Geo-Marine Letters (2024) 44:2
https://doi.org/10.1007/s00367-024-00765-6

RESEARCH

Assessing erosion and sediment removal in the Isla Salamanca coastal barrier: implications for the Barranquilla-Ciénaga highway and coastal marine biodiversity – Colombia

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Received: 28 June 2023 / Accepted: 15 February 2024 / Published online: 22 February 2024

Abstract

The Isla Salamanca coastal barrier on the Colombian Caribbean coast faces significant erosion, driven by climate change-induced, sea level rise and human activities such as highway construction. The Barranquilla-Ciénaga highway, particularly at kilometers 19 and 29, is at risk, with severe consequences for the region's socio-economic and environmental well-being. Human interventions like the highway construction and seawall installations have disrupted the natural coastal dynamics, leading to increased erosion rates. The study, conducted between 2004 and 2021, reveals that the Isla Salamanca coastal barrier is experiencing substantial transgression, with erosion rates peaking at -16.1 $m \cdot yr^{-1}$. The highway protection measures, with seawall construction, have proven inadequate, exacerbating erosion downstream. The mangrove loss due to hydrological changes and increased salinity is further threatening the fragile ecosystem. The research emphasizes the importance of considering biodiversity loss in the context of rapid erosion rates. The region, declared a Ramsar Site and Biosphere Reserve, hosts vital ecosystems like mangroves and dunes, whose destruction negatively impacts marine biodiversity. The study suggests the relocation of the highway, acknowledging the challenges of preserving wetlands and mangroves in the process. Balancing the need for infrastructure with ecological preservation is essential, and the study proposes comprehensive solutions, including shoreline management, ecosystem-based protection, and community involvement. The goal is to mitigate erosion's adverse effects on biodiversity, habitat integrity, and the overall health of this ecologically sensitive region.

Introducción

The behavior of the shoreline is one of the most changing environments on the earth's surface, characterized by the effects of coastal progradation and erosion (Bird 2008). Sea level rise, induced by climate change, results in more frequent storm surges resulting in chronic coastal erosion (Ranasinghe 2016), which could lead to devastating socio-economic effects, such as the degradation of urban structures. In addition to these factors, human intervention in coastal areas, including the construction of highway and other infrastructure and urban services, alters this system and introduces high values of environmental imbalance, resulting in increased erosion rates (Posada and Henao 2008; Fant et al. 2022; Cai et al. 2022; Chadwick et al. 2022). The negative consequences of this process include loss of

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natural habitats, degradation of water quality, increased vulnerability of coastal communities to natural disasters, and loss of cultural and historical heritage (Portz et al. 2015; Turner et al. 2022; Bombino et al. 2022; Cai et al. 2022; Arkhurst et al. 2022; Mishra et al. 2023).

In the Colombian Caribbean coast there are erosive tendencies causing negative coastal morphological changes due to a marked anthropic influence (Posada and Henao 2008; Rangel Buitrago 2009; Manzolli et al. 2020; Villate et al. 2020). The department of Magdalena has moderate to critical erosion, with the worst scenarios located on the highway RN90 connecting Barranquilla-Pueblo Viejo at kilometers 19 and 29. Mangrove, dune and wetland areas in this region are also severely eroded. The Isla Salamanca National Park, an important wetland ecosystem (Saldaña 2017), is located within this region. The area has faced several erosion problems over the years due to factors such as human activity, lack of maintenance, and climate variability (Rangel Buitrago 2009). The construction of the Highway has had serious consequences in the Ciénaga Grande de Santa Marta lagoon, such as the massive loss of mangrove forests due to hydrological changes and increased salinity (Elster et al. 1999). Although some hydraulic works have been carried out to mitigate these effects, some consequences persist, such as the deficit in water flow between both sides of the road, which causes an increase in salinity in the water bodies and mangrove forests north of the road and erosion on the northern coast due to the lack of sediments (Saldaña 2017). Another problem is the indiscriminate felling of trees in the areas surrounding Isla Salamanca Natural Park (Saldaña 2017) which has significantly reduced the soil's ability to retain the moisture and nutrients needed to support vegetation.

The risk to the road and the constant interventions to reduce the progress of erosion and impacts on the road generate constant debates. On the other hand, land transport is one of the most important strategic means of communication for global economic and social development, since it guarantees the land mobility of citizens as well as the free commercial and economic circulation, which constitute a basic tool for the productivity of a country. In this sense, having a good estimation of erosion, including the associated uncertainty, is the first step for decision making.

The research aims to analyze the dynamic evolution of the coastline and quantify sediment volume changes in Isla Salamanca National Park along the Colombian Caribbean coast. Specifically, it focuses on assessing erosive tendencies at kilometers 19 and 29 of the Barranquilla-Ciénaga highway. This investigation seeks to understand the average annual rate of coastal transgression, sediment removal, and shoreline retreat, providing insights into medium-term erosive processes and variations in sediment transport.

Methodology

Study area

The study area is located on the Colombian Caribbean coast between the mouth of the Magdalena River (Boca de Ceniza) and the municipality of Pueblo Viejo (Magdalena) (Fig. 1 and photographs in Supplementary material). It has important biological diversity, with a lagoon complex, mangrove areas, dune systems and was declared a National Park in 1964, a Ramsar Site and a Biosphere Reserve. In addition, it has an important highway (National Route 90 - RN90) that crosses the Natural Park connecting the cities of Barranquilla and Santa Marta.

Since 2014, work has been underway to protect the RN90, which was built in the 1950s, as seen in Google Earth images and reports in local newspapers. These works consist of protecting the shore of the road by means of seawall parallel to the shoreline. However, the advance of erosion has not stopped and continues to advance longitudinally, becoming more noticeable between km 19 and 18. There were several stages of expansion of the seawall, in which by the end of 2022 there was already 1,600 m of seawall. Works were also carried out in the area of Bocas de Ceniza (Magdalena River), from the fixing of the margins, as well as requiring dredging works in the approach line of the vessels, since there is sedimentation that limits the draft of the vessels to enter the access channel.

