Ocean & Coastal Management 114 (2015) 129–144

Contents lists available at ScienceDirect

Ocean & Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Coastal erosion along the Caribbean coast of Colombia: Magnitudes, causes and management

Nelson Guillermo Rangel-Buitrago [a, *], Giorgio Anfuso [b], Allan Thomas Williams [c, d]

[a] Departamento de Física, Facultad de Ciencias Básicas, Universidad del Atlántico, Km 7 Antigua vía Puerto Colombia, Barranquilla, Atlántico, Colombia
[b] Departamento de Ciencias de la Tierra, Facultad de Ciencias del Mar y Ambientales, Universidad de Cádiz, Polígono río San Pedro s/n, 11510 Puerto Real, Cádiz, Spain
[c] Faculty of Architecture, Computing and Engineering, University of Wales: Trinity Saint David (Swansea), SA1 6ED, Mount Pleasant, Swansea, Wales, United Kingdom
[d] CICA NOVA, Nova Universidade de Lisboa, Lisboa, Portugal

ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form
23 June 2015
Accepted 23 June 2015
Available online 2 July 2015

Keywords:
Satellite image
Coastal occupation
Sediments protection structures

ABSTRACT

"Sun, Sea and Sand" tourism is one of the fastest increasing activities in Colombia. The coast, specifically the Caribbean coast, represents the favourite destination for national and foreign visitors. However, over the last 30 years while tourism activities increased, coastal erosion became a serious problem rising in magnitude and dominance. This paper deals with a historic overview of Colombian Caribbean coastal erosion, the calculus of associated magnitudes and deepens knowledge and understanding of the different factors that control this process in this location. Coastal change in terms of erosion-sedimentation was determined by comparatives analysis of satellite images for the 1980–2014 period, as well as field surveys. Results showed *circa* 50% of the Colombian Caribbean coast is undergoing serious erosion. In detail, 48.3% (1182 km) of the investigated coast is experiencing erosion; 33.2% (812.6 km) can be considered stable, and 18.4% (450.5 km) is accreting. Coastal erosion can be associated with a diversity of factors contrasting in their degree of magnitude and influence, such as, amongst others: sedimentary imbalance, extreme waves, ecosystem destruction and sea level rise. These processes are often multiplied by human activities e.g. inappropriate building of coastal infrastructures, e.g. groins, illegal mining of sand and destruction of mangroves. Currently, coastal erosion produces not only beach loss but also deterioration of scenic quality and further significant financial investments for hard shore protection structures (groins and breakwaters, principally). Therefore, coastal erosion has become an obstacle that hinders the economic growth of Colombia. Results obtained can be used in the correct application of coastal management policies in order to preserve socio-economic activities, such tourism. Specifically, stronger management laws in line with Marine Spatial Planning attributes need to be implemented and enforced; more sustainable funding found for legislation and a better support network for decision making with the over riding objective of increased sustainability.

1. Introduction

The coast usually concentrates better economic, social and recreational opportunities than does the hinterland, in spite of presenting higher risk of subsidence, tsunamis, extreme waves and coastal erosion (Goldberg, 1994; Nicholls, 2002). It is a very dynamic geomorphic system where constant change occurs at diverse temporal and spatial scales (Crowell et al., 1991), mostly related to erosion, due to natural and/or anthropogenic activities (Van Rijin, 2011).

In the long-term (millennium to centuries), coastal erosion includes regional domains mainly caused by processes comprising sea level variations and global climatic changes (Becker et al., 2012; Jevrejeva et al., 2012). On a medium-term (decades), the factors involved are complex and relate mainly to the sediment budget role, principally influenced by river discharge and damming, and shore protection (armouring), among others (Cooper and Pilkey, 2012). In the short-term (years), erosion is associated with wave energy variations and related processes, e.g. storms (Rangel-Buitrago and Anfuso, 2013).

* Corresponding author.
E-mail address: nelsonrangel@mail.uniatlantico.edu.co (N.G. Rangel-Buitrago).

http://dx.doi.org/10.1016/j.ocecoaman.2015.06.024
0964-5691/

Caribbean beaches offer excellent space for relaxation, sports and enjoyment, suggesting idyllic pictures of good weather conditions, white sands, clean water and shady trees combined with the prospect of relaxed living and revitalization (Cambers, 1998). The Caribbean is one of the most important world tourist destinations and the area has regained ground lost in the 2008/2009 global economic depression. During 2012, the Caribbean received nearly 25 million tourists, 5.4% more than in 2011 and this represents the largest number of stay-over visitors in the last five years with arrivals increasing by 4% (CTO, 2013). In 2013, tourism arrivals in the Caribbean coast of Colombia increased by 13% bringing a Gross National Product (GNP) contribution of US$3400 million (ANATO, 2013). Tourism is the 4th source of foreign exchange (after coffee, oil and coal) contributing significantly to the GNP of the country that in 2013 was US$374,000 million (ANATO, 2013).

Over the last 30 years whilst tourism activities grew, coastal erosion became a serious problem of rising magnitude and dominant trend (Correa et al., 2005; Rangel-Buitrago and Anfuso, 2009; Correa and Morton, 2011; Rangel et al., 2013). Currently, Colombian Caribbean coastal erosion produces beach loss, deterioration of scenic quality and high financial investments for construction of hard protection structures, i.e. it has become an obstacle hindering economic growth. Coastal retreat and/or flooding affect not only coastal zones, which are worth billions of tourist money, but also human activities and the associated infrastructure (Clark, 1996). Management plans have to take cognisance of the tourism model together with an increasing coastal loss (Cooper and McKenna, 2008); therefore local and regional causes/trends of the latter are indispensable for *effective* coastal management. This paper aims to present a coastal erosion overview, in order to increase knowledge and understanding of the different parameters that control this process, so that results can be utilized for proper application of coastal management policies in order to preserve socio-economic activities, especially tourism.

2. The Caribbean coast of Colombia

In a 1:60,000 scale (derived from satellite images), the Colombian Caribbean coast extends for 2,445 km, between, the W boundary with Panama, and the E boundary with Venezuela (Fig. 1). Its general coastal orientation is NE–SW with some sectors oriented W–E so that long linear segments alternate with bays. The study area is a complex region where tectonic movements have defined a contrasting topography with landscape units including extensive low relief deltaic plains and medium – high relief mountain areas (Correa and Morton, 2011; Rangel-Buitrago et al., 2013).

From a geological viewpoint the Caribbean coast of Colombia can be divided from north to south into different morpho-structural sectors (Fig. 1).

- La Guajira Peninsula: a set of tectonically raised Jurassic to Tertiary blocks of granite, metamorphic and sedimentary rocks adjacent to sedimentary basins filled with Tertiary sedimentary sediments (Alvarez, 1967).
- The Sierra Nevada de Santa Marta (SNSM): is a massif considered to be the highest coastal mountain range in the world, with a maximum elevation of 5775 m at the Pico Bolivar (65 km from the coastline), composed with schist's and gneisses (Cretaceous) and Tertiary granite rocks (Restrepo-Pace and Cediel, 2010).
- Magdalena River and Cienaga Grande de Santa Marta (CGSM) – Pajarales Lagoon Complex (PC): probably the most extensive depositional area with a sediment yield of 560 t km^{-2} yr^{-1} (Restrepo and Lopez, 2008).
- Cartagena – Barranquilla sector: predominantly formed by Middle Eocene sequences of hemipelagic, pelagic and turbiditic sediments (Martínez et al., 2010).
- Sinú Belt: mainly of mudstones, conglomerates and coral reef limestone associated with mud volcanism phenomena (Vernette et al., 1992).

Quaternary interactions among tropical climate, oceanographic processes and tectonic activity makes a mixed unstable littoral geomorphology characterized by spits, bars and beaches along the flat coastal plains and cliffed coastlines (Correa and Morton, 2011; Martínez et al., 2010). The geomorphology has been influenced by mud intrusions evidenced by weakened rock zones, domes and several active mud volcanoes. Historical records of violent mud eruptions and explosive events have often been triggered by seismic events (Correa et al., 2007a; Correa and Morton, 2011).

Seasonal precipitation shows two rain periods (e.g. April–May and October–November) and two dry periods, e.g. (November–April and July–September). Maximum annual precipitation values, *circa* 2500 mm, while mean temperatures of <28 °C, make it attractive for tourism development (Rangel-Buitrago and Anfuso, 2013).

Tides are mixed semi-diurnal, with maximum amplitudes of 65 cm (Andrade, 2008). Coastal dynamics are influenced by how both the intensity and trade wind seasonality affect wave propagation in the shallow waters and rising sea levels (Restrepo et al., 2012). The average significant wave height fluctuates between 1 and 2 m and peak period average varies between 6 and 10 s. From November to July, the wave system is dominated by NE swells; for the remainder of the time, waves from NW, WSW even SW occur. This wave direction seasonal variation corresponds with a decrease in significant wave height, with the lowest values occurring between August and October ($\leq$1.5 m); whereas the highest energy conditions occur from November to July where wave heights can exceed 2 m (INVEMAR, 2006; Restrepo et al., 2012). Net 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 study area is a developing region divided into eight Departments including 28 Municipalities with 4,049,867 inhabitants. This population (72% of the total), is mainly concentrated in four commercial and tourist cities: Barranquilla, Cartagena, Santa Marta and Riohacha (DANE, 2013). "Sun, Sea and Sand" tourism represents a significant economic activity with 1,906,909 international arrivals and close to 6,000,000 domestic tourism arrivals in the last 6 years (PROEXPORT – Ministerio de Comercio, Industria y Turismo, 2013). Cartagena, San Andres and Santa Marta are the most visited destination for "Sun, Sea and Sand" associated tourism and these cities are experiencing a considerable increase of "high level" tourism developments principally consisting of five star hotel chains and golf courses. Further developments are observed in the Magdalena and La Guajira departments consisting of enlargement of existing coastal towns and villages with associated impacts on landscape scenery (Rangel-Buitrago et al., 2013). Tremendous pressure to erect hotel and summer house construction for local and especially foreign tourists has resulted in significant building construction holdings on National Natural Parks. This tourism explosion has led to a rising demand for sand and coastal space, as well as increased activity in protected areas (diving and snorkeling) which clashes with the existing coastal erosion problem.

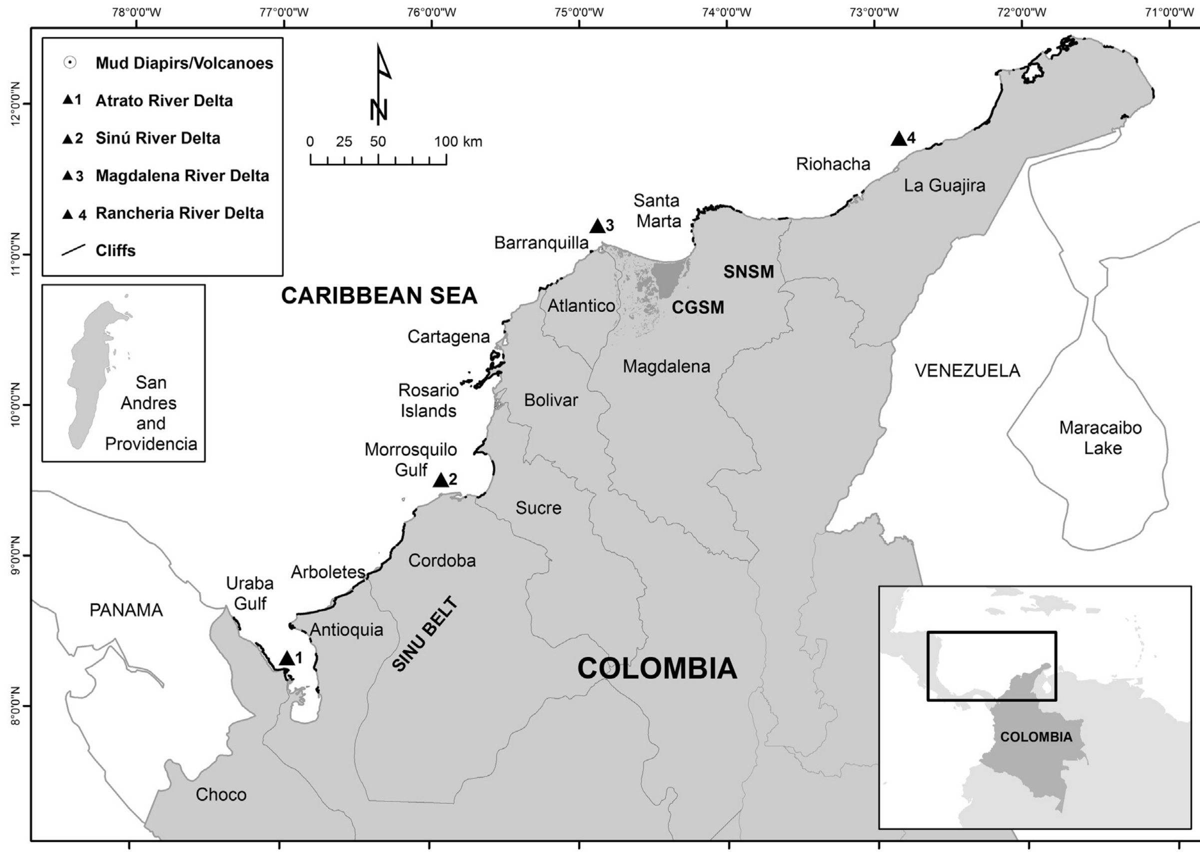

Fig. 1. Study area with indication of cliffed sectors, deltas and mud volcanoes.

