Journal of South American Earth Sciences 127 (2023) 104371

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

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

Coastal erosion and accretion on the Caribbean coastline of Costa Rica long-term observations

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A R T I C L E I N F O

Keywords:
Coastal erosion
Shoreline change
Satellite image
Caribbean coastline
Costa Rica

A B S T R A C T

Several studies show erosive processes on the Caribbean coastline of Costa Rica. These processes may be accelerated as a result of an increase in the sea level. This study covered the entire Caribbean coastline of Costa Rica between 1986 and 2019. This allowed reporting new sites with accelerated coastal accretion and erosion processes, as well as confirming other processes that have already been identified. The methodology was based on shoreline rising images obtained from Landsat and on their processing in a Geographical Information System supported with the "Digital Shoreline Analysis System" (DSAS) tool. The presence of important accretion areas related to the mouth of significant fluvial systems, such as Colorado, Parismina, Matina, Estrella, and Sixaola rivers is highlighted. Moreover, eight beach sectors showing erosion problems have been analyzed. The beach located to the south of Isla Portillos and beaches located on Cahuita Point stand out due to their intensity. Additionally, an intense beach erosion process has been detected at Soropta in Panamá. It should be highlighted that six of the eight sites showing erosion are located within protected zones. This confirms the little anthropic interference on these processes. It was not possible to find a difference between the north and the south of the Caribbean Coast in terms of the magnitude of coastal erosion. The contribution of the rivers is a key factor in the North Caribbean while the responses to the 1991 earthquake conditioned the behavior on the South coast. The results may serve as a basis for management plans or adaptation to climate change proposals.

1. Introduction

Coastal erosion has currently become important due to the rising sea level (Zhang et al., 2004; Ashton et al., 2008), and mainly due to the social and economic exposure experienced in low-elevation zones (IPCC, 2014; Hinkel et al., 2013).

Globally, a net coastal land loss of 14,000 km^2 is estimated between 1984 and 2015 (Mentaschi et al., 2018). Anthropogenic and natural factors, and the change in the sea level are mentioned among the causes. The construction of dams, mangrove degradation, land use changes, and the construction of breakwaters are included among the anthropogenic factors. Regarding natural factors, special reference should be stated to the effect of tsunamis, storms, and climate variability, i.e., the Niño phenomenon, which favors the generation of more frequent storms in some regions. Finally, it is clear that the increase in the sea level is already affecting lands experiencing subsidence, (Mentaschi et al., 2018).

On the other hand, Luijendijk et al. (2018) state that 24% of sandy beaches in the world are permanently eroded at a rate exceeding 0.5 m/y, from which, 16% experience erosion rates above 1 m/y. In addition to the causes already stated sand mining, the construction of works on the coastline, i.e., ports and breakwaters, and the sand drift from fluvial systems should be included (Mentaschi et al., 2018).

While in the papers mentioned Caribbean coastlines show low to moderate change rates, Rangel et al. (2015) report that 50% of shows erosion for the Colombia coastline, and Torres et al. (2010) obtain rates of up to 17.1 m/year, in Campeche state, Mexico. Some other reports document relevant erosion processes related to tropical storms and extreme waves (Guido et al., 2009; Barrantes et al., 2020b; Barreto et al., 2021).

In Costa Rica, some studies have warned about coastal erosion in the Caribbean (Barrantes et al., 2020a; Lizano, 2013; Lizano and Gutiérrez, 2011). On the other hand, Barrantes and Sandoval (2021) documented that for the Southern Caribbean coastline (from Limón city to the border with Panama), 23.4% of the shoreline experiences a retreat greater than 0.5 m/y. These authors highlight significant erosive processes between

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https://doi.org/10.1016/j.jsames.2023.104371
Received 20 October 2022; Received in revised form 18 April 2023; Accepted 24 April 2023
Available online 5 May 2023
0895-9811/

Fig. 1. Caribbean coast of Costa Rica.

Table 1
Images used according to the zone.

Zone	Date	Zone	Date
Northern Caribbean	2019/05/03	Southern Caribbean	2019/14/03
	2014/07/03		2014/01/04
	2000/13/02		2000/25/03
	1998/19/09		1998/28/09
	–		1992/27/03
	1991/24/03		1991/02/04
	1990/05/03		1990/18/02
	1986/06/02		1986/30/11

Table 2
Uncertainty in coastline digitalization.

Image date	Pixel size (m)	Error due to georeferencing (m)	Error due to digitalization (m)	Total error (m)
2019-05-03	30	6.338	6.596	31.364
2019-14-03	30	6.335	8.953	31.942
2014-07-03	30	5.648	12.332	32.924
2014-01-03	30	6.342	11.089	32.607
2000-13-02	30	ND	13.774	-[a]
2000-25-03	30	4.528	14.416	33.590
1998-19-09	30	4.699	9.016	31.676
1998-28-09	30	6.602	11.365	32.753
1992-27-03	30	4.468	14.120	33.456
1991-24-03	30	4.637	14.424	33.609
1991-02-04	30	4.554	11.801	32.558
1990-05-03	30	4.636	7.350	31.233
1990-18-02	30	4.501	9.812	31.883
1986-06-02	30	5.001	13.175	33.145
1986-30-11	30	4.438	6.407	30.996

[a] It was not possible to obtain the data to make the calculation.

Table 3
Categories where the changes in the shoreline were analyzed.

Category	Retreat (erosion) m/y	Advance (accretion) m/y	Stability m/y
Stable	–	–	0.5 to −0.5
Minor	−0.5 to −1	0.5 to 1	–
Intense	−1 to −3	1 to 3	–
Severe	−3 to −5	3 to 5	–
Extreme	< −5	<5	–

Table 4
Status of the Caribbean shoreline of Costa Rica based on LRR.

Status	Caribbean (%)	Northern Caribbean (%)	Southern Caribbean (%)
Erosion	13.1	13.6	12.3
Stability	36.5	27.5	49.8
Accretion	50.4	59.0	37.9

Cieneguita and Banano river mouth with mean rates of −1.58 m/y, −2.15 m/y in Cahuita, −2.1 m/year in Manzanillo, −1.2 m/year in Gandoca, and intensive erosion also in Puerto Vargas.

Table 5
Sectors of the Caribbean coastline showing greater accretion between 1986 and 2019.