The area is micromareal and prevails NE trade winds with average speed $< 12\ \mathrm{m \cdot s^{-1}}$, with greater intensity between December-March and weaker values associated between September-November (CIOH 2022). As a result, a wave-dominated regime is generated, with Mean significant wave height (Hs) 2.5 m (Hersbach et al. 2023), generating longshore currents and with sediment transport predominantly towards the W (Restrepo and López 2008). The dominant sea surface current is the Caribbean Current, which flows almost year-round from east to west (CIOH 2022).

Image analysis

To quantify the shoreline changes, a multitemporal analysis of historical RGB satellite images obtained from Google Earth Pro (medium-term) and current RGB images taken from photogrammetry applied with Unmanned Aircraft Vehicle - UAV (short-term) was performed. The combined use of these images is widely accepted and used in different works (Portz et al. 2018; De Oliveira et al. 2020; Manzolli et al. 2020; Villate et al. 2020, Alcántara-Carrio et al., 2023). The geographic information was compiled for the period 2004 and 2021, by processing the images using ArcMap® 10.8.2. The WGS84 geographic coordinate system was

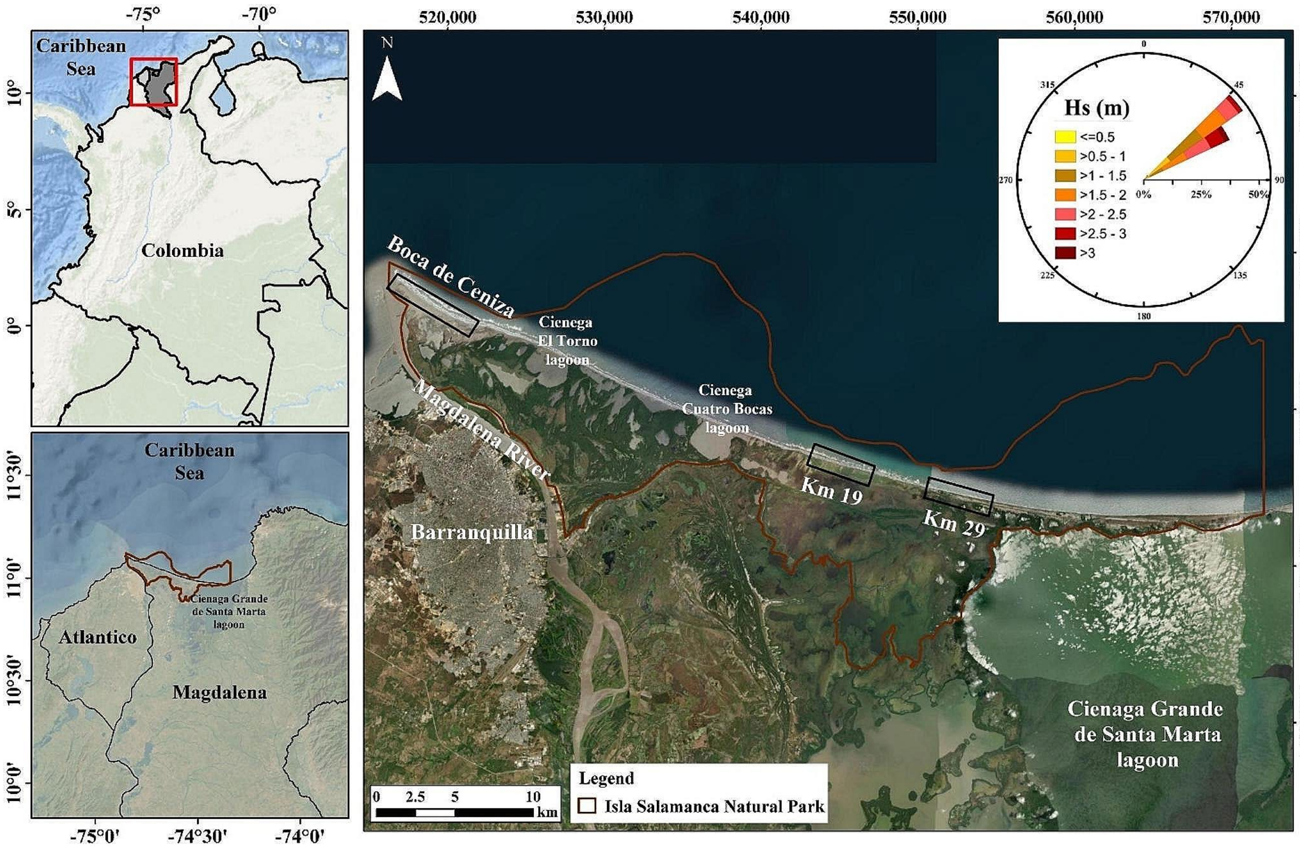

Fig. 1 Location of the study area, between Boca de Ceniza and Pueblo Viejo (Magdalena). Outstanding the 3 areas analyzed km 19, km 29 of the Barranquilla-Pueblo Viejo highway and Boca de Ceniza at the mouth of the Magdalena River. The wave rose shows the characteristics of direction and significant wave height (Hs) for the study area (hourly data from 01/01/2017 to 12/31/2020: ERA5 Hourly Data on Single Levels from 1940 to Present; Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (Hersbach et al. 2023)