3. Data and methodology

Shoreline change and evolution trends are important issues since they provide an understanding into the complex and dynamic large scale systems (Addo and Lamptey, 2013). Understanding the system's behaviour facilitates developing sustainable and pragmatic policies to management. The recent shoreline evolution was assessed over the 1980–2014 period (Table 1) by aerial photographs and satellite images of different scales.

All images were rectified into the same coordinate system (Moore, 2000) and Ground Control Points (GCPs) obtained from the newest satellite image (2014), and information presented in the coordinate system UTM zone 18. As the topography is flat, a polynomial transformation was applied in the registration process (Chuvieco, 2000). The number of GCPs used in each image/photo ranged from 10 to 15, and their position located in miscellaneous places along each image (Thieler and Danforth, 1994).

The photograph error (Crowell et al., 1991; Moore, 2000) was controlled in georeferenced images by comparing the registered photo-image with the newest image (base image), and through the root mean square error (RMSE), calculated by using the GCPs as reference points for each image, allowing a geometrical accuracy of approximately 1 m.

A critical issue is selection of an adequate feature that can serve as a shoreline indicator that correctly reflects real shoreline position and evolution (Boak and Turner, 2005). For differentiation and later digitizing, the infrared band on each available image (i.e. fourth band of the Landsat image) was selected. In this micro-tidal environment, this shoreline indicator is defined as the water line when the image was taken (Boak and Turner, 2005). Because it was not possible to reconstruct tidal conditions at the moment the image was taken, it was assumed that the daily water line position is subject to a maximum uncertainty of 7 m, taking into account the average intertidal slope of Colombian Caribbean beaches (Rangel-

Table 1
Satellite images and aerial photogrammetric flights used in this work.

Satellite images and aereal flights			
Source	Year	Resolution (m)	Coverage
Glovis Nasa Landsat	1983 to 2014	30	Entire Caribbean coast of Colombia
Instituto Geografico Agustin Codazzi – IGAC	1953 1974 1980	30	Arboletes. Broqueles
Terraserver Geoglove	2003 to 2014	0.5	Riohacha. Tasajera. Puerto Colombia. Tierrabomba. Berrugas. Broqueles. Arboletes. San Andres

Buitrago and Anfuso, 2009). Wave height effects were not considered because no storm conditions were observed in any of the images used. Because of the spatial resolution limitations of images an additional shoreline position error was determined with an accuracy of 3 m. Overall, the whole shoreline mapping error was assumed to be 10 m.

After shoreline position identification, images were digitized on a GIS environment (ARCGIS 9.3) for subsequent shoreline change analysis. The DSAS 3.2 extension for ArcGIS, developed by the USGS (Thieler et al., 2005), was used to estimate shoreline changes. DSAS uses as an input a series of shoreline positions, which need to be referenced to an arbitrary baseline. Transects perpendicular to the shoreline were generated at 100 m intervals. The DSAS allowed calculation of erosion/accretion rates between points, on the basis of the distance between them and the elapsed time, assuming changes to be linear processes. Rate of change of shoreline positions were evaluated using the End Point Rate (EPR) and Lineal Regression (LRR) approaches (Thieler et al., 2005).

Retreat/accretion rates for all Departments were calculated and grouped into four categories of coastal evolution trend: "high erosion" (≥ -1.5 m/yr), "erosion" (between -0.2 and -1.5 m/yr), "stability" (between -0.2 and $+0.2$ m/yr) and "accretion" ($\geq +0.2$ m/yr). For each Department, the most critical erosion area (hot spot) was chosen and coastal evolution analysed in greater detail by comparing the two most recent shorelines available in terms of mean shoreline displacement rate (m/yr).

4. Results and discussion

4.1. Recent historic overview

Coastal erosion research in this area is very recent and no available high-resolution updated shoreline change assessments exist. Information came from comparisons of non-georeferenced coastal contours obtained from ancient charts and aerial photographs dating from the commencement of the 20th century (Correa and Alcántara, 2005). Sanchez and Forero (1983) established that the high dynamics in coastal processes were responsible for a large percentage of the observed erosion; Vernette (1985), Javelaud (1987) and Leblanck (1988) studied the sedimentological aspects with the goal of characterizing the existing sedimentary facies and their influence over coastal erosion processes. In the 90s coastal erosion became a very serious problem: Correa (1990) identified important erosion events along the Bolivar department coastline; Martinez et al. (1990) studied existing relationships between coastal erosion and groins construction at the Magdalena River mouth at Barranquilla city; Martínez (1993) carried out geomorphological coastal erosion studies along Cordoba, Sucre and Bolivar departments and Martínez and Robertson (1997) studied Quaternary sea level variations and their influence on recent coastal erosion processes. At the end of this decade, the former Colombian Geological Survey (INGEOMINAS) classified the state of the entire Caribbean coast in terms of: high erosive state (erosion rates >10 m/yr), low variable coastlines and accreting coastlines. According to INGEOMINAS (1998) results for the end of the 90s, *circa* 278 km of the Caribbean coastline of Colombia were in a high state of erosion.

Aristizabal et al. (2001) considering coastal erosion along the Antioquia Department, estimated the economic cost to counteract this problem as an annual investment close to US$2 million. Florez and Robertson (2001) established that coastal erosion along the Caribbean coast was a product of a transgressive event over the last 150 years. Correa et al. (2007a,b) carried out an inventory of coastline changes, calculating erosion rates in the order of 1.5 m/yr for the 1938–2005 period along the southern Caribbean strip. Ortiz (2007) conducted the first characterization of wave extreme events and the relationship with erosion, establishing a direct relation between extreme wave events and high erosion rates, particularly at the Atlántico Department. Parra et al. (2008) defined the rising sea level trend in the order of 5 mm per year and attempted to evaluate its influence along the most important cities of the Caribbean coast.

Investigations by Rangel-Buitrago (2009), Rangel-Buitrago and Anfuso (2009), Rangel-Buitrago et al. (2011) and Botero et al. (2013) focused on analysing recent coast changes, associated vulnerability and the related anthropogenic intervention degree along Bolivar, Magdalena and La Guajira Departments, finding erosion rates of 2.5 m/yr, a high percentage of associated vulnerability and an extreme level of human intervention evidenced by construction of >350 coastal protection structures.

4.2. Magnitudes of coastal changes

Analysis coastal evolution trend by mean of satellite images and aerial photographs for the 1980–2014 period revealed that 49% of the Caribbean coast of Colombia is undergoing serious erosion (Table 2).

Specifically, along the **La Guajira Department**, maximum erosion rates were recorded in Dibulla (3 m/yr), Camarones (2.3 m/yr) and Riohacha (4 m/yr – Fig. 2). The area western of Riohacha city, a 5.2 km sector, has been experiencing erosion trends at least since the last 11 years, and rates have reached 4 m/yr (Fig. 3), mainly related to a groin field east of the city that retains sand and impedes sediment movement westwards. US$9 million was approved by the government for a series of projects to mitigate these effects.

Magdalena Department shows maximum retreat rates of 15 m/yr; The Cienaga – Tasajera sector shows high erosion rates of 3 m/yr near Tasajera town. The "erosion" category was associated with the Tayrona National Natural Park (PNNT) and the Muchachitos sector (Fig. 2). Both areas are characterized by high grade fracturing and faulting (Fig. 2). The most critical area is named "Km 19", on the main road between Barranquilla and Santa Marta. This 2 km sector length has experienced significant changes in the last ten years with erosion rates that reached values of 19 m/yr (Fig. 3) – mainly related to a human-induced sedimentary imbalance that affects a significant ecosystem, i.e. the barrier islands system of the Cienaga Grande de Santa Marta (CGSM) – Pajarales Lagoon Complex (PC). In the last two years, the National government has invested close of US$6 million for building a series of hard structures that includes groins, seawall and rip-rap revetment that have so far been unsuccessful.

Within the **Atlántico Department**, maximum erosion rates were recorded immediately on the western side of the Magdalena River delta and at Puerto Colombia beaches (Fig. 4), due to migration of vast sand bodies linked to important sedimentary supplies from the Magdalena River. The most critical area is Puerto Colombia beach. Along this 6.5 km length beach, erosion values reached 29.5 m/yr in the last 20 years (Fig. 5). The high erosion rates and destruction of structures are related to the areas high susceptibility to waves associated with cold fronts and hurricanes, wave propagation patterns, influenced by jetties at the Magdalena River mouth and to bathymetric characteristics. Around US$ 25 million will be invested to mitigate the impact of coastal erosion and to execute works that will improve the Puerto Colombia pier environment.

Along the **Bolivar Department**, maximum erosion rates (Fig. 4) were recorded at the areas of Playetas (2 m/yr), Tierrabomba (3 m/yr) and Cartagena urban area (1.7 m/yr). More than 100 groins (emplaced in the 1970s) occur at the latter area all along important sand beaches, such as, El Laguito, Bocagrande, Las Tenazas and

Table 2
Coastal evolution trend categories along the Caribbean coast of Colombia.

