



# Impacts of anthropogenic structures in long- and short-term shoreline evolution of Santa Marta Bay (Colombian Caribbean)

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## Abstract

Interaction of Anthropogenic interventions (rigid structures) with coasts is an essential aspect for understanding their geomorphic evolution and incorporating these data into adequate coastal management. This study analyses the short and long-term behavior (1985 to 2019) of shoreline at Santa Marta Bay (Caribbean - Colombia) and their relationship with coastal protection structures. The shoreline variations were analyzed through aerial photographs and satellite images using DSAS tools. The short-term assessment showed initial intense 1985–1991 erosion, with an average retreat speed rate of  $-1.6 \text{ m}\cdot\text{y}^{-1}$ . It changed gradually since 2003, due to the construction of rigid structures and beach nourishment, decreasing shoreline retreat and even a progradation rate of  $0.2 \text{ m}\cdot\text{y}^{-1}$  was observed. The 2009–2019 period, despite recording a positive average value, exhibited a high percentage of erosion profiles. Therefore, in a decadal or long-term analysis (1985–2019), despite engineering works present positive results in the short term, new interventions are required. The coastal erosion is not uniform along the shoreline, because the area is a closed bay with small sediment inputs, the variations in erosion and accretion rates change with human intervention and the installation of new structures. Therefore, quantifying the scale and rate of shoreline changes and correlating them with anthropogenic structures is an essential step in assessing shoreline vulnerability.

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## Introduction

Beaches are natural spaces providing attractive resources and services for tourism as a means of economic development. Tourists seek recreational activities. In turn, these recreational activities must be supported by adequate infrastructure and facilities to meet this growing demand (Orams 1999). As illustrated in several papers, natural coastal processes, coupled with the pressure applied by the increased demand from the tourism industry, generate a series of negative impacts (Phillips and Jones 2006; Portz et al. 2007; Cristiano et al. 2018; Pathak et al. 2021). Therefore, some authors express concerns regarding the negative impacts exerted on beaches by rigid coastal protective infrastructures (Manno et al. 2016; Pranzini 2018; Villate et al. 2020; Manzolli et al. 2022, 2024).

At a global level, all shoreline vulnerability factors are being treated as a prerequisite for zoning decisions, thus leading to the implementation of control strategies against threats such as erosion (Salman et al. 2004). The foregoing is added to the factors that foster sustainable tourist exploitation when improving the living conditions of the host communities, tourist satisfaction, and land care (Gauna Ruiz and de Leon 2017). In fact, mitigating erosional processes has become one of the main responsibilities for shoreline managers. As reasonably possible, these managers must preserve the quality of the landscape in its natural state while promoting an enjoyable environment for visitors (Phillips and Jones 2006; Gargiulo et al. 2020).

Coastal erosion can cause several consequences not only on beaches but also on other coastal ecosystems, as in the case of adjacent dune systems (Portz et al. 2021). Moreover, the loss of coastal areas due to erosional processes causes economic losses owing to the destruction of residences, a decrease in tourism, leisure, fishing, and aquaculture activities, as well as in port, business and industrial activities, and services related to all the afore-mentioned activities (Souza 2009; Portz et al. 2015, 2018). The development of erosion processes in coastal areas is generally fought by a progressive addition of engineering structures (Cooper et al. 2009). These structures can be, e.g., seawalls, breakwaters, and piers. In most coastal areas around the world, hard engineering structures are implemented to contain negative dynamics impacting sandy beaches in the face of an increasing risk of losing beach areas to rising sea levels (Nordstrom 2014). These structures may have as their objective the protection of urban constructions (piers), recovery of beach profiles (hydraulic nourishment), and consolidation of port infrastructures (starlings) (Airoldi et al. 2005). Rigid structures exert variable impacts on coastal protection. Rigid structures such as groynes and rockfills occasionally stabilize coastal erosion but can significantly contribute to

the disruption of coastal drift. These structures obstruct the longitudinal transport of sediments, which consequently results in an erosion risk for adjacent beaches. Moreover, seawalls secure the shoreline and prevent the sediments contained behind them from entering the beach (de Santiago et al. 2021). These structures also have an impact on biota and can act as physical barriers against the movement of mobile benthic animals and propagules along the coast (Dugan et al. 2012). To address these issues more sustainably and effectively, Nature-Based Solutions (NBS) emerge as a promising alternative (Unguendoli et al. 2023). NBS, such as the restoration of dunes, mangroves, and coastal wetlands, not only offer effective natural protection against waves and storms, but also play a crucial role in stabilizing coastal margins. In addition, these natural approaches promote sediment retention and contribute to reducing coastal erosion, while providing additional benefits such as supporting coastal biodiversity and improving water quality.