River	Mean net shoreline advance (NSM) m	Maximum Net shoreline advance (NSM) M	Mean Shoreline change rate (LRR) m/y	Category	Basin area km^2
Colorado	183.0	656.8	5.4	Extreme	38,640
Parismina	59.1	113.3	2.4	Intense	2953
Matina	70.5	150.2	2.8	Intense	1619
Moín	56.7	134.5	1.2	Intense	163
Banano	30.4	118.7	1.3	Intense	207
Estrella	101.6	168.4	3.8	Severe	1031
Sixaola	83.6	149.0	3.9	Severe	2415

The urban population in the coastal areas of Costa Rica has been increasing consistently since 1950, increasing exposure to hazards. On the Caribbean coast, the percentage of urban population reached 57%, standing out the canton of Limón, which concentrates 24% of the population of the Limón province (Segovia, 2018). It is important to note that the lack of coastal erosion problems in The Northern Caribbean littoral of Costa Rica is related to the difficult access to this sector, the low density of urban land use and the presence of protected zones.

This research aims about identifying the critical points of erosion and accretion of the Caribbean coastline of Costa Rica in the long-term trend (decades), by using satellite images. These results could be used to establish trends, assess mitigation and adaptation measures and, mainly, to guide the coastal-zone management and its land-use planning. Likewise, the results determine the sites where starting studies regarding risk due to coastal erosion are required -such as the ones performed in Colombia (Ricaurte-Villota et al., 2021).

1.1. Analysis of shoreline changes

Erosion, transport, and accumulation of sediments along the coastline are usually evidenced as changes in the position of the shoreline, and their record in the long term (decades) is reliable for studying its changes (Bird, 2005). In this way, change rates of the shoreline may represent the speed of its movement (Oertel, 2005). The generalization of these changes is interpreted as sediment gain or loss (erosion or accretion), which could result from sudden or intermittent processes instead of constant and gradual processes (Bird, 2005).

The shoreline concept refers to the interface between land and sea (Burningham and Fernández-Núnez, 2020) which, for Oertel (2005), corresponds to a precise limit, which makes its establishment complex in the practice. In this regard, Boak and Turner (2005) make a significant effort to analyze different indicators regarding its accuracy and practical use. Some of them are the base of cliffs, landward edge of a shore protection structure, seaward stable dune vegetation line; erosion escarp, wet/dry line or runup maxima, instantaneous water line.

Since the 70s, the Shoreline Change Analysis (ACLC) has been used to define and quantify the changes in the location of the shoreline (Burningham and Fernández-Núnez, 2020). Remote sensors for obtaining shorelines with the purpose of analyzing their temporal and spatial distribution are highly used nowadays (Jiménez et al., 1997; Toure et al., 2019), as well as for determining average change rates in the short and long term, in conjunction with Geographic Information Systems (SIG) (Morton et al., 2005; Kermani et al., 2016; Ford, 2013).

When analyzing shoreline changes, a linear behavior in time is usually assumed; therefore, change rates expressed as linear changes in meters per year (m/y) are used. Positive linear changes are interpreted as accretion while negative as erosion (Appeaning-Addo and Lamptey, 2013). The statistical analysis of changes can be made through value rates, average rates, regression line, weighted linear regression, among others (Morton et al., 2005).

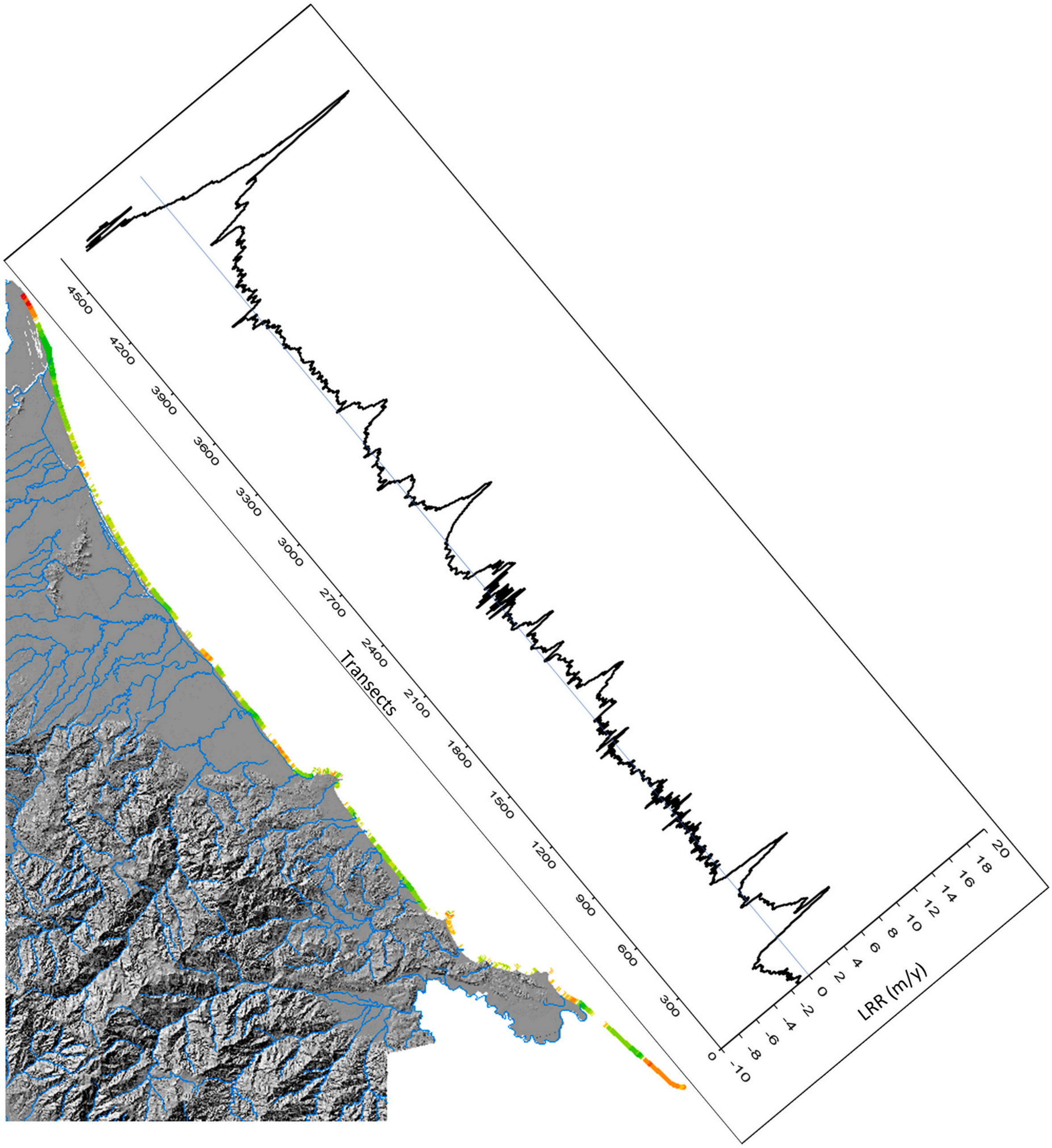

Fig. 2. Distribution of change rates in the shoreline (LRR) in the Caribbean of Costa Rica.