Department		Type				
		High erosion	Erosion	Stability	Accumulation	Total
La Guajira	Length (km)	153.0	154.9	348.1	41.1	697
	Percentage (%)	22	22	50	6	
Magdalena		52.1	186.9	24.1	38.9	302
		17	62	8	13	
Atlántico		18.4	18.3	16.5	17.8	71
		26	26	23	25	
Bolívar		111.0	83.0	228.1	46.9	469
		24	18	49	10	
Sucre		26.5	19.8	54.5	11.2	112
		24	18	49	10	
Córdoba		52.8	70.6	36.2	69.4	229
		23	31	16	30	
Antioquia		76.5	128.4	60.4	223.8	489
		16	26	12	46	
San Andres and Providencia		11.3	18.6	44.9	1.3	76
		15	24	59	2	
Total		502	680	813	450	2445
		21	28	33	18	100

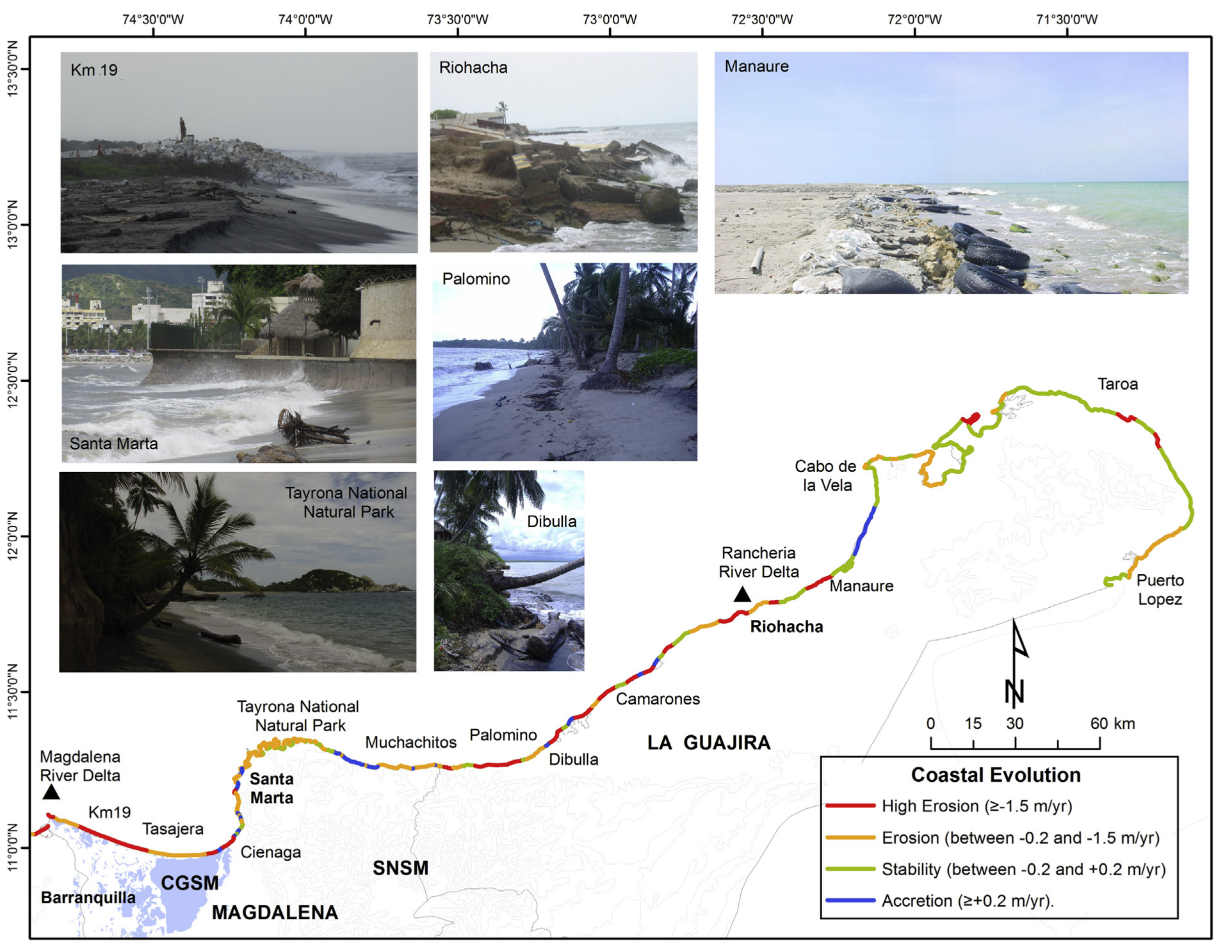

Fig. 2. Coastal evolution trend for the 1983–2013 period and erosion examples along the La Guajira and Magdalena Departments.

Marbella. The most critical area is a 1.5 km length at Tierrabomba Island with erosion rates of 2.7 m/yr in the last nine years (Fig. 5). High erosion rates are related to wave energy concentration and propagation patterns, sea level rise, neotectonic processes as well as human interventions. Local government authority mitigation measures have seen the construction of 9 groins, 5 breakwaters and 1 seawall, at an approximate cost of US $ 650,000.

For the **Sucre Department**, San Bernardo and Berrugas sectors show maximum retreat rates of 2 m/yr and 1.7 m/yr respectively (Fig. 4). The most critical area is a 1 km length stretch in the Tolu

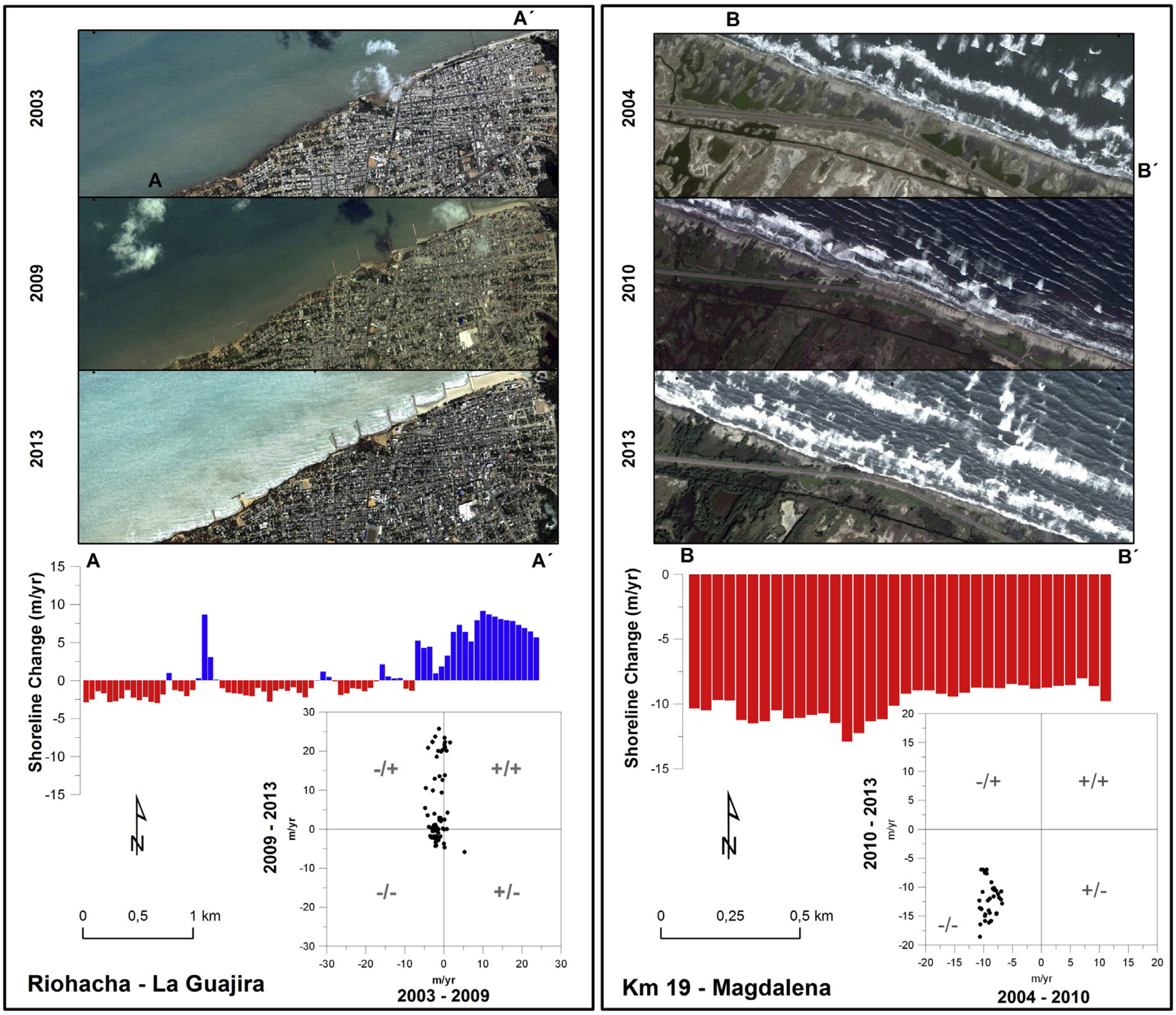

Fig. 3. Satellite images, shoreline changes and mean shoreline displacement calculated along Riohacha (La Guajira) and "Km 19" (Magdalena) Hotspots.

sector, which has experienced considerable erosion rate variations in the last ten years, with values reaching 3 m/yr (Fig. 5), primarily related to human-induced sedimentary imbalances associated with the development of more than 150 hard shore protection structures. Local government is planning to invest US $ 7 million to mitigate erosion by hard structures construction, beach nourishment and installation of reef balls together with mangrove restoration.

Within the **Cordoba Department**, high erosion rates were identified between Puerto Rey and Punta Brava related to retreat values of 90 m–220 m (Fig. 6). One of the most critical areas is "Punta de Broqueles", this sector – a 2 km length, has been experiencing erosion at least since the last three years, reaching rates of 56.5 m/yr (Fig. 7), mainly related to an imbalance in the terrigenous sediment supply derived from river catchment (dams). In 2013 about US $ 10 million was made available for a series of projects to mitigate coastal erosion effects in this tourist area.

At the northern part of the **Antioquia Department**, at Punta Sabanilla and at Punta Arenas – Punta Caiman sector, maximum retreat rates of 3.4 m/yr and 3 m/yr were respectively recorded (Fig. 6). In the southern part, between Punta Yarumal and Punta Las Vacas, erosion rates reached values of 3.5 m/yr (Fig. 6). According to Correa and Vernette (2004), the erosion along Uraba sector (northern part of the Antioquia Department) could be related primarily to relative sea level rise, tectonic movements, as well as the effects of mud diapirism and hydro-isostacy plus anthropogenic action. In the last two decades, shoreline retreats of some 50–100 m occurred in places, such as, Zapata and Turbo municipalities and in the Punta Rey-Arboletes area rates of 30 m/yr are related to shoreline retreat of 900 m in the last 30 years (Fig. 7). The National Government of Colombia plans to invest close to US$ 25 million for reconstruction of Punta Rey (by means of a 1.6 km groin) and building a series of groins.

San Andres and **Providencia Islands** are two volcanic islands with a total length of 75 km located northwest of Colombia and 220 km from the coast of Nicaragua. Along both islands, 39% (29.8 km) of the investigated coast was included within the categories of "high erosion" (14.8% – 11.2 km) and "erosion" (24.4%–18.5 km – Fig. 8). 59% and 1.7% (44.8 km and 1.3 km) were respectively included within the "stability" and "accretion" categories (Fig. 8). The most critical area corresponds with San Luis Area. This sector of 0.5 km length has been experiencing considerable erosion rate variations in the last eight years with rates that reached values of 2.5 m/yr (Fig. 7). Coastal erosion along the islands is mainly related to sedimentary imbalances associated with destruction of ecosystems, such as, algae and corals that are the primary source of calcareous sediment. The previous hypothesis is supported by López-Victoria and Zea (2004, 2005) and Rodriguez-

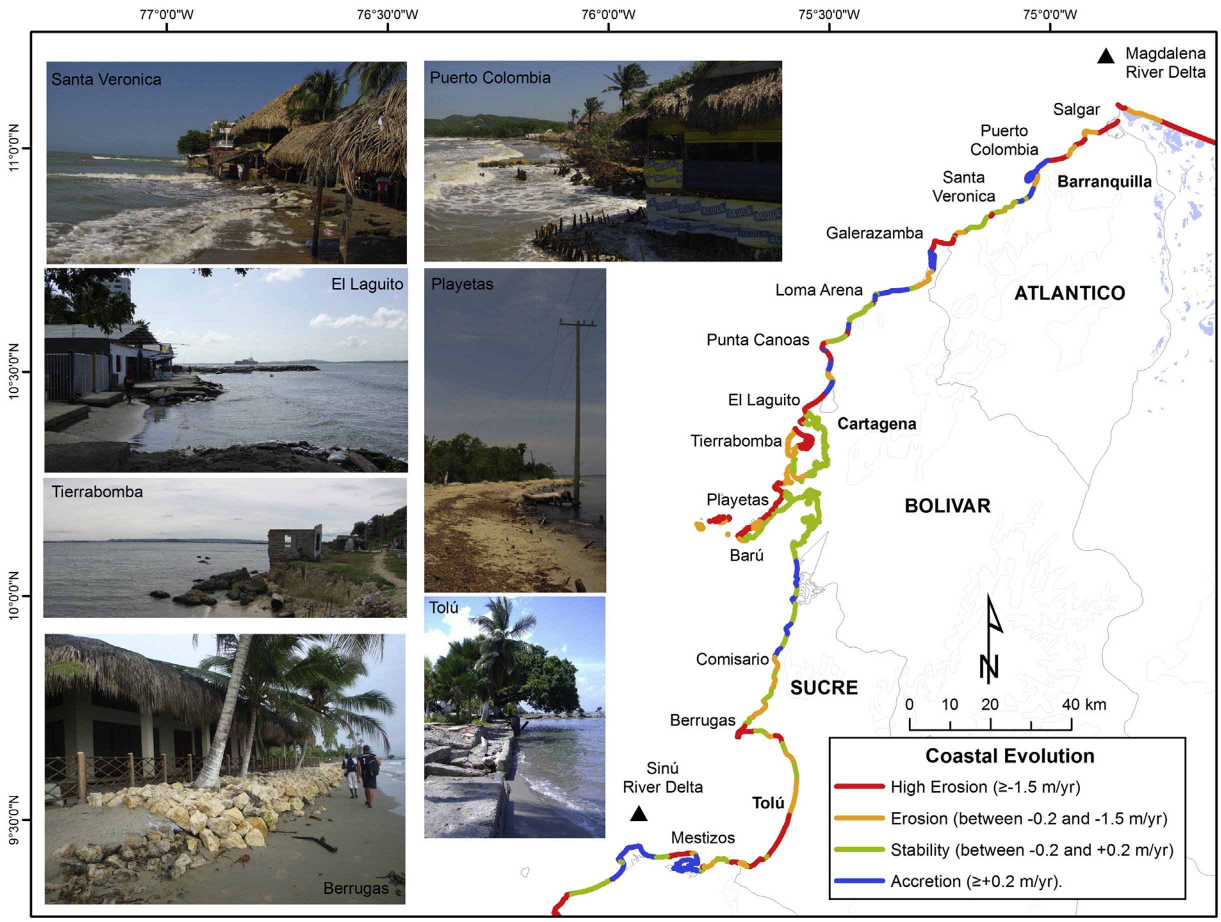

Fig. 4. Coastal evolution trend for the 1983–2013 period and erosion examples along the Atlántico, Bolivar and Sucre Departments.