used, in UTM-Zone18N planar coordinates. The processing of the drone images was performed in the software Pix4Dmapper PRO by Pix4D, for the generation of ortomosaicos and Digital Surface Model - DSM in 2 areas with 2,436 m and 1,814 m long (additional information in Supplementary material Table S1; S2 and S3). For this work, the definition of shoreline was considered by the position of the land-sea interface marked by the boundary during high tide (Crowell et al. 1991). Shoreline migration was analyzed using the Digital Shoreline Analysis System - DSAS 5.1 module (Thieler et al. 2009). This tool made it possible to generate transects in relation to a baseline, at a separation of 10 m for the total area and 1 m for the two specific areas (km 19 and km 29). Two methods were applied to characterize the evolutionary trends: Net Shoreline Movement (NSM), which is the total movement between the two shoreline positions (m) and the End Point Rate (EPR), which is the migration rate (m·yr^{-1}) calculated by dividing the distance between the most recent and the oldest shoreline by the time elapsed. The sediment volume was calculated by subtracting the DSM between the different dates with 20 m long profiles (Global Mapper V21.1 software). 1000 m of coastline were analyzed in km 29 (Fig. 2C) and for km 19 two separate areas of 600 and 560 m, sector 1 and 2 (Fig. 2B), respectively, were analyzed. The volumes of the areas with erosion and with accretion were calculated, and the residual volume was calculated as the difference between the two. For each method, statistical parameters were determined with a 95% confidence interval. For more details on the methodology, see the supplementary material.

Results and discussion

The medium-term analysis showed that along the 43,230 m of the Isla Salamanca coastal barrier, most of it (37,850 m) is in a process of frank transgression, with average annual rates of -4.8 m·yr^{-1}, with a maximum erosion of -277.6 m from the shoreline, between March 2004 and January 2021. On the other hand, adjacent to the mouth of the Magdalena River, at Boca de Ceniza, the western 5,535 m of the coastal barrier presents a maximum deposition of 499.8 m in extent (Fig. 2A; Table 1). The two specific areas of the coastal barrier studied are the areas with the highest erosion rates near

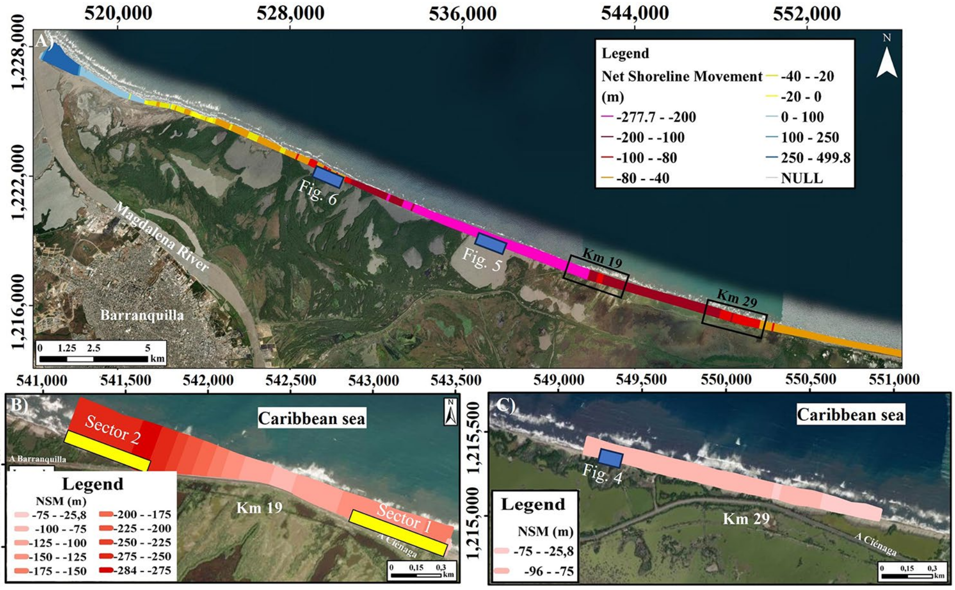

Fig. 2 (A) Results of NSM rates for the Isla Salamanca coastal barrier using satellite imagery between March 2004 and January 2021; (B) Results of NSM rates - km 19; (C) Results of NSM rates - km 29 (in both cases using satellite imagery, for the period between March 2004 and January 2021, and RPA's imagery from October 2020 and July 2021). ArcMap 10.8.2® Base Image

Table 1 Statistic summary of shoreline migration rates using the NSM (m) and EPR (m·yr^{-1}) methods, subdivided into total area; km 19 area; km 29 area; (see Fig. 1 for location of each sector)

			Km 19	km 29
Total number of transects		4,323	2,436	1,814
Total transects that record erosion		3,785	2,436	1,814
Total transects that record accretion		535	0	0
Shoreline length (m)		43,230	2,436	1,814
NSM (m)	Mean mobility shoreline change	-82.8	-172.5	-81.2
	Maximum mobility shoreline change	-277.6	-284.0	-96.0
	Minimum mobility shoreline change	499.8	-25.8	-59.3
	Standard deviation of mobility	88.1	119.1	1.58
EPR (m·yr^{-1})	Mean mobility shoreline change	-4.8	-10.0	-4.7
	Minimum mobility shoreline change	-16.1	-16.4	-6.2
	Maximum mobility shoreline change	29.0	-5.2	-3.4
	Standard deviation of mobility	5.1	3.5	1.3

the road connecting the cities of Barranquilla and Pueblo Viejo. At km 19 the average erosion rate was – 10.0 m·yr^{-1}, attaining a maximum erosion rate of -284 m and with the lowest retreat of -25.8 m from the shoreline (Fig. 2B; Table 1). These lower erosion rates are in the central portion of km 19, in which is due to the containment works with the construction of the seawall from the year of 2014. While at km 29 erosion rates reach a maximum of -6.2 m·yr^{-1} with a shoreline retraction of -96 m (Fig. 2C y Table 1).