Natural processes are highly responsible for the retreat or advance in the shoreline in the long term while, in the short term (months or years), although these trends remain (Morton, 1979), they also reflect ancient variations in the sea level and in human activities such as engineering works. However, in the mid-term (decades), it is also possible to identify anthropic causes that generate erosion processes, i.e., the construction of berths and ports (Gracia et al., 2005).

1.2. Area under study

The area under study covers the Caribbean littoral of Costa Rica located between coordinates 10°55′47.53″N 83°40′2.75″W in its northern end, and 9°34′20.38″N and 82°33′53.24″W in its southern end, with an approximate length of 220 km (Fig. 1). This coastline comprises several natural reserves: in this sense minimizing human-induced effects.

Tectonically, this littoral zone can be divided into two sections, from Moín to the border with Nicaragua it comprises the Cocos Plate, and the southern section to the Panama Microplate. The northern section shows features of a passive continental margin and an extensive tectonic regime (normal faults), while the southern section shows a compressive regime with occurrence of significant earthquakes (Alvarado and Cárdenas, 2016).

This tectonic differentiation is evidenced on geomorphology. The northern sector is characterized by the presence of large plains linked to river sedimentation processes and its redistribution on the littoral currents (Bergoeing, 2007). The coast is a Holocene beach ridge plain which forms coastal belts up to the headlands of Limón, extending 80 km, which, in the inland are characterized by fresh water coastal lagoons (Denyer and Cárdenes, 2000). Rivers usually flow into lagoon systems that have been connected by artificial channels, jointly known as "Tortuguero Canals" which allow navigating between Moín to the Colorado river mouth (Fig. 1). These channels are close to the coastline and are surrounded by lush vegetation of palm swamps *Raphia taedigera*

Table 6
Sectors with greater shoreline retreat and their management category.

Beach or location	Management Category	Mean NSM (m)	Maximum NSM (m)	LRR (m/y)	Category
South of Isla Portillos	*Barra del Colorado* Wildlife Refuge	−109.8	−165.7	−4,7	Severe
Boca Pacuare	–	−39.9	−63.7	−1.0	Minor
Pantano beach (to the north of the new Moín port)	–	−31.9	−57.9	−0.8	Minor
Cahuita (Blanca Beach)	Cahuita National Park	−38.9	−67.89	−1.2	Intense
Punta de Puerto Vargas	Cahuita National Park	−37.3	−59.8	−1.1	Intense
Puerto Vargas beach	Cahuita National Park	−24.2	−41.5	−0.6	Minor
Gandoca (to the south of the lagoon)	Gandoca-Manzanillo National Wildlife Refuge	−24.5	−51.1	−0.9	Minor
Soropta beach (Changuinola Canal) Panama	San Pond Sak Wetland	−59.0	−99.0	−2,0	Intense

(Arecaceae) and fairly straight and densely forested beach ridges (Battistini and Bergoeing, 1984). These ridges can be 9 km long, 3 m high over the sea level, and 10 m thick (Nieuwenhuyse and Kroonenberg, 1994)). The coastline between Tortuguero lagoon, Parismina, Pacuare, and Matina evolved under the action of an intense littoral drift to the SE (Battistini and Bergoeing, 1984). However, from the south of Parismina River to Matina River, the estuaries, and the sediment plumes, are oriented NW-SE, possibly as a result of the prevailing direction of trade winds.

On the other hand, the southern section between Puerto Limón and Puerto Viejo is characterized by a closer proximity of the mountain ranges and by large sandy beaches. However, the shoreline becomes more intricate, and beaches become shorter (pocket beaches), interfingered with rocky capes (Barrantes et al., 2020a). This coast is characterized by rocky headlands composed of coral reefs of Pleistocene and Holocene ages (Cortés, 2016) of up to 100 m above sea level alternating with coastal plains such as the ones located in Manzanillo and Gandoca.

The weather is characterized for not having a defined dry season, showing two periods when rainfall decreases (February to March and September to October; *Instituto Meteorológico Nacional* [IMN], 2017). Herrera (1986) classifies the weather in the Northern Caribbean -up to Matina River, as very humid, very hot without dry season, while the weather in the Southern sector is humid and warm with a short dry season. Rainfall in this watershed ranges from 100 to 200 mm in the