Ramirez and Reyes-Nivia (2008) who explains impacts on ecosystems along the islands related by human and natural factors, as well their possible influences in medium and short-term changes along coastal zone. Both islands are susceptible to extreme wave events and sea level rise. Local government is planning to invest US$9 million to mitigate erosion specifically for beach nourishment, cliff recovery and strengthening of risk management strategies.

4.3. Main causes of erosion along the Colombian Caribbean coastline

The complexity of coastal erosion causes has been addressed in many studies (Van Rijin, 2011; Dean and Dalrymple, 2013; Pranzini and Williams, 2013), and interrelationships between natural processes and anthropogenic influences have been emphasized (Correa and Vernette, 2004). The high erosion rates measured suggests the strong importance of regional natural and human induced processes, such as:

- Relative sea level rise (RSLR)

This region only has the Cartagena station, which is part of the sea level worldwide data network collected by the Global Sea Level Observing System – http://www.psmsl.org/data/obtaining/stations/572.php. Hourly data allows determination, by means of the use of a least-square linear regression, of the trend in RSLS for the 1950–2000 periods. The time series indicates an RSLR increment of 5.5 mm/yr (Fig. 9), which is close of the values of 5.9 mm/yr and 5.5 mm/yr obtained by Restrepo and Lopez (2008) and Restrepo et al. (2012) respectively and fits with the global trend estimated by the IPCC (2013). The value of 5.5 mm/yr would mean an approximate elevation of 0.50 m in the next 100 years; when RSLR increases, low coasts (the study region) and deltaic lowlands with their related ecosystems as mangroves, corals and sea grasses, become more susceptible to erosion associated with inundations and flood events (Ericson et al., 2006). During a period of rapid RSLR, as is currently happening, there may not have been enough time for constructive forces to reach equilibrium along the beaches and much sand delivered by the rivers was left *in situ*. The most dramatic effects of RSLR changes occur along Cartagena city and near islands (i.e., Rosario and San Bernardo), where an extreme high tide produces significant inundations along these tourist areas.

- Extreme events

Along the Colombian Caribbean coast extreme waves are associated with hurricanes and cold fronts (Ortiz, 2012; Rangel-Buitrago et al., 2013). Hurricanes often originate in the Caribbean area from June to November and affect the coast with high winds, heavy rains and storm waves. Cold fronts – January, February and March, causes strong swell waves whose impact may be increased by Trade winds blowing from ENE, often striking the coast 48 h later with an average occurrence of six events per year (Ortiz et al., 2013). However, the islands of the San Andres and La Guajira and Atlantico sectors are the most susceptible areas. Extreme wave

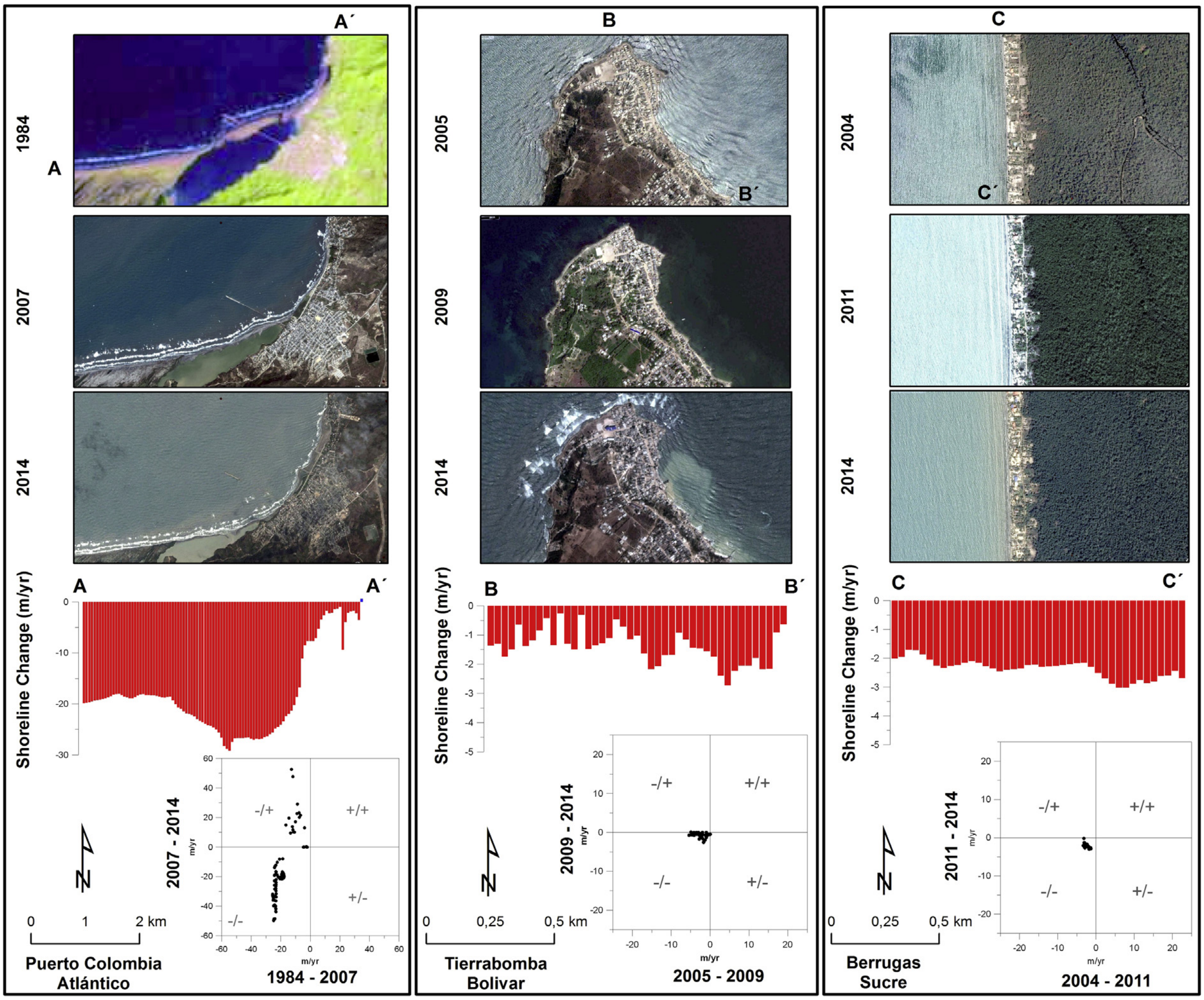

Fig. 5. Satellite images, shoreline changes and mean shoreline displacement calculated along Puerto Colombia (Atlántico), Tierrabomba (Bolivar) and Berrugas (Sucre) Hotspots.

events trigger beach flattering, erosion escarpments, overwash processes and destruction of anthropogenic structures especially on steep beaches because of their higher susceptibility to changes in the wave regime (Cooper and Pilkey, 2004). The most intense extreme wave event of the last 15 years along the coast was the cold front of 5 and 9 March 2009 (Ortiz et al., 2012). Waves generated by this event reached 2.5 m in significant height and led to severe erosion and damages along the entire study area. Damage depends on its relative magnitude, for instance on the relationship between storm wave height and modal wave height in the study area (Cooper and Pilkey, 2004; Cooper et al., 2009). High-energy events produce serious damage and a long recovery period is necessary for beaches to return to equilibrium (Benavente et al., 2000; Rangel-Buitrago and Anfuso, 2011), because the system requires greater sediment amounts and longer time periods to build up new systems and recover the eroded beach (Lentz and Hapke, 2011).

- Sediment supply

The primary source of terrigenous sediments is four large rivers (Atrato, Sinú, Magdalena and Rancheria) which drain the Andean region, as well as numerous small distributaries. The Caribbean drainage basins of these rivers are characterized by high-moderate rainfall patterns ranging from 1750 to 4944 mm in their watersheds, resulting in 1464 t km^{-2} yr^{-1} of sediment yield (Polania et al., 2001; Restrepo and Lopez, 2008). Sands from rivers and cliff erosion are the major sediment component for local beaches and availability is partially controlled by the seasonal wave regimes. At Colombian insular areas (i.e. San Andres Islands, San Bernardo and El Rosario archipelagos) and between Cartagena de Indias and the southern tip of the Morrosquillo Gulf, abundant calcareous materials is provided by sub-aerial and marine erosion of Plio-Pleistocene to recent coral reefs terraces and living reefs (Restrepo et al., 2012; Rangel-Buitrago et al., 2013).

Sediment transport intensity increases from NE towards the SW, the main direction of the littoral drift. The high erosion rates suggest that terrigenous and calcareous sediment supply to the coast is much less than the littoral transport capacity. Additionally, sediment supplies derived from eroding cliffs, sand bars and dunes are also insufficient to balance the sediment budget deficit.

The coastal morphology of the neighbouring areas of the four principal rivers deltas has been subject of substantial changes, due to the river basin interventions. Legal's (farmers) and non-legal's (drug dealers) have produced intense deforestation along these fluvial basins.