Erosion levels on Colombian beaches are not different from most countries (Posada and Henao 2008; Anfuso et al. 2015; Manzolli et al. 2020, 2024; Villate et al. 2020). At several beaches, the process is quite severe and requires containment and/or emergency recovery measures. These issues and matters have only been slightly addressed because coastal development is regularly aligned to current needs with a particular economic focus fostered by a constant imbalance in policies, regulations, and institutions (Botero et al. 2016). Furthermore, we must also consider mitigating the erosion that affects most of the Caribbean coast of Colombia (Rangel Buitrago and Posada-Posada 2005). The data collected in the Guajira Peninsula and coasts of the Sierra Nevada de Santa Marta Mountain range suggest a coastal retreat of 20 to 30 m in the last century, whereas for the southern Caribbean region, which spans from the Magdalena Delta to the Gulf of Urabá, a coastal retreat of up to 12 km and the maximum erosion rates up to  $40 \text{ m}\cdot\text{y}^{-1}$  are reported in some areas (Correa et al. 2005; Alcántara-Carrió et al. 2019). In response to these processes, implementing rigid works has been offered as a solution aimed at stopping material losses on private beaches or in beach areas with buildings constructed on lowlands, berms, or dunes, thus directly impacting the physical environment of the location (Rangel-Buitrago et al. 2018).

Owing to the socioeconomic and ecological importance of the Colombian coast, especially in the Santa Marta region, coastal evolution must be reconstructed to evaluate the impact from the different rigid infrastructure installation stages. Consequently, coastal risks can be assessed and later avoided within a context of climate change, mainly marked by rising sea levels. The derivations from coastal dynamic changes continue to be poorly studied and have become groundwork for securing sustainable development

in preserving coastal ecosystems and maintaining socio-economic activities along the Santa Marta shoreline.

Santa Marta bay has been moderately altered by humans, and it is characterized by significant tourist activities. Santa Marta offers port facilities, marinas, and intense infrastructures aimed at meeting tourist demands. Quantifying the scale and rate of shoreline changes and determining their relationship with anthropogenic structures is an essential step in assessing shoreline vulnerability. Therefore, this study assesses coastal change patterns and their relationship with the development of coastal and tourist infrastructure at Santa Marta Bay. Moreover, we explore the positive and negative aspects of the construction of anthropic structures along the coast while seeking an effective and sustainable management. Despite serving as a case study, references to specific works and their accomplishments remain limited. Often, the available references primarily focus on providing a step-by-step description of the actions carried out. Furthermore, the number of comprehensive studies that effectively evaluate the medium- and long-term impacts resulting from environmental changes is comparatively small.

## Materials and methods

### Study area

The Bay of Santa Marta is in the narrowest section of the continental shelf of the Colombian Caribbean region, which is associated with the Sierra Nevada de Santa Marta Mountain range. Its shape is semicircular and concave, extending for approximately 2.4 km toward the west. Manzanares River is the main water and sedimentary source flowing into the Bay of Santa Marta. In this study, the bay has been divided into four sectors, with extensions of 652.5 m, 673.0 m, 284.4 m, and 785.6 m for sector 1 to 4, respectively (Fig. 1).

The climate of the Colombian Caribbean region is modulated by the location of the Intertropical Convergence Zone and by the cycles of the American Monsoon System (Andrade-Amaya 2015). Winds prevail at speeds ranging from 4.5 to 6.0  $\text{m}\cdot\text{s}^{-1}$ . Between April and July, there is an atmospheric period of transition, with low to almost zero rainfall, wind speeds ranging between 1.5 and 3.0  $\text{m}\cdot\text{s}^{-1}$ , and peaks reaching 4.0  $\text{m}\cdot\text{s}^{-1}$  (IDEAM 2022). The Santa Marta area reports less than 500  $\text{mm}\cdot\text{y}^{-1}$  in rainfall owing to the effect of dry and hot winds caused by divergences from differential frictions between the ocean and land (Guzmán et al. 2008).