Sheet piling is a technique used to control coastal erosion and protect coastal infrastructure, such as Highway, bridges, and homes, from the damaging effects of storms and rising sea levels (Griggs and Reguero 2021). This technique involves placing large rocks or concrete blocks along the shoreline to reduce the force of waves and stabilize the beach (Isla et al. 2018). Fencing can be a temporary solution to protect coastal infrastructure as it does not address the underlying cause. Coastal erosion processes are affected by different causes, from eustatic or isostatic processes, to natural or anthropogenic decrease in sediment supply, to the construction of coastal infrastructures that alter the dynamics of the coast, which can act together or in isolation. However, seawall can be a quick and effective solution to reduce coastal erosion and protect coastal infrastructures in the short term (Hosseinzadeh et al. 2022). At first, the proposed containment work to protect the RN90 highway accelerated the erosion processes in the western portion of the seawall, where the highest erosion rates are found in sector 2, with maximum transgression of the shoreline – 284 m (Fig. 2B).

Compared to other coastal areas with erosional processes the Isla Salamanca coastal barrier area has a significantly elevated rate. For the case of the southern coastal zone of India a study on coastal erosional processes between 1980 and 2020, using DSAS provided a detailed assessment of coastal migration rates (Chrisben Sam and Gurugnanam 2022). The results of the study indicate that coastal erosion rates are relatively much lower than those found in this study, with an average annual erosion rate of -0.28 m·yr^{-1}. Meanwhile the researchers show that the rate of coastal erosion has increased significantly over the last decade, indicating that coastal erosion is an increasingly serious problem for this region of India. The researchers warn that these rates of coastal erosion can have a significant impact on coastal communities, infrastructure, and biodiversity in the region (Chrisben Sam and Gurugnanam 2022).

For the coast of Venice, Italy, the study of Fogarin et al. (2023) show that the coast is experiencing a significant erosion rate in a short period of time and that this is due to a combination of factors, such as sea level rise and human activities. In addition, it reveals a stability in certain sectors, correlated with the large presence of coastal protection structures that stabilize the beaches, enhancing sediment deposition processes. In detail, with respect to the total length of the considered shoreline (about 83 km), 5% of the coast is erding, 36% is stable, 52% isaccretionary an 7% is not assessable.Thus, it highlights the need to take appropriate measures to address coastal erosion in the region and protect the coast and its communities from the adverse effects of shoreline change (Fogarin et al. 2023).

Also, in the study developed in Libertador Bolivar on the coast of Ecuador a mean rate of erosion of 0.64 m·yr^{-1}with the net transport, influenced by waves, was calculated in 470 m^3·day^{-1}, in which littoral transport is proportional to the longitudinal component of the wave energy flow (Nativí-Merchán et al. 2021).

In this regard, as can be seen in Figs. 2A and 3, substantial accretion is occurring adjacent to the mouth of the Magdalena River. Considering the study period, the westernmost sector of the Isla Salamanca coastal barrier, next to Boca de Ceniza, there was a shoreline regression of ≈490 m, with a maximum progradation rate of 29.0 m·yr^{-1} for this sector of the barrier.

Part of the progradation in this area is linked to the demobilization of sediments along the Isla Salamanca coastal barrier by erosional processes, in which a portion of the sediments is transported by the longshore current in the direction of Boca de Ceniza. Another component that may contribute to the supply of sediment for this rapid deposition is the Magdalena River itself (Restrepo and López 2008; Torres-Marchena et al. 2023). To estimate the volume of sediment that may be being transported in the direction of Boca de Ceniza, it was calculated through the decrease between the two DSM obtained. For the Km 29 sector of total length were analyzed, obtaining a difference of -1,922.8 m^3, i.e., there was a frontal erosion of the berm of -6,792.1 m^3 and a deposition of +4,869.3 m^3 in the backshore (see Table S5 Supplementary material). This deposition occurs mainly in areas devoid of vegetation, creating Washover deposits (Fig. 4).

At the sector 19 km, a comprehensive analysis of sediment demobilization was conducted in two distinct sectors, both adjacent to the seawall, as illustrated in Fig. 2B. In the first sector of km 19, encompassing a beach length of 600 m, a sediment erosion totaling −7,585.2 m^3 was observed. This remobilization was attributed entirely to berm erosion, with no discernible sediment accumulation in the backshore, as detailed in Table S3 of the Supplementary material. Conversely, in the second sector at km 19, featuring a beach length of 560 m, a more substantial demobilization of -16,925.9 m^3 was recorded. Within this demobilization, -18,982.5 m^3 was attributed to berm erosion, while a positive deposition of +2,056.6 m^3 occurred in the backshore by Washover deposits, as highlighted in Table S4 of the Supplementary material. This nuanced analysis emphasises the dynamic interplay between vegetation, berm erosion, and backshore deposition in shaping coastal landscapes at the 19 km area.