Dams construction favours accumulation of coarser sediments in artificial lakes and only fine sediments, not stable on beach, arrive to the coast. Dam construction and deforestation not only affect the fluvial sediment supply, but also the one of calcareous origin. Suspended sediment along the continental shelf has

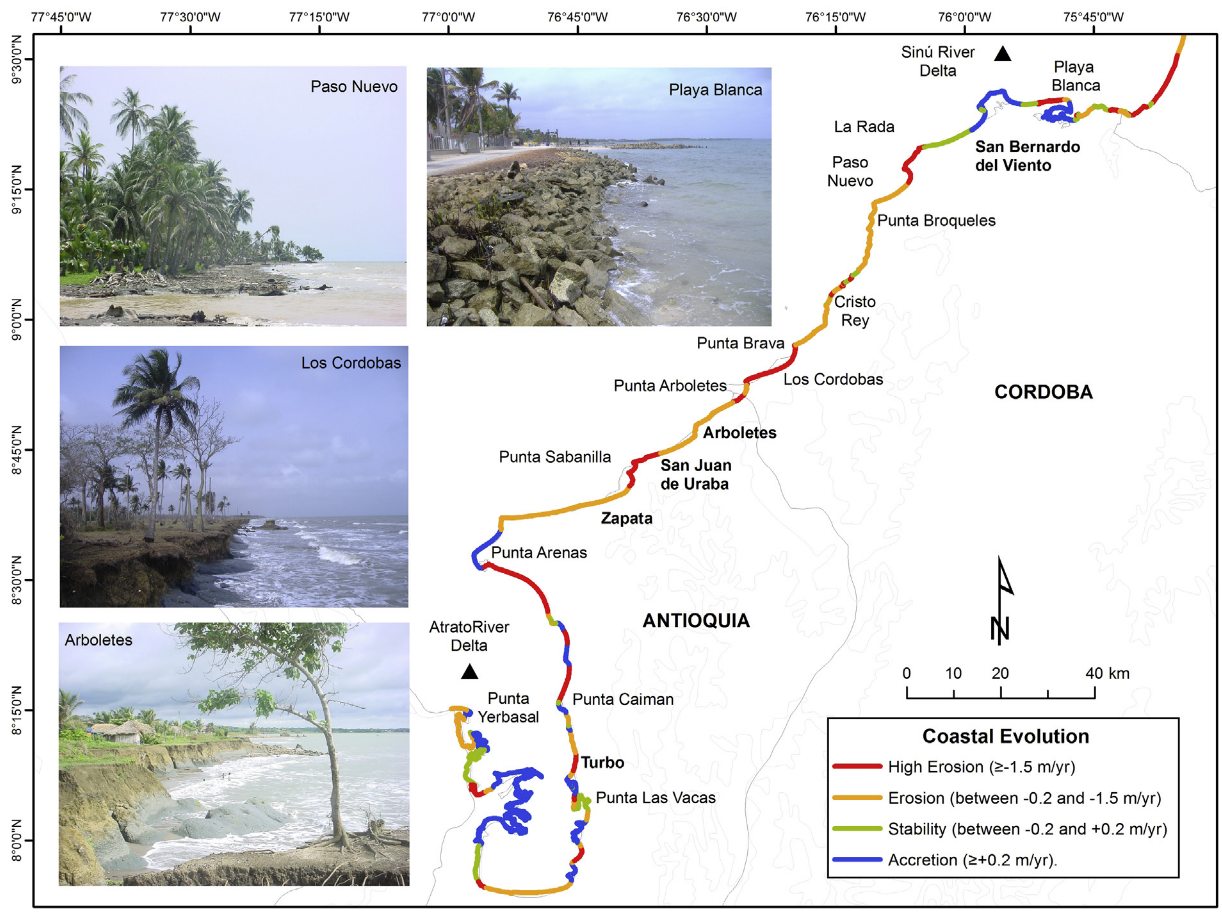

Fig. 6. Coastal evolution trend for the 1983–2013 period and erosion examples along the Cordoba and Antioquia Departments.

significantly contributed to the partial disappearance of coral and algae ecosystems and to a considerable reduction in abundance of sea grass beds, confirmed by Gardner et al. (2003) and Restrepo et al. (2012) who associated coastal ecosystem destruction with the fluvial fluxes derived from the Magdalena River.

- Anthropogenic induced sedimentary imbalances

The Magdalena River system is the primary drainage basin area (258,000 km^2) in Colombia with a length of 1700 km and occupies a significant portion of the Colombian Andes (Martinez et al., 1990; Restrepo and Lopez, 2008). From 21 years of daily data, Restrepo and Kjerfve (2000) established that this river provides a sediment load of 144 $\times$ 10^6 t/yr, corresponding to a sediment yield of 560 t/km^2/yr^1, the highest sediment yield of any medium-sized river along the entire South America eastern seaboard. However, most is lost offshore due a series of jetties called Bocas de Ceniza jetties, built in 1935 with the objective of facilitating ship navigation into Barranquilla port. The Bocas de Ceniza jetties were built in the apex of a turbidity system (Shepard, 1973), resulting in sediment transport directly to deep water. This sediment loss is the primary factor contributing to high erosion rates specifically between Barranquilla and Cartagena Cities. Physical changes caused by these jetties are related directly to the interruption of the net southwestward sand drift in the area (Martinez et al. (1990), Alvarado (2005), Anfuso et al. (2015) and this paper). This process triggered complete destruction of several offshore sand shoals located between Bocas de Ceniza and Cartagena.

These also impacted on important ecosystems, as in the case of the barrier islands system of the Cienaga Grande de Santa Marta (CGSM) – Pajarales Lagoon Complex (PC). The CGSM – PC is Colombia's largest coastal lagoon system (nearly 850 km^2) located between the Sierra Nevada de Santa Marta (SNSM) and the Magdalena River. During the early 70s, the Magdalena River water flow to the system was disrupted by road construction between Palermo and Salamina (Magdalena). Dikes and levees were built for flood prevention purposes in agricultural and pastoral areas, as well as diverting water for irrigation purposes. These works blocked the vast majority of saltwater and freshwater inlets of the Magdalena River. At present, this coastal lagoon has just one inlet (Boca de la Cienaga), which is insufficient for water circulation between the sea and lagoon. Most available sediment is trapped in the lagoon with high sedimentation rates of between 10 and 13 cm/yr (Vilardy et al., 2011), which is responsible for the intense coastal erosion observed along the Barranquilla-Santa Marta sector (i.e. Km 19) and the cause of severe ecological impact along this lagoon is reflected in mangrove forest composition and degradation, and massive occurrences of oyster mortality (Botero and Salzwedel, 1999; Vilardy et al., 2011).

Until they were dammed, the Rancheria and Sinú Rivers were the primary sources of fluvial sediment supplied to the north and south Colombian Caribbean coast. Constructed in the early 1990s and in the beginning of the 2010s they were increased in size in order to cover a catchment area of 75 km^2 and 7 km^2 respectively. Dam construction brought a significant reduction in water volume reaching the sea and hence an alteration of fluvial sediment transport, as upstream sediment is trapped in the dam lake. This has also significantly affected the water inlet performance in terms

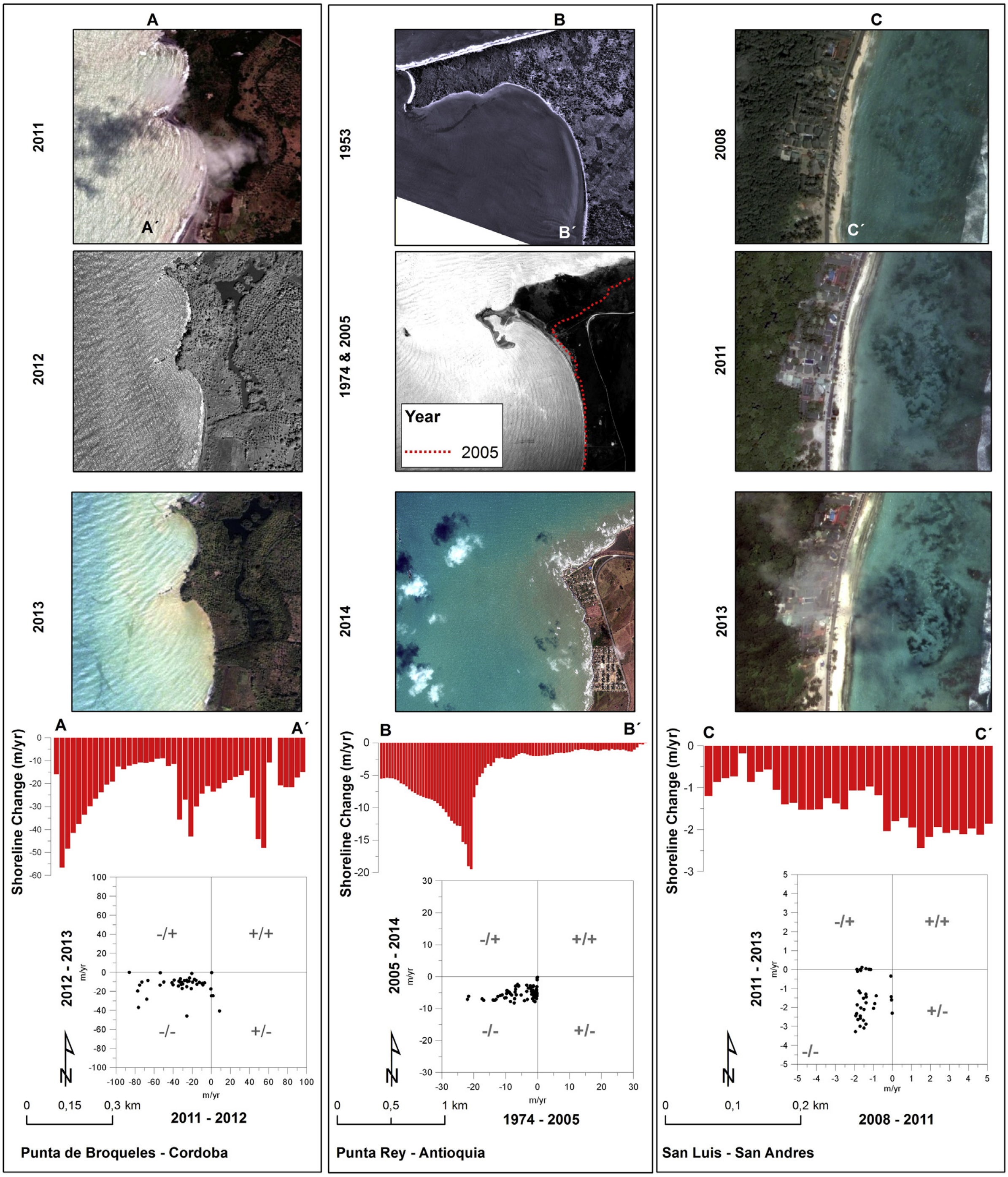

Fig. 7. Satellite images, shoreline changes and mean shoreline displacement calculated along Punta de Broqueles (Cordoba), Punta Rey (Antioquia) and San Luis (San Andres) Hotspots. In order to illustrate the extreme erosion in Arboletes the 1953 aerial photograph is also shown (dot red line represents the 2005 shoreline). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of facilitating new sediment laden water flow to the sea, which partly explains the high coastal erosion rates calculated along the La Guajira and Cordoba departments.

Where this practice is still active, sand mining activities are partly responsible for the observed long-term erosion trend along the Caribbean coastline. In some areas, significant beach sand amounts (coastal mining), sand collected from small river mouths (fluvial mining) and sediment extracted from cliff areas (bluff top mining) have been taken and used for construction purposes/landfill, despite it being deemed illegal under Colombian laws. In some localities beach sand was used to construct entire small towns in the early 1950s (i.e. Paso Nuevo, La Rada, Cristo Rey, Arboletes, along Cordoba and Antioquia Departments). Beach sand dissipates extreme wave energy within the surf zone and extraction has reduced the shore-connected sand bars prevalent along some parts of the coast, e.g. Sucre, Cordoba and Antioquia Departments. Absence of these sand bars allows wave energy to reach the shore faster and beach erosion occurs. Dean (2004) and Thornton et al.