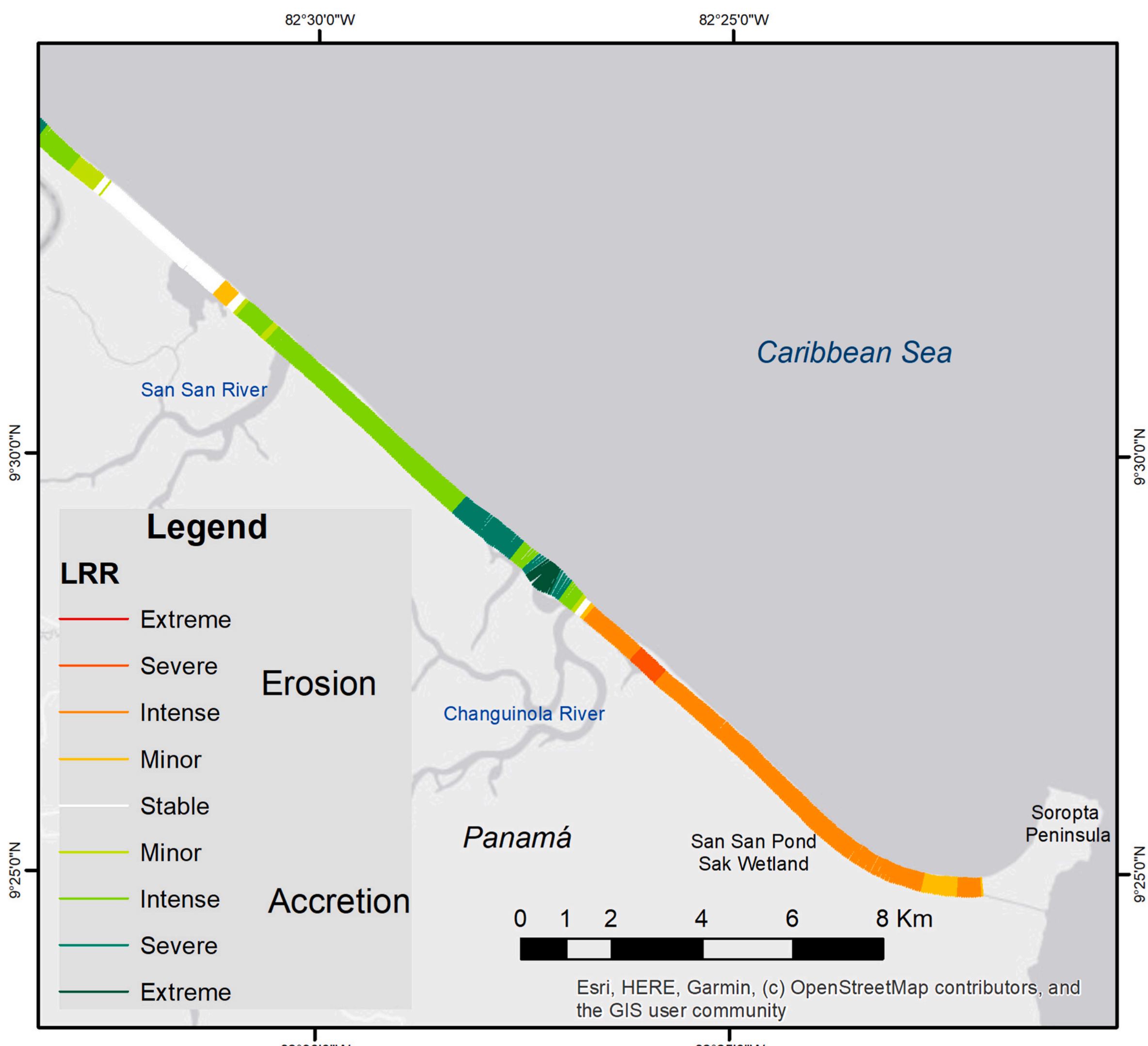

Fig. 3. Distribution of change rates in the shoreline (LRR) in the far north of Panama.

Fig. 4. Beach ridges at Barra del Colorado. Note the presence of beach ridges around the landing strip. Source: satellite image on 01/04/2018, Esri imagery.

least rainy months (IMN, 2017). The rainiest months are influenced by cold fronts coming from the Northern Hemisphere, which occur between November and May, with greater probability of heavy rains between November and March (IMN, 2017).

The Caribbean coastline shows a microtidal regime where tides rarely exceed 30 cm (Bolaños, 2001), with a mean tidal range of 15 cm (Lizano, 2006). Waves come from the northeast, with average wave periods of 7.4 s, and a notably local character. Higher wave energy is produced in the last and in the first months of the year; conversely, the least wave energy occurs from September to October, when trade winds decrease (Lizano, 2009). The main currents along the coastline flow from northwest to southeast, as part of the so-called cyclonic rotation of the Giro Panamá-Colombia (GPC) (Andrade et al., 2003). Consequently, littoral currents flow mainly to the southeast, with magnitudes not exceeding 0.5 m/s (Lizano Rodríguez, 2018).

2. Materials and methods

The methodology consists of three stages: 1) Survey of shoreline changes from satellite images 2) Collection of change rates through the *Digital Shoreline Analysis System* (DSAS; Himmelstoss et al., 2018), and 3) Identification of sites with high rates of advance or retreat for their analysis.

2.1. Definition of shoreline

Two proxies to the shoreline were used in this research. First was the vegetation line along the beach which, reduces uncertainty regarding other features of the beach which might be submerged at the time of obtaining the image (Ford, 2011). When this indicator is not available due to anthropic intervention, the seaward limit of human structures along the coastline is used, i.e., sidewalks, roads, or buildings (Boak and Turner, 2005; Moore, 2012).

Thematic Mapper (TM) images from Landsat satellites were used (30 m space resolution). The input from this satellite is usually used for analyzing vegetation, agriculture, and land use (Vega-Guzmán et al., 2008). However, they are often used to analyze changes in the shoreline (Otto et al., 2018; Rangel et al., 2015; Melet et al., 2020).

The dates of the images used, regarding the coastal sector where they are located are shown in Table 1. It is important to note that the images of the northern and southern Caribbean not always match temporarily due to variations in the coverage of images and cloud cover. The images chosen are the result of a massive search that allowed excluding those with presence of clouds or those showing any distortion such as displacements and color alterations.

The atmospheric correction of images was made through the *Semi-automatic Classification Plugin* (SCP) complement of the QGIS software. The method used is the *Dark Object Subtraction* 1 (DOS1), which assumes

Fig. 5. Beach ridges near the mouth of Parismina River. Note the presence of beach ridges in the deforested land between the shoreline and the estuary (canal). Source: satellite image on 24/12/2023, Esri imagery.

that in the image there are shadow pixels and that radiances emitted to the satellite are due to atmospheric dispersion. The aforementioned is combined with the fact that there are very few objects on Earth that are absolute black, assuming that a minimum reflectance of 1% is better than one of 0% (Chávez, 1996). The correction formulas can be enquired in Moran et al. (1992), Chávez (1996) and Sobrino (2004).

False color composition used near infrared, red, and green bands. In this way, the vegetation was detected showing it in red tones that vary depending on the reflectance of chlorophyll on the infrared band (Imam, 2019). Verifications are made in a normal color composition by using the bands that are visible to the human eye: red, green, and blue (Imam, 2019).

Digitalization was made on a 1:50,000 scale in order to avoid errors due to changes of scales and to standardize the process. The shoreline error (total error) was calculated as the root of the sum of the squares of all shoreline positions, based on three determined error sources: rectification, interpretation, and pixel size (Ford, 2013). The rectification error is obtained from the metadata file of each Landsat image. The error due to interpretation was calculated as the standard deviation from the shoreline position obtained through the repeated digitalization of the same segment, by the same digitizer, and for each date. As a result, errors between 31.0 and 33.6 m are obtained. (Table 2).

2.2. *Collection of change rates*

Changes in the shoreline position were processed through the DSAS extension in the Geographic Information System ArcGIS. The first step consisted of creating a baseline used as reference for making the calculations (Himmelstoss et al., 2018). Then, transects perpendicular to this baseline were made every 50 m, intersecting the shoreline. Based on this input, the DSAS extension automatically generates different statistics, i.e., Shoreline Change Envelope (SCE), Net Shoreline Movement (NSM), and the Linear Regression Rate (LRR). SCE quantifies the maximum distance among all the shorelines. NSM quantifies the total net movement (adding positive and negative displacements) of the shoreline, while the LRR allows obtaining the annual movement rate from a regression line among all the shoreline positions (Himmelstoss et al., 2018).