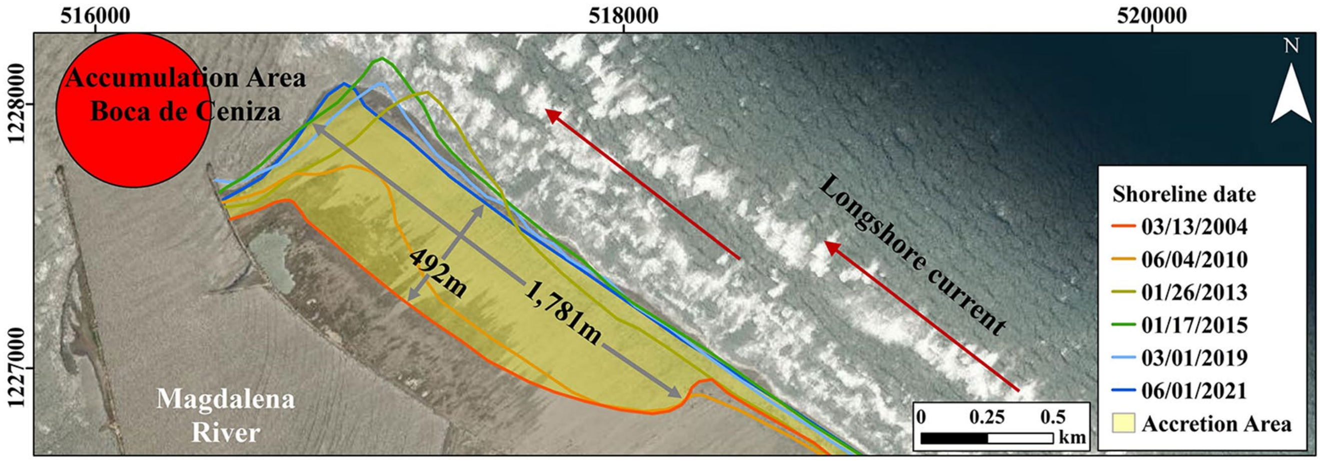

Fig. 3 Variation of the shoreline at the mouth of the Magdalena River. ArcMap 10.8.2® base image

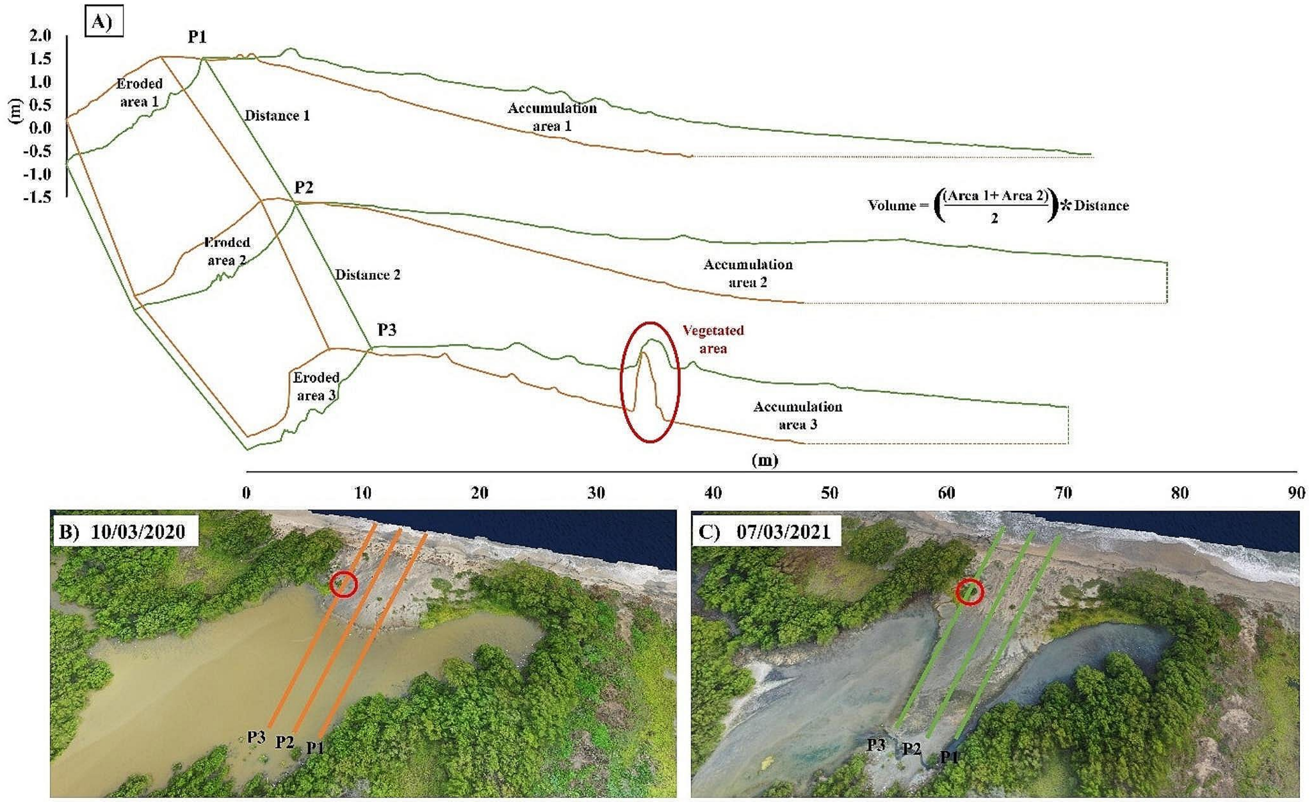

Fig. 4 (A) DSM topographic profiles for demobilized sediment volume calculation, from the Km 29 area, with focus on the Washover deposit; (B) and (C) Oblique image of Orthomosaics of the October 2020 and July 2021 dates with. See location in the blue frame on Fig. 2C