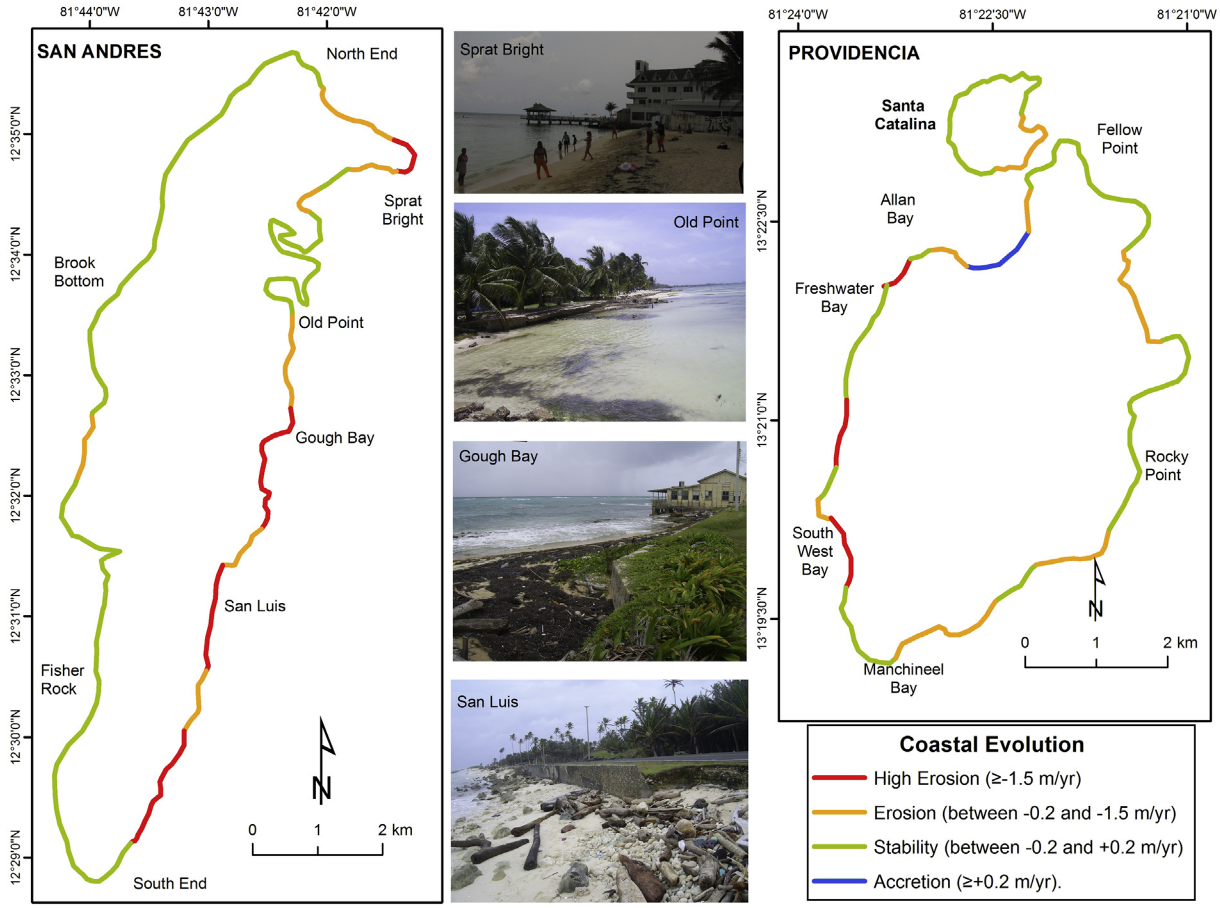

Fig. 8. Coastal evolution trend for the 1983–2013 period and erosion examples along San Andres and Providencia Islands.

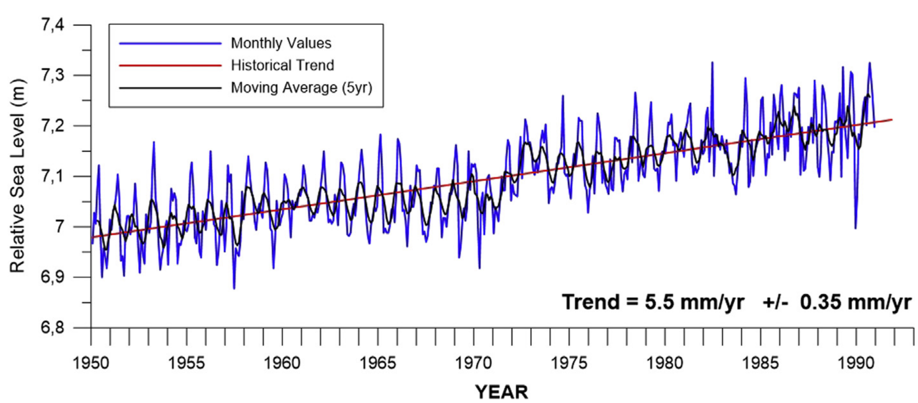

Fig. 9. Relative sea level time series for the Cartagena de Indias station (the only one along the Colombian Caribbean coast). Data source: http://www.psmsl.org/data/obtaining/stations/572.php.

(2006) considered that sand extraction can be seen as "digging a hole" in the surf zone and it would be expected that this would be filled by upcoast drift. The SW transport of sand intercepted by mining would reduce sand availability to beaches SW of the mining operations, as happens along the Cordoba department.

Another important factor is emplacement of coastal engineering structures. At the beginning of 2014, more than 1000 hard structures (both cross and longshore – groins, concrete walls, breakwaters, among others) had been built along the Colombian Caribbean coast, with highest concentrations located in Cordoba, Sucre and Bolivar Departments and the city of Santa Marta, where 623 hard structures along 538 km coastline length (23% of the total Caribbean coast length) were identified. This data exceeds that presented by Rangel-Buitrago et al. (2011), which had 496 hard structures for the same area. A high percentage (close to 90%) of these 623 hard structures, have had very limited success (Fig. 10). Also, the hard engineering structures have had adverse environmental impacts because they changed coastal sediment transport patterns due to primary processes as: groins catching sediments transported alongshore, creating a sediment deficit downdrift (i.e., Cartagena); diffracting incoming waves, concentrating in some places wave energy with subsequent coastal erosion (i.e., Sucre);

Fig. 10. Examples of structures used along the study area in order to protect the coast from erosion. A) tyres used as groins along Palomino – La Guajira, B) Sand-Bags used in Palmarito – Atlántico, C) Rock revetments in Cartagena, D and E) Rip-rap revetments and groins at Tolu and Coveñas (Sucre), F and G) Groins at Playa Blanca and Arboletes – Cordoba and Antioquia Departaments, H) Revetment located at San Luis (San Andres Island).

reflecting incoming waves, sporadic rip-currents, hampering energy dissipation with subsequent increase in turbulence and cross-shore erosion e.g. the Rosario islands.

Within the last ten years, the population of the area increased from 3,540,684 to 4,049,867 inhabitants, i.e. by 15% (DANE, 2013). This large population increment has also initiated and, in some cases favoured, coastal erosion. Work opportunities, as well as violence in some areas of Colombia due to illegal army groups, have brought a large migration of people from inland to the coast triggering inhabitation for large portions of the coastal zone (in some cases in non-legal ways). As a result, many coastal resources, such as, mangroves have been drained and destroyed for human settlement purposes. This kind of practice has broken the natural windbreak and coastal erosion protection system. Currently, with high urbanization rate along the coastal zone, less space is available to adequately respond to eroding forces or to adjust to changes, such as, sea-level rise. Population growth has also created irrational coastal land use development and, with this, unwise management practices by local community and authorities.

4.4. Caribbean Colombian erosion control measures

Cooper and McKenna (2008), McKenna et al. (2008) and Anfuso et al. (2012) considered that the term 'coastal protection' meant different things to different people. To environmentalists and ecologists it means letting nature take its course to protect the ecosystem; whilst to landowners and engineers it meant constructing something to protect property. However, protection is satisfactory only if its impacts are disregarded (Anfuso et al., 2012), but these are usually very high in socio-economic, demographic, ecological, physical and climatic terms (Fabbri, 1998).

Protection was the common denominator for Colombia and, over the past 30 years, the first option (almost always) was a hard structure – groins and breakwaters – the "people's favourite choice", as the most common engineering practices for protecting coasts against erosion (Charlier et al., 2005; Stancheva et al., 2011).

Coastal erosion management is currently only on an "action-reaction or post-disaster" basis; i.e. initiatives to control it are triggered by emergencies and not risk prevention. While planning for post-disaster response is an important function in disaster management, a disaster management policy based on this alone is flawed (Wenzel et al., 2007). Many protection structures have been built and installed in response to local stakeholder pressure when properties are exposed to destruction, without carrying out required environmental impacts assessment or preliminary potential risk and collateral effects evaluations. Many examples exist where millions of dollars of public investment were urgently approved to control erosion (i.e. Km 19, Tierrabomba, and Arboletes). In most cases, the "urgent coastal erosion solutions" were emplaced in order to reduce – in a "fast way" – the immediate erosion process impact. Most times, these "fast" coastal defence structures are useless and general knowledge about their success are usually unknown.

Hard stabilization structures have altered the natural environment of the Colombian Caribbean coast, producing:

- Coastal armouring.
- Sediment accumulation in some specific areas;
- Significantly reduced sediment supplies to downdrift areas e.g. Bolivar and Cordoba coastlines;
- Intensified erosion processes or generated new erosion hot spots nearby. In this coastline, forces that continue building hard protection structures cause the well-known "Domino Effect" (Cooper et al., 2009).

Other problems associated with emplacement of coastal protection structures are the increased risk of drowning and the negative impact of structures on coastal scenery (Williams and Micallef, 2009), especially evident at Bolivar, Sucre, and Cordoba departments where groins and breakwaters create a significant visual impact. Cooper and McKenna (2008) and Cooper et al. (2009) argued that these actions are a typical sequence of events where one ill-advised action is "countered" by a subsequent one, which in turn creates other problems. The coastal Caribbean situation also show an additional common problem in the degradation caused by efforts to preserve the interest of a small number of stakeholders, which is not only suffered by society in general through loss of environmental quality and amenity, but is paid for through public funding of such structures (Cooper and McKenna, 2008).

From a coastal erosion management viewpoint, determination of the best effective and efficient solutions must be based on knowledge of erosion/accretion patterns and trends (Komar and McDougal, 1988). As stated earlier, the hard protection option was virtually always carried out regardless of such assumptions and other protection options (such as beach nourishment or other soft solutions) and even other alternatives, such as “relocation”, “adaptation”, or “do nothing” have not been considered along the Caribbean coast of Colombia.

Soft engineering measures deserve a priority consideration, due to its ability of working with nature. A wide beach protects backing beach structures and activities and favours tourism enlarging the bathing area (Anfuso et al., 2012). In this sense, periodic nourishment works could be implemented in touristic places such as San Andres, Santa Marta, Puerto Colombia and Cartagena.

Relocation option seems an inevitable solution in fast eroding areas and probably the most appropriate solution for human settlements at Tierrabomba, Arboletes and for erosive hot spots along important coastal roads such as the Km 19 case (along the littoral road between Barranquilla and Santa Marta) and the Muchachitos sector along the coastal road connecting Santa Marta and Riohacha.

Adaptation consists in land use changes or adaptation of human structures to erosion/flooding processes. In the latter case, stilt houses can be emplaced along rural coastal areas sporadically affected by inundation processes, such as, San Andres Island and some sectors of Cartagena. Abandonment could be a solution for areas of low economic value strongly that are threatened by erosive processes, such as, coastal properties, – essentially small rural houses, found at La Guajira and Cordoba departments.

Prevention is of great importance by regulating future developments, e.g. by restricting certain activities in specific eroding zones which, in the near future, will probably experience severe erosion. This is the case of large portion of land close to tourist areas, such as, Cartagena and Tolu and Coveñas (Sucre).

4.5. Colombian institutions involved in managing the coast

There are three government institutions in charge of coastal erosion: The Ministry of Environment and Sustainable Development (MADS – acronym in Spanish), General Maritime Directorate (DIMAR) and the Colombian Oceanic Commission (CCO). However, it is not clear which Institution is directly responsible for addressing coastal erosion; similarly for the particular interferences and functions associated with this issue. Advances regarding coastal protection are very recent and considering the high magnitude of erosion recorded in the last 30 years, results are only sketchy.

MADS was created in 1993 and underwent two structural reorganizations in 2003 and 2011 and is the national public agency responsible for matters related to the environment and sustainable development. It performs and promotes activities directed at sustainable development through formulation, adoption and technical and regulatory orchestration of policies, based on the principles of participation and integrity in public administration. Under the denominate “Law 99” of 1993, a division of Marine Affairs was established with the objective of acting against coastal zone degradation. Similarly, the Integrated Coastal Management Policy was approved in 2000, and economically supported by a particular budget set by the Colombian Government; unfortunately, this Policy is currently much less applied than expected (Botero et al., 2013).

DIMAR is in charge of executing government maritime policy and its purpose is to direct, coordinate and controls all maritime activities in the terms indicated by Decree-Law 2324 of 1984 and following regulations. Therefore, it has a structure that contributes to strengthening Colombian maritime power, ensuring comprehensive maritime safety, protecting human life at sea, promoting maritime activities and the maritime scientific and technological development of the country. Despite challenges, administration of collective goods in coastal areas is among DIMAR responsibilities and these have not changed in the past 30 years, but coastal erosion and climate change are not yet among into the responsibilities of DIMAR, despite it being the Colombian Maritime Authority.