In order to interpret the movement rates of the shoreline, was used so results could be easily compared (Barrantes and Sandoval, 2021). It is a four-interval chart for the retreat, four for the advance, and one for stability (Table 3).

3. Results

According to the LRR values obtained between 1986 and 2019,

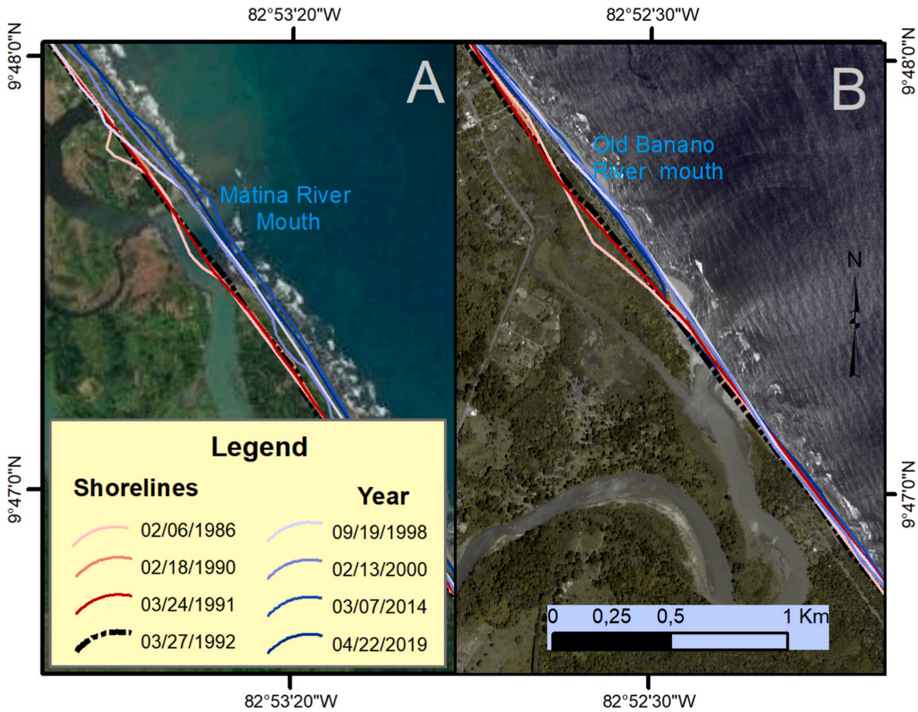

Fig. 6. Changes in the shoreline before and after the earthquake on April 22nd, 1991. The red continuous lines represent the shoreline before the earthquake; the dotted black line represents the shoreline in March 1992, the blue lines represent the shoreline after the earthquake. A) Mouth of Matina River. B) Mouht of Banano River. Note that shorelines have evolved as of an intensive progradation after 1992, probably as a result of the influx of detrital material brought by river courses within a six-year period (between 1992 and 1998). Source: modified from Barrantes et al. (2021b).

50.4% accretion prevails, and it corresponds to an average SNM of 24.9 m. These values are consistent with the presence of significant fluvial systems that provide large amounts of sediment to the littoral (Colorado, Parismina, Pacuare, and Matina, Banano, Estrella, and Sixaola rivers). However, 13.1% of the coastline shows a notably marked retreat (Table 4).

When comparing the North Caribbean with the South Caribbean coast of Costa Rica, a change in the predominance of the type of movement of the shoreline was observed. In the North, the SNM was 30.5 m between 1986 and 2019, while in the southern Caribbean it was barely 13.0 m. In terms of percentages, 59% of the northern sector shows accretion, compared to 37.9% in the southern sector (Table 4). In other words, the Northern Caribbean is characterized by increased sedimentation causing the advance of the shoreline, mainly at the mouth of the main fluvial systems (Fig. 1) while 49.8% of stability prevails in the Southern Caribbean (Table 4).

The places with accretion that stand out in the 33 years of the study period, occurred at the mouths of the main river courses, rivers with small basins registered lower advance rates (Table 5).

Sectors showing significant erosion between 1986 and 2019 are distributed along the entire littoral (Fig. 2; Table 6). A finding to highlight is the high rate reported in the coastline to the south of Isla Portillos, where erosion is considered severe. Intense erosion is registered in both sides of Cahuita point, while minor processes occur in Boca Pacuare, Pantano Beach, Puerto Vargas Beach, and Gandoca.

This research included a sector of about 30 km along the Panamanian coastline (Figs. 2 and 3), where intense coastal erosion was detected between the mouth of Changuinola river and the beginning of Soropta Peninsula, with a mean rate of −2,0 m/y (LRR) -considered as intense (Table 6).

4. Discussion

4.1. Accretion areas

Colorado river is a branch of San Juan River, and it constitutes its main outlet. The river basin of San Juan River is the second largest in Central America, with an area of 38,640 km^2, of which the Colorado and Tortuguero sub-basins are part with an extension of 1,321 km^2 (*Oficina de Desarrollo Sostenible y Medio Ambiente, 1997*; *Programa de las Naciones Unidas para el Medio Ambiente* [PNUMA], 1997). The coastline along the Colorado river mouth, shows a long-standing accretion (progradation) (Fig. 4).

"Beach ridges" term is reserved for coastal ridges that became isolated from the impact of shore erosion and accretion processes through shore progradation (Otvos, 2000). Beach ridges are typically wave-generated features, but fluvial discharge and tides can also exert a significant influence on their formation (Isla et al., 2023). According to Otvos (2000), along the microtidal beaches increased sand supply results in steady foreshore outbuilding and consequent progradation of narrow, closely-spaced ridges, as those recorded in northern Costa Rica (Battistini and Bergoeing, 1984) (Fig. 4), usually located between 2 km and 4 km from the coastline (Parkinson et al., 1998).

Parismina River, which belongs to the Reventazón watershed, covers an area of 2953 km^2 with a mean flow of 136,000 m^3/s (*Instituto Costarricense de Electricidad* [ICE] 1990). This coastline also shows beach ridges (Fig. 5), but without a delta. It is important to consider the effect that the Reventazón Hydroelectric Power Station might have on the coastline, mainly on the beach located to the north of the Parismina River mouth, where erosion occurs as a result of the reduction of the sediment load trapped in the reservoir.