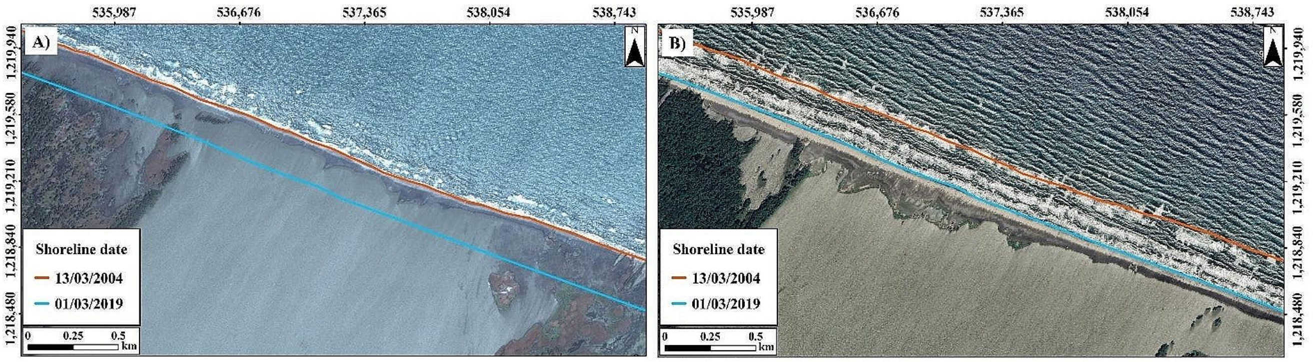

Fig. 5 Shoreline variation at Ciénaga de Cuatro Bocas lagoon sector (See location in the blue frame on Fig. 2A), focusing on the width of the coastal barrier, with washover deposits and loss of mangrove vegetation area, in (A) image 2004 and (B) image 2019 (Google Earth PRO)

The presence of dense vegetation adjacent to the berm reduces the speed of erosive processes, acting as a physical barrier against the action of waves. Gedan et al. (2011) and Powell et al. (2019) have consistently demonstrated that areas characterized by a present of vegetation exhibit a remarkable reduction in berm erosion. In Fig. 5 it is possible to visualize the area of the Ciénaga de Cuatro Bocas Lagoon, in which it is possible to see evidence of the rapid advance of the coastline and the formation of washover deposits due to the lack of vegetation on the coastal barrier. In Fig. 6, near the Ciénaga El Torno Lagoon area, there is an interspersion of vegetated and non-vegetated areas, in which we can see a difference in the speed of transgression of the coastline. In areas devoid of vegetation, the transgression is more accentuated and washover deposits are also formed.

The fundamental connection between the presence of intercropped vegetation and the Washover deposits highlights an important ecological dynamic. The protective

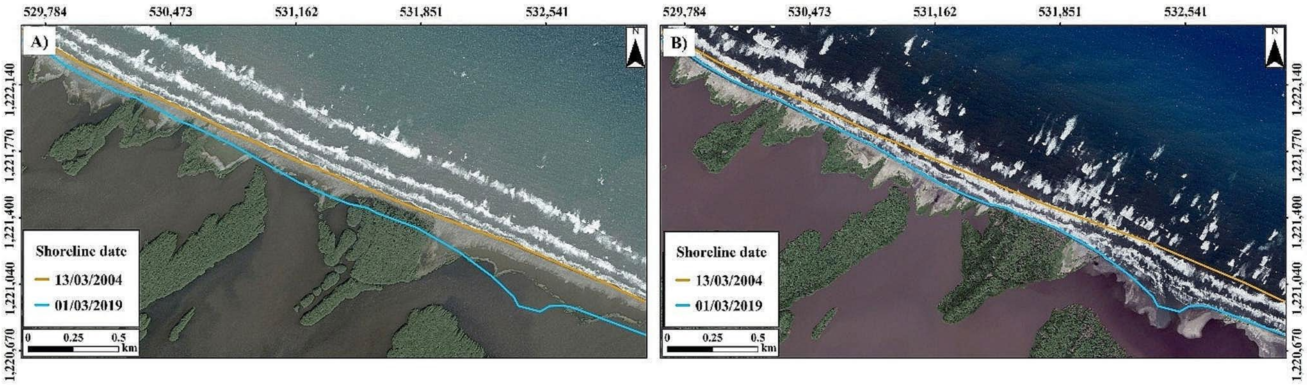

Fig. 6 Shoreline variation at between Ciénaga Cuatro Bocas lagoon and Ciénaga El Torno lagoon sector (See location in the blue frame on Fig. 2A), focusing on the loss of mangrove vegetated area and washover deposits in the portions where the frontal mangroves were absent, in (A) image 2004 and (B) image 2019 (Google Earth PRO)

influence of vegetation becomes fundamental as it acts as a natural barrier, limiting the erosive forces that impact the berms. Consequently, reducing berm erosion decreases the likelihood of sediments being remobilized, thereby decreasing the formation of washover deposits that fill the lagoons. Overwash can have either a positive or negative effect on backbarrier evolution, depending on the frequency and intensity of overwash events (Godfrey and Godfrey 1974).

Excessive sediment input from overwashing can lead to sedimentation in lagoons. This can smother benthic organisms and their habitats, reducing the availability of suitable substrates for attachment, feeding, and reproduction. Also, overwashing may carry nutrients, such as nitrogen and phosphorus, into lagoons. While these nutrients are essential for life, an excess can lead to eutrophication. Eutrophication can cause algal blooms (Heisler et al. 2008), leading to reduced oxygen levels in the water. The altered sedimentation patterns and nutrient levels can result in changes to the physical and chemical characteristics of the lagoon habitat. Benthic organisms are adapted to specific environmental conditions, and alterations can disrupt their habitats and food sources. The changes in habitat conditions may favor certain species over others. Overall, the combination of sedimentation, nutrient enrichment, and habitat alterations can contribute to a decline in benthic biodiversity. Species that are less tolerant to these changes may decrease in abundance or disappear, while more resilient species may dominate.

On the other hand, the area of km 19, with a greater anthropic influence due to the construction of the seawall, has a different dynamic. The seawall is effective in stabilizing the shoreline directly in front of it, but the mention of a progressive increase in erosive processes downstream suggests that the structure may be altering the natural flow of sediments along the coast. Placing large boulders and concrete blocks can indeed interfere with the natural dynamics of the beach. This might impede the movement of sediments and disrupt the equilibrium of the coastal ecosystem. The placement of large boulders and concrete blocks can alter the natural dynamics of the beach and negatively affect marine and coastal biodiversity. The seawalls can also impede beach recharge and coastal sediment erosion, which can affect water quality and the health of coastal ecosystems (Hosseinzadeh et al. 2022). In general, seawalls can be an effective solution to control coastal erosion and protect coastal infrastructure in the short term. However, the environmental impact must be considered and long-term solutions that address the underlying cause of coastal erosion, such as restoration of coastal ecosystems and implementation of sustainable coastal management practices, must be explored. The alteration of natural dynamics can have negative consequences for marine and coastal biodiversity. Habitats that rely on specific sediment compositions and tidal movements may be disrupted, potentially leading to a decline in certain species.