DIMAR is supported by the Research Centre Caribbean Oceanographic and Hydrographic (CIOH), created in 1975. This Centre prepares official nautical charting and also conducts basic and applied research in various disciplines of oceanography and hydrography, orienting knowledge obtained for the use of renewable marine resources in the country. Another significant effort made by this Institution was the use of LIDAR technology to scan the entire Caribbean coastline over the last eight years. Unfortunately most results and the LIDAR data obtained are not accessible due national order security restrictions. DIMAR is part of the Navy and has a highly centralized organization; this point favours coastal protection from short-term developments, but on the other hand they often take far too long in decision-making (Avella et al., 2009; Botero et al., 2013).

The CCO is an inter-sectorial body of advisory, consultation, planning and coordination of the National Government regarding matters of policies related with an ocean/coastal theme, as well as environmental issues related to sustainable development of Colombian seas and their resources. The CCO is, therefore, the highest level arena for decision-making on oceanic/coastal themes. Its most remarkable achievement was the National Oceanic and Coastal Areas Policy, approved in 2008, although implementation is currently less effective than expected. The highest level of this commission is a consultancy and advisory board and its decisions constitute only guidelines that can be easily disregarded (Avella et al., 2009).

Within this institutional framework coastal erosion problems has been a frequent issue, but no one has legal responsibility for its implementation. The main development has been the National Programme for Research, Prevention, Mitigation and Control of Coastal Erosion in Colombia (Guzman et al., 2008), established for the 2009–2019 period and headed by INVEMAR, a National Research Centre in marine issues linked to MADS.

Currently, MADS has begun a master plan to protect coastal areas of the country with a US$12,000 million total investment, which is expected to be almost 25 years in duration, partly funded by the German government. The primary goal is developing adaptation strategies in order to mitigate coastal hazards, such as, erosion, flooding and sea level rise. The first phase of this plan (development of study cases)will be executed in the next five years with the help of Regional Autonomous Corporations, which are the first environmental authority in the regional order.

4.6. Considerations for coastal management now subsumed into marine spatial

Coastal planning authorities need a robust and clear management framework in order to resolve issues related to coastal erosion. And these need to be focused on specific points:

- Identification of significant coastal erosion hot spots.
- Comprehension of the underlying coastal processes involved in the evolution of the above.
- Facilitate community involvement on coastal erosion issues and related problems to land uses.
- Evaluate and determine the optimal options for erosion protection and management taking into account viewpoints of all stakeholders.

Such objectives can be achieved by the Colombian government by undertaking a coastal law reform agenda based on three key elements:

- Refresh the current legislation with strong coastal management laws, which must be implemented. Unfortunately this is the key issue in which global coastal management seemingly fails (Van der Meulen, 2005).
- New arrangements to better support decision-making, including a decision support framework, a new-optimal coastal management/marine/spatial planning manual, and improved technical advice.
- More sustainable arrangements for funding and financing coastal management legislation.

At the same time, reforms must ensure:

- Reducing the consequences for individuals, communities, businesses and the environment of coastal erosion effects.
- Raising public awareness about coastal erosion risks.
- Providing an effective and sustained response to coastal erosion events.
- Prioritizing investment in communities most at risk.

Implementing these points will be the responsibility of everyone involved in or affected by coastal erosion. This includes: the Colombian Government; the regional and local Authorities; and the public. If all these stakeholders work together, avoiding overlapping competencies, they can reduce coastal erosion related risks and improve the quality of life for communities across the Caribbean region of Colombia.

5. Conclusions

Available data in the last 34 years confirmed the presence of a serious erosion process affecting the Colombian Caribbean coast. By means of aerial photographs, ortho-photographs and satellite images of different scales, this paper has shown the magnitudes of shoreline evolution for the 1980–2014 period. Some 48.3% (1182 km) of the coast is under “high erosion” and “erosion” categories and only 18.4% (450.5 km) and 33.2% (812.6 km) exhibit “accumulation” and “stability” categories respectively.

Despite only partial knowledge related with natural and human processes involved in erosion, this hazard can be generally associated with a diversity of factors contrasting in their degree of magnitude and influence. Evidences indicates that coastal erosion is related to natural factors, such as sea level rise, extreme wave events, sediment imbalances, among others, that interact together with an increasing number of anthropogenic interventions, carried out both alongshore and along adjacent drainage basins. Coastal erosion and the associated impacts are also closely related to fast growing developmental processes. This problem must be confronted and sustainably solved through high coastal management regulations, which are, currently, conspicuous by its absence in Colombia.

There exist negative experiences from implementation of hard structures as protection measures against coastal erosion. Direct and indirect experience indicates that optimal results, on money and a time basis, can be reached by means of a combination of different types of hard and soft solutions. Soft engineering measures deserve a priority consideration, due to its ability in ‘working with nature.’ Many examples prove that current coastal infrastructures have been more of a problem than a solution.

Stable and long-term coastal erosion monitoring does not exist and for this reason, it is not possible to evaluate the consequences of currently adopted decisions. Today, some improvement can be seen due to development of environmental studies, collaboration with research entities and elaboration of general management guidelines at regional and national level. Information already obtained with new technologies, such as, RADAR, LIDAR, could be a crucial input for future monitoring, but first a harmonic institutional framework should be developed to support data acquisition and analysis. The introduction of Maritime Spatial Planning as a single instrument, can reduce sectorial conflicts; produce transparency, facilitate investment and protect the environment. This could necessitate new laws which must be implemented as well as new arrangements geared to decision support networks.

Acknowledgements

This work is a contribution to research group “Geology, Geophysics and Littoral Process” (Barranquilla, Colombia) and “RNM-328” (Andalusia, Spain) and it was developed at the Basics Sciences Faculty (Physics Program) of the Universidad del Atlántico (Barranquilla, Colombia). Thanks to NASA (GLOVIS), USGS and Instituto Geografico Agustin Codazzi (IGAC) for providing the images used in this work.

References

Addo, K., Lamptey, E., 2013. Innovative technique of predicting shoreline change in developing countries: case of Accra erosion and causal factors. In: Finkl, C. (Ed.), Coastal Hazards. Springer, New York, pp. 367–402.

Alvarado, M., 2005. Cartagena y el plan de restauración ambiental del Canal del Dique, y Barranquilla y las obras de profundización del canal navegable de acceso a la zona portuaria: Visión general. In: Restrepo, J.D. (Ed.), Los Sedimentos del Río Magdalena: Reflejo de la Crisis Ambiental. EAFIT Univ. Press, Medellín, pp. 217–254.

Alvarez, W., 1967. Geology of the Simaura and Carpintero Areas Guajira Peninsula, Colombia. Phd. thesis. Department og Geology Princeton University, New Jersey.

ANATO (Asociación Colombiana de Agencias de Viajes y Turismo), 2013. Compendio de estadísticas turísticas de ANATO, 2013 ed.

Andrade, C., 2008. Cambios Recientes del Nivel del Mar en Colombia. In: Restrepo, J.D. (Ed.), Deltas de Colombia: morfodinámica y vulnerabilidad ante el Cambio Global. EAFIT Univ. Press, Medellin, pp. 103–122.

Anfuso, G., Martinez, J.A., Rangel-Buitrago, N., 2012. Bad erosion management: the southern sicily case study. In: Pilkey, O., Cooper, A. (Eds.), Pitfalls of Shoreline Stabilization. Springer, New York, pp. 215–233.

Anfuso, G., Rangel-Buitrago, N., Correa, I., 2015. Evolution of four different sandy features along the Caribbean littoral of Colombia. In: Randazzo, G., Jackson, D., Cooper, A. (Eds.), Sand and Gravel Spits – Coastal Research Library nº 12. Springer, New York, pp. 1–21.

Aristizabal, O., Calderón, B., Susana, A., Ignacio, P., Vernette, G., Siegert, E., Correa, I., 2001. Erosión marina en el litoral Caribe colombiano (Sector Punta Rey – Turbo): Introducción a sus causas naturales y antropicas. In: Memorias del congreso latinoamericano sobre ciencias del mar. San Andrés Isla. 6 pp.

Avella, F., Burgos, B., Osorio, A., Parra, E., Vilardy, S., Botero, C., Ramos, A., Mendoza, J., Sierra, P., López, A., Alonso, D., Reyna, J., Mojica, D., 2009. Gestión del litoral en Colombia. Reto de un país de tres costas. In: Arenas, P., Chica, A. (Eds.), Manejo Costero Integrado y Política Pública en Iberoamérica: Un Diagnóstico. Necesidad de cambio. Red Iberoamericana en Manejo Costero Integrado (CYTED), Cadiz, pp. 175–209.

Becker, M., Meyssignac, B., Letetrel, C., Llovel, W., Cazenave, A., Delcroix, T., 2012. Sea level variations at tropical Pacific islands since 1950. Glob. Planet. Change 80–81, 85–98.

Benavente, J., Gracia, F.J., López-Aguayo, F., 2000. Empirical model of morphodynamic beachface behaviour for low-energy mesotidal environments. Mar. Geol. 167, 375–390.

Boak, E., Turner, I., 2005. Shoreline definition and detection: a review. J. Coast. Res. 21 (4), 688–703.

Botero, C., Anfuso, G., Rangel-Buitrago, N., Correa, I., 2013. Coastal erosion monitoring in Colombia: overview and study cases on Caribbean and Pacific coasts. In: Cipriani, L. (Ed.), Coastal Erosion Monitoring: a Network of Regional Observatories. Nouva Grafica Fiorentina, Florenc, pp. 199–214.

Botero, L., Salzwedel, H., 1999. Rehabilitation of the Ciénaga Grande de Santa Marta, a mangrove-estuarine system in the Caribbean coast of Colombia. Ocean. Coast. Manag. 42, 243–256.

Cambers, G., 1998. Planning for Coastal Change in the Eastern Caribbean e Summary of the COSALC Project Activities 1996–1997. Technical Report. COSALC-UNESCO, Puerto Rico, p. 98.

Charlier, R.H., Chaineux, M.C.P., Morcos, S., 2005. Panorama of the history of Coastal Protection. J. Coast. Res. 21 (1), 79–111.