Matina River basin has an extension of 1,619 km^2 (Rojas, 2011) and a mean annual flow of 65,700 m^3/s at the Chirripó River (ICE, 1990). The high accretion rate is related to the sediment contribution of this river, which goes up to 3800 m above sea level and allows carrying a significant amount of sediment -in addition to an intensive land use by banana companies that implement a dense network of channels that ensure an efficient drainage to the river at the plains. This basin was mainly affected by landslides triggered by the Limón earthquake of 1991, that caused a slide area of about 65.4 Km^2 corresponding to 7.1% of the total area of the basin (Barrantes et al., 2021b). Additionally, these authors document an accretion process at its mouth as a result of the influx of landslide material to the coastline (Fig. 6 A).

Estrella River basin has an extension of 1,031 km^2 (Rojas, 2011) and a mean flow (at Valle la Estrella) of 38,200 m^3/s (ICE, 1990). Significant extensions of banana plantations that facilitate the transport of

Fig. 7. Abandoned channel of the San Juan River. It is currently constituted as a waterway on which an intermittent river called Taura river flows. Source: Instituto *Geográfico Nacional (1988)*.

sediments through drainage channels are located both at Valle de la Estrella and at the coastal plain. This basin was the second largest slide area during the Limón earthquake, with a total of 33,3 km^2 that represented 5,4% of the total basin area (Barrantes et al., 2021b). According to these authors, during March 1992, an accelerated progradation at the mouth was recorded, probably as a result of the influx of materials, until 1998 when the accretion rate diminished.

Moín and Banano are the smallest basins on the list (Table 5). The limited extension is remarkable in the case of Moín. The accretion is related to the construction and subsequent modification of the Costa Rican Oil Refinery (RECOPE) starting in the 1960s (Pérez and Lizano, 2021), as well as the uplift of the coastlines that were important in this coastal section, after the Limón earthquake (De Obaldia et al., 1991; Denyer et al., 1994a). However, in the last years, an erosive process near Moín river mouth, as a result of the construction of the Moín Container Terminal has been verified (Barrantes et al., 2021a). The Banano basin was another one that was greatly affected by landslides, with progradation observed (Fig. 6B), such as what occurred at the mouths of Matina and Estrella (Barrantes et al., 2021b).

Finally, Sixaola river basin has an extension of 2,414.92 km^2 (Rojas, 2011) and a flow of 231,000 m^3/s (ICE, 1990). This basin also reaches around 3800 m above sea level (Rojas, 2011); therefore, the river has higher erosive potential. Just like in the previous cases, the plain presents significant extensions occupied by banana and plantain plantations, and was affected by mass movements during Limón earthquake, but to a lesser extent (Barrantes et al., 2021b).

4.2. Coastal erosion areas

The San Juan River mouth prograde leaving a record of beach ridges like those of the Colorado river. However, no coastal belts or beach ridges are observed between Punta Castilla and Taura lagoon (Fig. 7).

To the south of Punta Castilla, a retreat of 300 m in 35 years was estimated based on aerial photographs, which would represent a rate of −8.5 m/y (Nieuwenhuyse and Krooenberg, 1994). The mentioned rate is greater to the one found in this research (−4,7 m). This discrepancy might be due to the different methods both studies, which is not clarified in the study, and to the fact that this research did not include enough shorelines to perform the analysis in Isla Portillos, due to cloud cover (Fig. 7).

Severe erosion process is recorded between Taura and Agua Dulce lagoons (Figs. 2 and 7), which might be related to the closure of an old mouth that currently constitutes an abandoned channel (intermittent river) called Taura river (Fig. 7). In this way, by no longer receiving a significant contribution of fluvial sediment, and due to its direct exposure to the waves (from NE), the redistribution of coastal sediments is produced in response to a strong littoral drift. Nieuwenhuyse and Kroonenberg (1994), who stated that erosion in this section has been

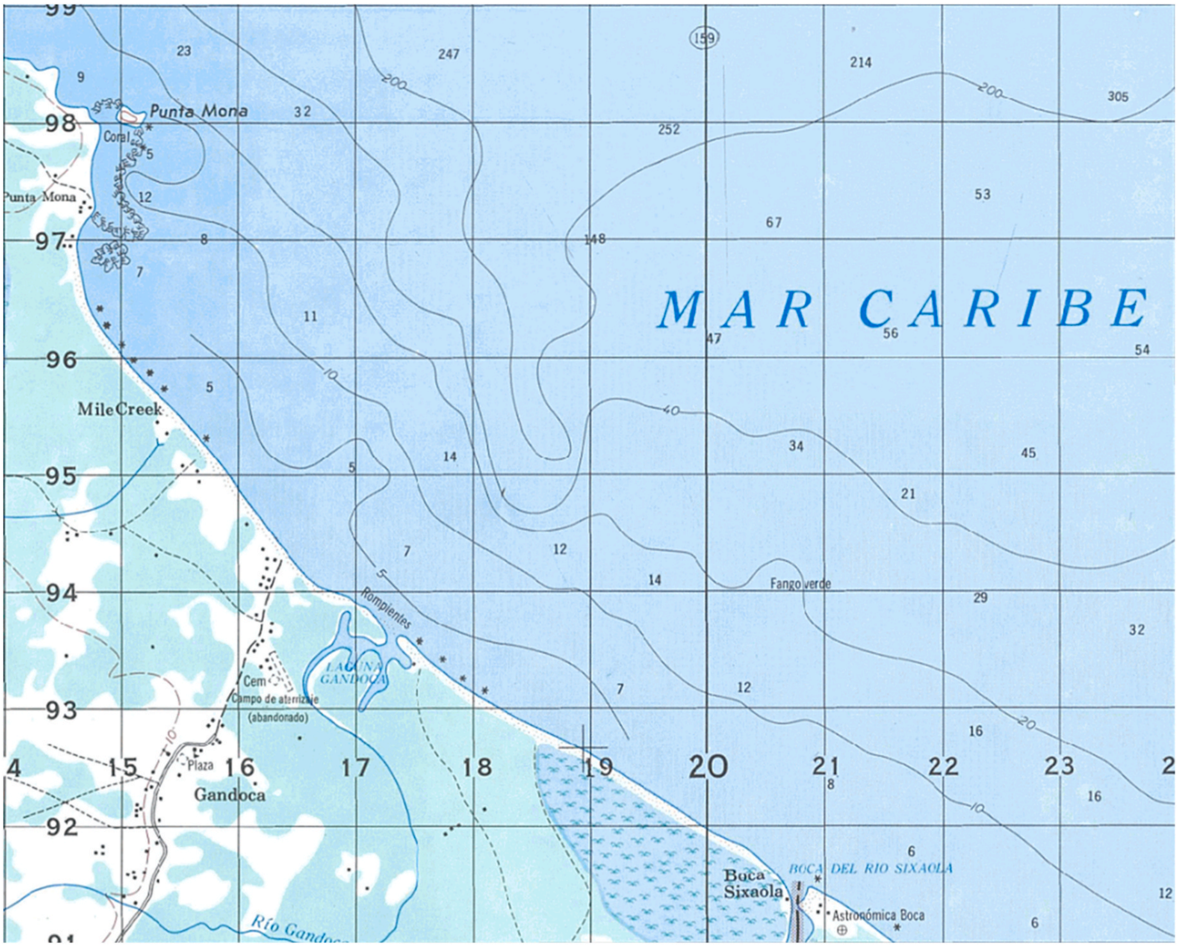

Fig. 8. Offshore bathymetry Gandoca beach with a submarine channel in front of the Gandoca Lagoon. Source: *Instituto Geográfico Nacional (1989)*.

produced since the 19th century based on the records provided by Cleto Gonzales-Víquez, who indicated a sudden change in the river course that caused the deviation of the main San Juan River mouth from Punta Castilla to its current position.