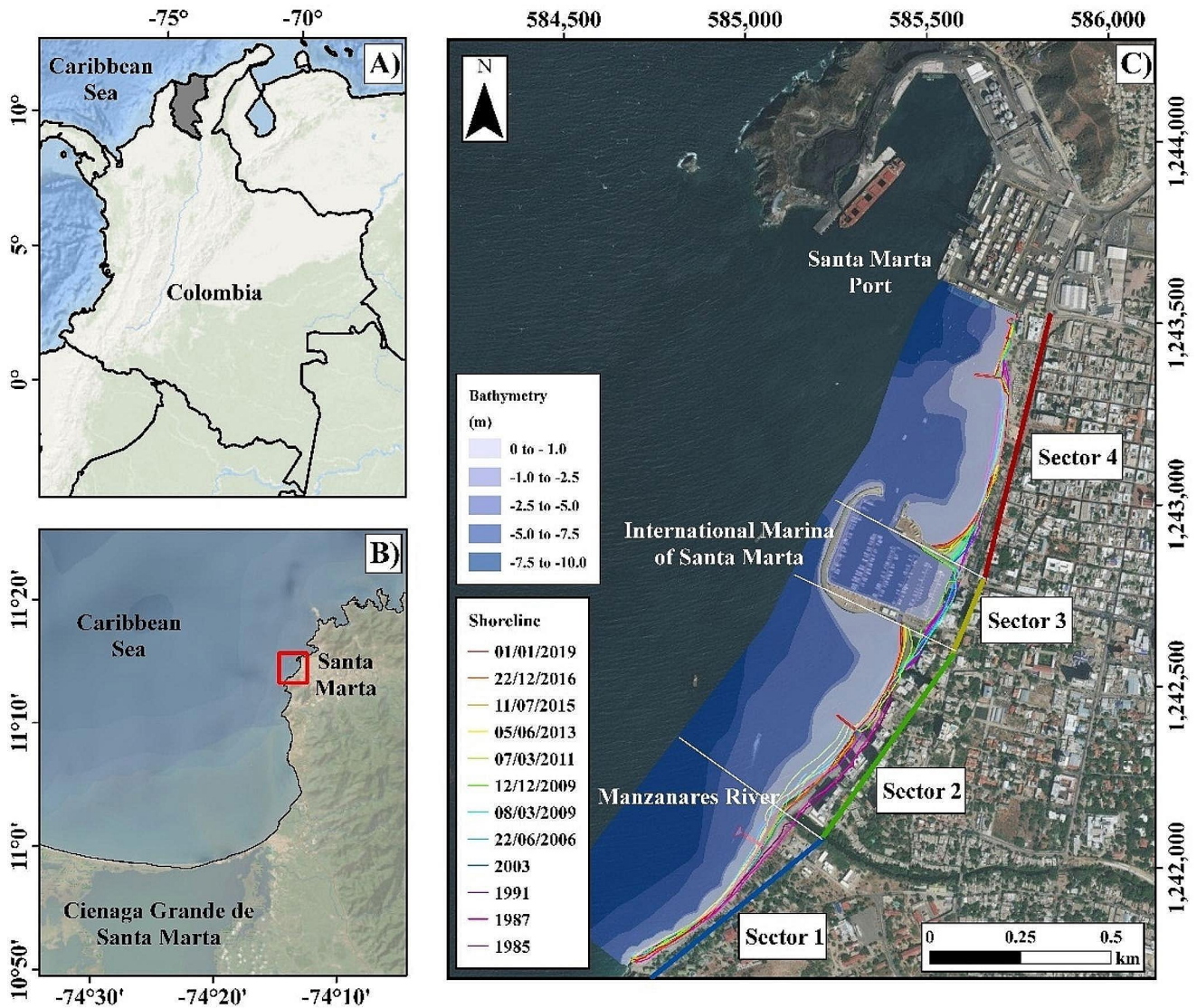
Because the direction of waves is closely related to the direction of wind, the waves exhibit a predominant NE–SW direction between December and April and an ENE–WSW trend for the rest of the year (Thomas et al. 2012).

The average of annual significant wave height ( $H_s$ ) is equal to 1.0 m. At low wave conditions, significant wave heights are associated with the orientation of the coastline and its sheltered condition. During extreme swell events, caused by either hurricanes or cold fronts coming in from the north, significant wave heights can reach 2.5 m, and their direction can change depending on wave train incidence (see Supplementary material for more information).