Loss of shoreline and risk to coastal marine biodiversity

It is relevant to note that although this research did not conduct a direct analysis on biodiversity loss, it is crucial to underline the importance of considering such an aspect in a region with such significant erosion rates. The area in question is home to delicate ecosystems, such as mangroves and dunes interconnected to the beach, the preservation of which is vital for the maintenance of marine biodiversity. It is necessary to recognize the potential impacts of these erosive processes on the integrity of coastal ecosystems.

Shoreline loss is a major threat to coastal marine biodiversity. Coastal erosion can negatively affect coastal marine biodiversity by destroying habitats and reducing water quality (Martens, 1992). Species that depend on coastal ecosystems for their survival may lose their habitats and face increased hunting and fishing pressure. In addition, the loss of the shoreline may negatively affect water quality and the health of marine fauna.

The study area is part of the protected area “Isla Salamanca Highway Park”, a region with great biodiversity. It has been declared an Important Bird Conservation Area and, in addition to the Ciénaga Grande de Santa Marta Flora and Fauna Reserve (contiguous area), it was declared a Ramsar Site of World Importance in 1998 and a Biosphere Reserve by UNESCO in November 2000. Salamanca is a group of small islands formed by the sediments of the Magdalena Delta, at the bottom of an ancient gulf; they are connected by small passages that form a barrier between the Ciénaga Grande de Santa Marta and the Caribbean Sea (Parques Nacionales 2023).

The loss of biodiversity in this area is intertwined with the coastal dynamics and human interventions. Previous studies highlight the intricate relationship between vegetation species and coastal morphology (Gómez et al. 2017). In this study, found the accelerated coastal retreat on erosive shorelines is encroaching upon woody vegetation (that normally grows at a distance from marine influence), leading to the transformation of landforms such as scarped dunes. These dunes, covered by mature species like *L. griseus, P. colombiana, P. juliflora*, and *C. flexuosa*, are indicative of the ecological impact of erosion. These findings underscore the intricate interplay between geomorphic processes and vegetation in coastal zones, emphasizing the need for a comprehensive understanding of the relationship between coastal changes and plant species composition.

In addition to the disappearance of vast tracts of land, hydrological changes and variations in salinity will result in the loss of mangroves (Jaramillo et al. 2018). This erosive phenomenon, induced by environmental and anthropogenic factors, has environmental and ecological consequences of great magnitude. Habitat destruction and fragmentation emerge as imminent outcomes, threatening the integrity of terrestrial and aquatic ecosystems.

The maintenance of the shoreline in this region is of great importance for the preservation of the wetland ecosystem present in this sector. In addition, protected areas play a key role in sustainable development if they are managed effectively. The land-sea portion faces a wide range of impacts resulting from human activities and natural events. Climate change, for example, including the stressors of increasing average temperature and extreme weather events result in impacts that affect all dimensions of the Sustainable Development Goals (Singh et al. 2019) and can amplify anthropogenic impacts.

The construction of the road and the preventive measures taken to protect it are other causes of habitat degradation. Crossing a region of great environmental importance, such as the wetland where the study area is located, directly results in impacts from terrestrial pressures and human activities, including increased erosion and sedimentation. In addition to the anthropogenic impact, the increase in extreme meteorological events, such as the increase in storm surges, results in higher erosion rates. Thus, sea level rise is associated with flooding and loss of intertidal habitat, which negatively affects erosion prevention functions.

In addition to this, the high erosion rates observed in the study area and the predicted increase in extreme events and sea level rise, there is significant evidence of critical environmental losses, as already occurs in other parts of the Colombian Caribbean coast and in other regions (Bolívar-Anillo et al. 2019; Villate Daza et al. 2020; Winterwerp et al. 2020; Veettil et al. 2023).

The consequences of coastal protection measures on the livelihood of coastal communities may also be present. According to Angnuureng et al. (2023), coastal protection structures have been identified as contributing to the loss or destruction of fishing assets, including boats and nets, along with adverse effects on fishing grounds. Additionally, the impediments in landing and dragging fishing nets onshore/offshore have resulted in reduced fish catch, impacting the daily occupations and livelihood activities of coastal communities. This emphasizes the need for a holistic approach in coastal protection strategies, considering both environmental preservation and the well-being of the coastal population.

Actions to protect the coast and its ecosystems

Rising sea levels, intensifying storms and increased human activity on the coast are among the factors that can accelerate erosion and cause the loss of beaches, dunes, and coastal wetlands, as well as the degradation of coral reefs and other marine ecosystems (Pranzini and Williams 2013). To protect the coast and its ecosystems from erosion, several actions have been implemented around the world. One option along a receding shoreline is some form of shoreline stabilization or protection. Stabilization is essentially maintaining the shoreline. Shoreline protection can be based on two types, structural such as a breakwater; or some form of shoreline protection based on the ecosystems present in the region. In conjunction, one can work with a combination of both techniques (Kamphuis 2020).

Coastal ecosystems, such as mangroves, salt marshes, coral reefs, beaches, and dunes, provide important roles on the coast, including protection against coastal hazards such as storm surges, flooding, and erosion (Martinez et al. 2011;

Portz et al. 2014; Strain et al. 2022). The role of mangroves in coastal protection is specific to the site and the local threat context (Spalding et al. 2014), and further research is needed to determine under what ecological and environmental conditions mangroves can provide coastal protection services comparable to man-made coastal infrastructure (Brathwaite et al. 2022; Strain et al. 2022).

