosystems is one of the aims of spatial planning, coastal marine planning also seeks to improve the economic and social well-being of coastal zones and help them develop their full potential for their human communities. In this sense, coastal erosion issues must be addressed on a proactive basis, in order to be able to adapt to and minimize the expected risks of erosion (EU 2004). A proactive approach in this context refers to a policy of anticipating the erosion hazard by implementing spatial planning and technical measures for coastline management and flood warning systems. In contrast, a reactive approach refers to the policy of implementing coastal defence measures to reduce the effects of existing erosion processes. In Colombia today, coastal erosion management is reactive. Almost all control strategies are triggered by emergencies (post-disaster action) and not under a scenario of risk prevention. Rangel-Buitrago et al. (2015) argue that coastal planning authorities in Colombia need a robust and transparent management framework to resolve issues related to coastal erosion. The application of the CHW with global open access data presented in this paper provides a straightforward and uniform erosion hazard identification method that can be used for this framework in Colombia and could also be applied to steer future coastal developments at erosion hotspots in other developing countries.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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