A beach of about 3,2 km long where minor erosion is being experienced, is located near Pacuare-Madre de Dios River mouth (Figs. 1 and 2). Besides the presence of two significant quarries that extract construction materials, a cause to justify this behavior different from the rest of the mouths has not yet been identified.

Cahuita National Park experiences intense erosion process with minor erosion at Puerto Vargas beach (Figs. 1 and 2). Among the reasons of this erosion are coral death and corresponding loss of height and roughness for waves, especially during extreme waves. The coral reef degradation is related to sedimentation and as well as other anthropogenic and natural causes (Cortés and Jiménez, 2003), and to the effects of the Limón earthquake which caused the cracking and collapse of large number of reef colonies, (Cortés et al., 1994).

Additionally, the presence of local depth variations along the channels that create wave refractions and redistribution of the coastal currents was highlighted (Barrantes et al., 2020a), thus notably changing the distribution of sediments during extreme waves (Segura, 2017). These conditions are not typical of this beach that rather corresponds to low energy; therefore, these disturbances might have caused loss of sediment that did not recover under normal circumstances (Silva et al., 2018).

In the case of Gandoca, among the potential causes of sediment loss is the presence of a submarine channel that could serve as a natural sand sinkhole (Fig. 8). It could be supplied by rip currents, which are highly common at this beach. In this way, the sediment distribution cell would present a deficit that is not compensated by sediments brought by the erosion of the rocky coastline or river discharge.

4.3. Comparison with previous publications

For the Southern Caribbean of Costa Rica, Barrantes et al. (2020a) record beaches with intense coastal erosion, while Barrantes and Sandoval (2021) quantify the shoreline change rate by using the statistics of LRR between 2005 and 2016. Fig. 9 shows the critical points reported and their corresponding erosion rates compared to the results of this research.

Four beaches reported in this research match the points previously reported (Barrantes et al., 2020a); namely, Cahuita, Puerto Vargas Point, Puerto Vargas and Gandoca beach (Fig. 9). However, these authors report other points that are not reported in this research; namely, Cienenguta-airport, Manzanillo, and Banano and Bananito river mouths.

In the case of Banano and Bananito, Barrantes et al. (2020a) attribute coastal erosion to the migration of both mouths. These processes could be linked to the hydrological and sediment imbalances caused by the Limón earthquake (Barrantes et al., 2021b; Denyer et al., 1994b). The opening of a new mouth of Banano river, about 3 km to the southeast of the previous one, apparently as result of the massive influx of sediments during severe flooding after the earthquake (Barrantes et al., 2021b).

At the Cieneguita beach and at the airport, the construction of a groyne around the year 1973 refers to a previous erosion process. However, this structure subsequently interferes with the sediment distribution, thus resulting in an advance of the shoreline upstream of the groyne and a retreat downstream of the groyne (Barrantes et al., 2017). Barrantes et al. (2020a) and Barrantes and Sandoval (2021)