The most appropriate solution to the problem of roads threatened by coastal erosion is to relocate the roads. Over the decades, several roads have been moved or abandoned. There are several examples of road relocation due to coastal erosion around the world. Some of the cases include: The Great Ocean Road in Victoria, Australia, which stretches for more than 240 km along the southern coast of Australia, has been affected by coastal erosion on several occasions. In 2016, a relocation of a section of the road in the Great Otway National Park was carried out due to coastal erosion. The Pacific Coast highway in California, USA has been affected by coastal erosion on several sections, leading to road closures and relocations. A critical section of the highway near Big Sur was closed for more than a year due to a landslide caused by coastal erosion. The coastal road in County Kerry, Ireland that winds along the cliffs of the Atlantic Ocean in southwest Ireland, in 2014, a section of the road was relocated due to coastal erosion and landslide risk. Washington State Highway 105 in the Cape Shoal water area, coastal U.S. This road was moved several times as this area has experienced some of the highest rates of long-term coastal erosion in the U.S. (FHWA 2023).

A major problem when considering the relocation of the highway in the study area is the new design. The logical location is further inland, retreating to the coast. However, these areas also have large tracts of wetlands and mangroves. Considering these problems and the historical impacts due to the interruption of the natural connections in the hydrological system of the region, the construction of an elevated highway is proposed as an option.

Another important action is shoreline management, which involves regulating construction and land occupation along the coast to minimize human impact on coastal ecosystems. Construction regulations, the creation of protection zones, and the promotion of sustainable practices are some of the measures that can be implemented to reduce erosion and protect the coast and its ecosystems. Additionally, exploring innovative solutions, such as bioconstructions in submerged areas, could be a promising approach. These structures not only reduce the energy of the waves, but also promote greater sediment deposition. The nature-based coastal defenses classified into two primary categories: soft, consisting solely of natural ecosystems, and hybrid, incorporating artificial elements for structural support. These strategies emerge as encouraging alternatives to rigid infrastructures, distinguishing themselves through sustainability, adaptability, and self-sustaining attributes facilitated by the incorporation of natural ecosystems (as discussed by Perricone et al. 2023). Ongoing initiatives showcase favorable outcomes, establishing their cost-effectiveness in contrast to conventional engineering solutions. This holistic approach, combining structural and ecosystem-based techniques, can be instrumental in addressing the challenges of coastal erosion and ensuring the long-term sustainability of coastal regions.

It is also crucial to involve local communities and coastal users in the conservation and protection of coastal ecosystems. Environmental education, the promotion of sustainable activities, and the promotion of ecotourism can help raise awareness of the importance of protecting the coast and its ecosystems (Kao et al. 2023). The question is, when will we adapt our human development to natural processes? We must be aware of the forcings acting in the coastal zone and have the habit of living in changing coastal environments. We must consider that the artificial structures present at the land-sea interface are temporary and only as a last resort consider the construction of engineered structures for coastal protection or preservation, only in heavily populated areas.

Conclusions

In examining the mid-term dynamics of Isla Salamanca's coastal barrier, it is evident that the majority of the shoreline is experiencing a transgressive process, marked by erosion rates peaking at $-16.1\ \mathrm{m \cdot yr^{-1}}$. However, the Boca de Ceniza sector, positioned near the mouth of the Magdalena River, exhibits a regressive process with a shoreline retreat of up to 490 m. This varied behavior is linked to a sediment deficiency on the eastern side of the barrier. Additionally, the prevailing westward longshore current contributes to the transport of eroded sediments toward Boca de Ceniza.

Eroded sediments from the beach berm are redeposited in the backshore as washover deposits, and the volume of mobilized sediment is directly related to the accommodation space in the backshore. Coastal lagoons in the backshore play a role in retaining some sediment, although the proximity of the highway to the shoreline limits sediment retention. At km 29, where the shoreline has not yet reached the road, sediment retention is higher due to small lagoons between the shoreline and the highway. Native vegetation further aids in reducing erosion rates.

Conversely, at km 19 sector 1, sediment retention is entirely absent due to the absence of frontal vegetation and lagoons between the shoreline and the highway. In km 19 sector 2, a small volume of sediments is retained in the backshore, initially supported by vegetation in the first drone campaign, but subsequent loss of vegetation in the second campaign is evident. Sector 2 of km 19 experiences increased erosion, likely attributed to the presence of a seawall and the gentle slope of the coast, causing sediments arriving from sector 1 of km 19 through coastal drift to be lost to the surf zone. The seawall at km 19 serves as only temporary protection for the highway, failing to counteract the erosive phenomenon effectively.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00367-024-00765-6.

Author contributions Conceptualization, Rogério Portantiolo Manzolli, Mulfor Cantillo-Sabalza, Luana Portz; methodology, Rogério Portantiolo Manzolli, Mulfor Cantillo-Sabalza, Luana Portz; software, Rogério Portantiolo Manzolli, Mulfor Cantillo-Sabalza, Luana Portz; formal analysis, Rogério Portantiolo Manzolli, Mulfor Cantillo-Sabalza, Luana Portz; writing-original draft preparation, Rogério Portantiolo Manzolli, Mulfor Cantillo-Sabalza, Luana Portz; writing—review and editing, Rogério Portantiolo Manzolli, Mulfor Cantillo-Sabalza, Luana Portz. All authors have read and agreed to the published version of the manuscript.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. No funding was received to assist with the preparation of this manuscript.
Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature.

Data availability The data to support this study are included within the article and can also be requested from the corresponding author.

Code availability Not applicable.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.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.

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