Chuvieco, E., 2000. In: . Fundamentos de Teledetección Espacial. Rialp, Madrid.
Clark, J.R., 1996. Coastal Zone Management Handbook. CRC Press/Lewis Publishers, Boca Raton.
Cooper, J.A.G., Pilkey, O.H., 2004. Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. Glob. Planet. Change 43, 157–171.
Cooper, J.A.G., McKenna, J., 2008. Working with natural processes: the challenge for coastal protection strategies. Geogr. J. 174 (4), ,315–331.
Cooper, J.A.G., Anfuso, G., Del Río, L., 2009. Bad beach management: European perspectives. Geol. Soc. Am. 460, 167–179.
Cooper, J.A.G., Pilkey, O.H., 2012. Pitfalls of Shoreline Stabilization. Springer, New York.
Correa, I.D., 1990. Inventario de erosión y acreción litoral (1793–1990) entre Los Morros y Galerazamba, Departamento de Bolívar, Colombia. In: Hermelin, M. (Ed.), Environmental Geology and Natural Hazards of the Andean Region. AGID, Medellin, pp. 129–142.
Correa, I.D., Vernette, G., 2004. Introducción al problema de la erosión litoral en Urabá (sector Arboletes – Turbo) costa Caribe colombiana. Bull. Mar. Coast. Res. 33, 7–28.
Correa, I.D., Alcántara, J., 2005. Historical and recent shore erosion along the Colombian Caribbean Coast. J. Coast. Res. SI 49, 52–57.
Correa, I.D., Acosta, S., Bedoya, G., 2007a. Análisis de las causas y monitoreo de la erosión litoral en el Departamento de Córdoba. Corporación Autónoma de los Valles del Sinú y San Jorge (CVS) - Universidad EAFIT, Medellín.
Correa, I.D., Rios, A., Gonzales, D., Toro, M., Ojeda, G., Restrepo, I., 2007b. Erosión litoral entre Arboletes y Punta San Bernardo, Costa Caribe Colombiana. Bol. Geol. 29 (2), 117–128.
Correa, I.D., Morton, R.A., 2011. Coasts of Colombia. U.S. Department of the Interior USGS, St. Petersburg, Florida. Available from: http://coastal.er.usgs.gov/coasts-colombia/.
Crowell, M., Letherman, S.P., Buckley, M.K., 1991. Historical shoreline change: error analysis and mapping accuracy. J. Coast. Res. 7 (3), 839–852.
CTO (Caribbean Tourism Organization), 2013. Caribean tourism e State of the industry year 2013 Ed. CTO, Barbados.
DANE (National Department of Statistics), 2013. General Census of Colombia y (Report 1). DANE, Santa Fe de Bogota.
Dean, R.G., 2004. Beach Nourishment: Theory and Practice. World Processes along the Central Coast of California. Scientific Publishing Co, Los Angeles.
Dean, R., Dalrymple, R.A., 2013. Coastal Processes with Engineering Applications. University Press, Cambridge.
Ericson, J.P., Vorosmarty, C.J., Dingman, S.L., Ward, L.G., Meybeck, M., 2006. Effective sea-level rise and deltas: causes of change and human dimension implications. Glob. Planet. Change 50, 63–82.
Fabbri, K.P., 1998. A methodology for supporting decision making in integrated coastal zone management. Ocean. Coast. Manag. 39, 51–62.
Florez, A., Robertson, K., 2001. Morfodinámica del litoral Caribe y amenazas naturales. Cuad. Geogr. Rev. Colomb. Geogr. 10 (1), 1–35.
Gardner, T.A., Cote, I.M., Gill, J.A., Grant, A., Watkinson, A.R., 2003. Long-term region-wide declines in Caribbean corals. Science 301, 958–960.
Goldberg, E.D., 1994. Coastal Zone Space: Prelude to Conflict. UNESCO Regional Forum, Paris.
Guzman, W., Posada, B., Guzman, G., Morales, D., 2008. Programa nacional de investigación para la prevención, mitigación y control de la erosión costera en Colombia – PNIEC: Plan de Acción 2009–2019. Invemar, Santa Marta.
INGEOMINAS, 1998. Geomorfología y aspectos erosivos del litoral Caribe colombiano. Publicación geológica especial – INGEOMINAS, Bogotá.
INVEMAR, 2006. Climatologie de la vitesse et la direction des vents pour la mer territoriale sous juridiction colombienne 8 a 19N e 69 a 84W. Atlas ERS 1 et 2 et Quickscat, Colombie. CNRS e UMRS 8591. Laboratoire de Géographie Physique - Instituto de Investigaciones Marinas y Costeras, Santa Marta.
IPCC (Intergovernmental Panel on Climate Change), 2013. Climate Change 2013: the Physical Science Basis. Cambridge University Press, New York.
Javelaud, O., 1987. La sedimentation du plateau continental de la Colombie caraibe au cours du quaternarie terminal. Tesis doctoral. Université Bordeaux.
Jevrejeva, S., Moore, J.C., Grinsted, A., 2012. Potential for bias in 21st century semiempirical sea level projections. J. Geophys. Res. 117, D20.
Komar, P.D., McDougal, W.G., 1988. Coastal erosion and engineering structures: the Oregon experience. J. Coast. Res. 4, 77–92.
Leblanck, L., 1988. Estudio geológico litoral Caribe colombiano Fase III (Isla del Rosario). Bol. Cient. CIOH 8, 83–107.
Lentz, E.E., Hapke, C.J., 2011. Geologic framework influences on the geomorphology of an anthropogenically modified barrier island: assessment of dune/beach changes at Fire Island, New York. Geomorphology 126, 82–96.
López-Victoria, M., Zea, S., 2004. Storm-mediated coral colonization by an excavating Caribbean sponge. Clim. Res. 26, 251–256.
López-Victoria, M., Zea, S., 2005. Current trends of space occupation by encrusting excavating sponges on Colombian coral reefs. Mar. Ecol. 26, 36–41.
Martinez, J.O., Pilkey, O.H., Neal, W.J., 1990. Rapid formation of large coastal sand bodies after emplacement of Magdalena River jetties, northern Colombia. Environ. Geol. Water Sci. 16, 187–194.
Martínez, J.O., 1993. Geomorfología y amenazas geológicas de la línea de costa del Caribe central colombiano (sector Cartagena-Bocas de Ceniza). INGEOMINAS, Bogotá.
Martínez, A.M., Robertson, K., 1997. Variaciones cuaternarias del nivel del mar y sus implicaciones en las amenazas litorales del Caribe colombiano. IDEAM, Bogotá.
Martínez, J., Yokoyama, Y., Gómez, A., Delgado, A., Matsuzaki, H., Rendón, E., 2010. Late Holocene marine terraces of the Cartagena region, southern Caribbean: the product of neotectonism or a former high stand in sea-level? J. South Am. Earth Sci. 29, 214–224.
McKenna, J., Cooper, J.A.G., O'Hagan, A.M., 2008. Managing by principle: a critical analysis of the European principles of Integrated Coastal Zone Management (ICZM). Mar. Policy 32, 941–955.
Moore, L., 2000. Shoreline mapping techniques. J. Coast. Res. 16 (1), 111–124.
Nicholls, R.J., 2002. Rising sea levels: potential impacts and responses. In: Hester, R., Harrison, R.M. (Eds.), Global Environmental Change. Issues in Environmental Science and Technology. Royal Society of Chemistry, Cambridge, pp. 83–107.
Ortiz, J.C., 2007. Hurricanes and storms in the Colombian Caribbean since 1900. Bol. Cient. CIOH 25, 54–60.
Ortiz, J.C., Salcedo, B., Otero, L.J., 2012. Investigating the collapse of the Puerto Colombia Pier (Colombian Caribbean Coast) in March 2009: methodology for the reconstruction of extreme events and the evaluation of their impact on the coastal infrastructure. J. Coast. Res. 30 (2), 291–300.
Ortiz, J.C., 2012. Exposure of the Colombian Caribbean coast, including San Andrés Island, to tropical storms and hurricanes, 1900–2010. Nat. Hazards 61 (2), 815–827.
Ortiz, J.C., Otero, L.J., Restrepo, J.C., Ruiz, J., Cadena, M., 2013. Cold fronts in the Colombian Caribbean Sea and their relationship to extreme wave events. Nat. Hazards 13, 2797–2804.
Parra, R., Otero, L.J., Franco, F., Marriaga, L., 2008. Comportamiento del nivel del mar en el litoral Caribe colombiano. Bol. Cient. CIOH 26, 8–21.
Polania, J., Santos-Martínez, A., Mancera-Pineda, J.E., Botero Arboleda, L., 2001. The coastal lagoon Ciénaga Grande de Santa Marta. In: Seeliger, U., Kjerfve, B. (Eds.), Coastal Marine Ecosystems of Latin America. Springer-Verlag, Berlin, pp. 34–45.
Pranzini, E., Williams, A.T., 2013. Coastal Erosion and Protection in Europe. Routledge/Earthscan, London.
PROEXPORT – Promoción de Turismo, Inversión y Exportaciones, 2013. Informe de rendición de cuentas para el sector comercio, industria y turismo. Ministerio de Comercio, Industria y Turismo, Bogota.
Rangel-Buitrago, N., 2009. Geomorfología y cambios en la línea de costa entre el Cabo San Juan de Guía y el Río Cañas (Departamentos del Magdalena y La Guajira). Universidad EAFIT, Medellin. Tesis de Maestría.
Rangel-Buitrago, N., Anfuso, G., 2009. Assessment of Coastal vulnerability in la Guajira Peninsula, Colombian Caribbean Sea. J. Coast. Res. SI56, 792–796.
Rangel-Buitrago, N., Anfuso, G., 2011. An application of Dolan and Davis (1992) classification to coastal storms in SW Spanish littoral. J. Coast. Res. SI64, 1891–1895.
Rangel-Buitrago, N., Stancheva, M., Anfuso, G., 2011. Effects of coastal armouring in the Bolivar department (Caribbean Sea of Colombia). Prob. Geogr. 1–2, 97–106.
Rangel-Buitrago, N., Anfuso, G., 2013. Winter wave climate, storms and regional cycles: the SW Spanish Atlantic coast. Int. J. Climatol. 33, 2142–2156.
Rangel-Buitrago, N., Correa, I., Anfuso, G., Ergin, A., Williams, A.T., 2013. Assessing and managing scenery in the Caribbean coast of Colombia. Tour. Manag. 35, 41–58.
Restrepo, J.D., Kjerfve, B., 2000. Magdalena river: inter-annual variability (1975–1995) and revised water discharge and sediment load estimates. J. Hydrol. 235, 137–149.
Restrepo, J.D., Lopez, S., 2008. Morphodynamics of the Pacific and Caribbean deltas of Colombia – South America. J. S. Am. Earth Sci. 25, 1–21.
Restrepo, J.C., Otero, L., Casas, A., Henao, A., Gutierrez, J., 2012. Shoreline changes between 1954 and 2007 in the marine protected area of the Rosario Island Archipielago. Ocean. Coast. Manag. 69, 133–142.
Restrepo-Pace, P.A., Cediel, F., 2010. Northern South America basement tectonics and implications for paleocontinental reconstructions of the Americas. J. South Am. Earth Sci. 29, 764–771.
Rodriguez-Ramirez, A., Reyes-Nivia, M.C., 2008. Rapid assessment of the hurricane Beta effects on Isla Providencia (Colombian Caribbean). Bol. Investig. Mar. Cost. 37 (1), 217–224.
Sanchez, G.A., Forero, L.M., 1983. Aspectos geomorfológicos y cartográficos del litoral Caribe colombiano entre las desembocaduras de los ríos Magdalena y Sinú. In: Memorias de la 10ª Conferencia Geológica del Caribe. Cartagena, pp. 283–302.
Shepard, F.P., 1973. Sea floor off Magdalena delta and Santa Marta area, Colombia. Geol. Soc. Am. Bull. 84, 1955–1972.
Stancheva, M., Rangel-Buitrago, N., Anfuso, G., Palazov, A., Stanchev, H., Correa, I., 2011. Expanding level of coastal armouring: case studies from different countries. J. Coast. Res. SI 64, 1815–1819.
Thieler, E.R., Danforth, W., 1994. Historical shoreline mapping: improving techniques and reducing positioning errors. J. Coast. Res. 10 (3), 549–563.
Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., Miller, T.L., 2005. Digital Shoreline Analysis System (DSAS) version 3.0. In: US Geological Survey (Ed.), An ArcGIS Extension for Calculating Shoreline Change. USGS, Woods Hole, pp. 33–56.
Thornton, E., Sallenger, A., Conforto, J., Egley, L., McGee, T., Parsons, R., 2006. San mining impacts on long-term dune erosion in southern Monterrey Bay. Mar. Geol. 229, 45–58.
Van der Meulen, F., 2005. ICZM some 10 years after Rio: where do we stand and which way to go?. In: Ozhan, E. (Ed.), Prov of the 7th Int. Conf. On the Mediterranean Coastal Environment, Medcoast, '05, vol. 1. METU, Ankara, Turkey, pp. 1–8.
Van Rijin, L., 2011. Coastal erosion and control. Ocean. Coast. Manag. 54, 867–887.
Vernette, G., Mauffret, A., Bobier, C., Briceño, L., Gayet, J., 1992. Mud diapirism fan sedimentation and strike-slip faulting, caribbean colombian margin.

Tectonophysics 2002, 335–349.
Vernette, G., 1985. La plateforme continentale Caraibe de Colombie (du debouchede Magdalena au golfe de Morrosquillo). Importance du diapirisme arigileux sur la morphologie et la sedimentation. Universidad de Bordeaux, Bordeaux.
Vilardy, S.P., González, J.A., Martín-López, B., Montes, C., 2011. Relationships between hydrological regime and ecosystem services supply in a Caribbean coastal wetland: a social-ecological approach. Hydrol. Sci. J. 56 (8), 1423–1435.
Wenzel, F., Bendimerad, F., Sinha, R., 2007. Megacities – megarisks. Nat. Hazards 42, 481–491.
Williams, A., Micallef, A., 2009. Beach management, Principles and Practice. Earthscan, London.