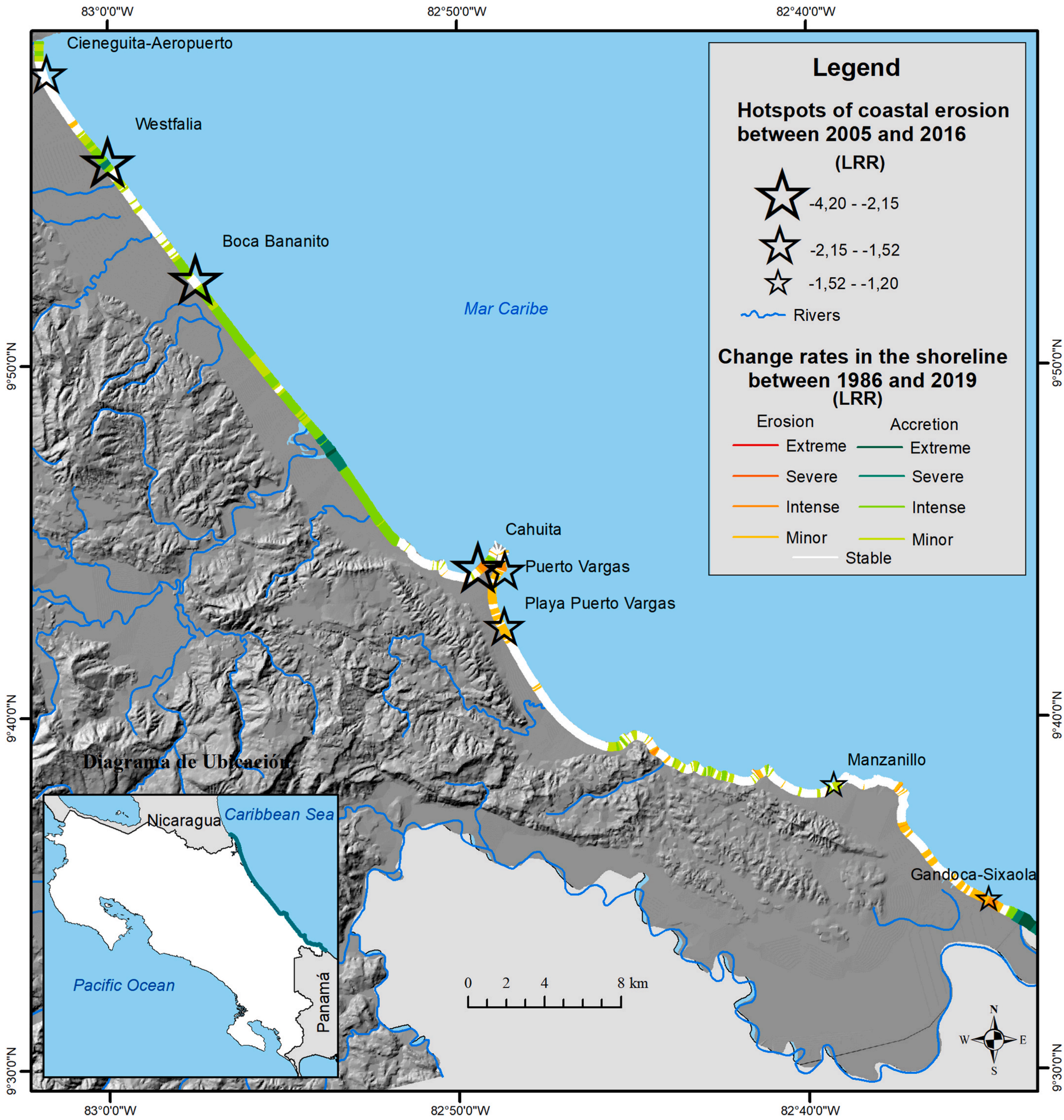

Fig. 9. Critical erosion points and shoreline change rates. This map allows comparing the results of this research with a previous work. The black stars represent hot spots of coastal erosion according to Barrantes et al. (2020a).

contributions were made for a relatively short period (2005–2016), but as stated by Morton (1979), that the impact of human interference on the coastline is better evidenced in short-term studies, seems to apply to this case.

According to inhabitants of Manzanillo, this place experienced an accelerated erosion process before the Limón earthquake. The co-seismic coastline uplift (De Obaldia et al., 1991); Denyer et al. (1994a) compensated the loss of land due to the previously experienced erosion, thus resuming the erosive process. This same effect is recorded in Cieneguita and in a sector of Gandoca (Denyer et al., 1994a). For these cases, shoreline changes are compensated by calculating the shoreline change rate (LRR); therefore, in this research, an erosion process is not registered in these places. In this regard, Burningham and Fernández-Núñez (2020) remark that the sites experiencing fluctuations in the rate and movement direction of the shoreline over time, are not well represented by the statistics of LRR.

Previously, a tectonic component in order to explain the existence of intense erosive processes along the Southern Caribbean coastline, was suggested (Barrantes and Sandoval, 2021) which is consistent with the evidence that shows a subduction zone being formed between the

Caribbean plate and the Panama microplate (Arroyo and Linkimer, 2021). In this regard, Paniagua-Jiménez et al. (2021) have started a research based on radar images in order to establish subsidence rates of the coast which is assumed to be taking place as part of the seismic cycle of this tectonic edge that was active after the earthquake and which, as happened in the Northern Pacific of Costa Rica, displaced the land with a vertical component (Protti et al., 2014).

On the other hand, 31% of the population is urban in the central canton (Limón), decreasing significantly towards the south (Segovia, 2018). In the Canton of Talamanca, the urban population is concentrated in four settlements, three of them are coastal (Cahuita, Puerto Viejo and Manzanillo). In these places, tourist activity has caused an urban expansion, increasing the risk of coastal erosion. In the case of the northern Caribbean, the main population centers are inland, mainly because the coast is managed by a government entity (Tortuguero canals) or fits under the category of protected area.

With greater exposure of road and service infrastructure, and tourist attractions, the greater socio-economic development in the Southern Caribbean (different from the Northern Caribbean littoral) have evidenced the erosion processes. Therefore, some monitoring was started by the *Universidad Nacional of Costa Rica*, which allowed establishing a diagnosis of the current situation of this section of the littoral (Sandoval and Barrantes, 2021; Barrantes et al., 2020a; Barrantes and Sandoval., 2021). In contrast, it was not possible to find publications about coastal erosion in the Northern Caribbean. However, this research allows having a general overview from which it can be stated that accretion prevails in the Northern Caribbean. However, it is not possible to establish a clear difference between both sectors of the Caribbean littoral, due in part to the potential consequences of seismic cycles, which imply sudden changes in the coastline and more far-reaching disturbances on the sedimentation patterns of fluvial systems.

On the other hand, the rising sea level is a process that affects the entire Caribbean littoral. However, the lack of updated local data only allows to be providing referenced historical data that indicates a local rise of 1.68 mm/year between 1948 and 1968 in the Limón station (Ballestero and Salazar, 2012). Despite all this, it can be expected that this rate has increased in the last years (Palanisamy et al., 2012; IPCC, 2021).

5. Conclusions

Based on the long-term observations, (1986–1919), it is possible to affirm that in the Caribbean littoral of Costa Rica there are seven sites with accretion greater than 1 m/y -all of them linked to the sediment input of fluvial systems that flow into the Caribbean Sea. The mouths of Colorado, Estrella and Sixaola rivers stand out due to their discharges. In Estrella and Sixaola rivers, the extension of their river basins, their hypsometric properties, the land use conditions, and the effects of the Limón earthquake in 1991 help to explain this behavior.

At least seven sites with coastal erosion were recorded for the same period (33 years), from which, the beach from the south of Isla Portillos and Cahuita Point stand out. In the first case, erosion is related to the closure of a previous mouth of San Juan River. In the second case, the loss of effectiveness of the reef against severe waves is contributory.

This research confirms the existence of beaches with coastal erosion problems in protected areas: Cahuita National Park, Mixed Wildlife Refuge, and Barra del Colorado Wildlife Refuge. Moreover, an intense erosion process is reported at the San Pond Sak Wetland in Panamanian territory for which no previous reference was recorded.

When comparing the Northern and the Southern Caribbean coasts, a clear difference in the extension of the accretionary areas is noted. 59% of the Northern Caribbean coastline experiences deposition, while the Southern Caribbean experiences only 38% of its coastline. Regarding coastal erosion, both littorals show similar figures 13.9% for the North and 12.3% for the South. On the other hand, the Southern Caribbean coastline shows 49.8% as stable compared to 27.5% of the Northern coastline.

Coastal erosion processes in the Southern Caribbean were reported because of a greater exposure of elements to risk; namely, roads, and service and tourism infrastructure. Additionally, the improving real-estate development in the Northern Caribbean represents an opportunity for environmental planning linked to protection areas (management plans).

CRediT authorship contribution statement

Gustavo Barrantes-Castillo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Keilor Ortega-Otárola:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We would like to thank Dr. Guillermo Alvarado for his revision and suggestions and Vladimir Rodriguez, our project assistant, for his contribution to run DSAS. This work was funded by the *Escuela de Ciencias Geográficas* of the *Universidad Nacional*, through the *Programa de Geomorfología Ambiental*.

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