### Remote sensing

Based on the criteria expressed by Pardo (1991) which focuses on the short- and long-term evolutionary processes and changes collected from a few weeks to decades, we conducted a diachronic assessment of the shoreline evolution experienced by the Bay of Santa Marta using the aerial photographs taken in 1985, 1987, 1991, and 2003 by the Agustín Codazzi Geographical Institute (IGAC) and Google Earth satellite images from 2006, 2009, 2011, 2013, 2015, 2016, and 2019 (Table S1–Supplementary material). In this study, the acquisition of shorelines for each year was conducted by carefully considering the coverage and unique characteristics of each raster image. For the present study, the coastline was characterized as the position of the terrestrial interface in the sandy coastal areas, marked by the limit reached during the high tides. The limit was defined by a change of tonality in the sands of the beach. This boundary is determined by the change in shade of the beach sand. Shorelines are manually vectorized. All the remote sensing products were reprojected to the UTM projection (zone 18 N) and WGS84 datum.

Shoreline change rates were generated in ArcMap 10.8.1 using version 5.0 of the Digital Shoreline Analysis System (DSAS-USGS) (Thieler et al. 2009), using a value of 1 m for data uncertainty in geostatistical processing. The statistical methods used to quantify the shoreline displacement: net shoreline movement (NSM) and endpoint rate (EPR), are also used in other studies such as Genz et al. (2007); Kabir et al. (2020); Abou Samra and Ali (2021) and Al-Attar and Basheer (2023). In this work, the end point rate (EPR), was calculated by dividing the distance between the most recent and oldest shorelines by the elapsed time, and the net shoreline movement (NSM), determined by the variation distance between the oldest and most recent shorelines (Manzoli et al. 2020; Villate et al. 2020) (see Supplementary material for more information). In our effort to establish a coastal evolution classification system, we subdivided the EPR value into seven distinct classes, as proposed by (del Río et al. 2013; Natesan et al. 2015; Cifuentes-Ossa et al. 2017). The interpretation ranges for the EPR module were derived from Table S2 (Supplementary material), which provided the necessary thresholds for assigning each coastal area to



**Fig. 1** Location of the Bay of Santa Marta study area. (A) Global background; and (B) Regional context (GCS-WGS1984); and (C) Santa Marta beach in the Magdalena Department (WGS1984-UTM-Zone18N, in meters). Image base: ArcMap® 10.8.1

a specific class. By utilizing this established framework, we aimed to create a more standardized approach for evaluating coastal evolution and ensure greater comparability with previous research in this sector.

### Results and discussion

Shorelines undergo continuous alterations due to both natural processes and human activities. Accurately detecting changes in shoreline configuration in relation to coastal infrastructure offers valuable insights into coastal dynamics, rendering it of paramount significance for future planning purposes.

### Shoreline hardening evolution

The Santa Marta Bay beaches have been subjected to continuous intervention, mainly aimed at stopping erosional processes. For example, in the 1970s, the Puertos de Colombia Company conducted beach dredging and filling works. Subsequently, the Central French Laboratory of Hydraulics conducted the “Defending the Santa Marta Beach” study, whose technical recommendations were not fully implemented. This gradually contributed to the continuous recession of the width of the beach and to losing its equilibrium profile, thus ultimately exposing the foundations of the pedestrian Rodrigo de Bastidas State Park in the northern sector of the study area (Sector 4). In 2000, a mitigation effort was conducted with implementing geotextile containers for straight

circular trochoidal sediments, which were planned as containment breakwaters for the particulate material. However, this intervention was not successful due to construction implementation issues and poor filling material selection.

Furthermore, a beach nourishment was conducted from September 26, 2000, to September 4, 2001. This beach nourishment used properly classified quarry sand and concentrated mostly in Sector 4, with an average width of 35 m to the north and 17 m to the south. However, on more than one occasion, strong waves and breeze completely washed away all the nourishment material, transporting it along the shoreline, especially to the south. A second beach nourishment was conducted in Sectors 2 and 3 as a beach recovery measure. In these sectors, the beach no longer existed because the ocean had totally displaced the sedimentary material and constructions along the shoreline. Consequently, the beach area increased to an average width of 22 m. In both cases, the design elevation was controlled at 0.60 m during construction. Also, two rigid breakwaters were built in 2002 (Sector 1, 3 and 4) (Figure S1-Supplementary material, image from 2003). The first breakwater was placed in the northern area (Sector 4), and the second one was built in the center of the bay, approximately 30 m away from the promenade (Sector 3). These works were supplemented with nourishments using classified external material with similar granulometric characteristics to the sand found at this beach. However, in the same manner as with previous nourishment dredging operations, most of the material was transported south by currents, waves, and wind.

In the year 2002, construction commenced on a pier located in the southern region of the Manzanares River mouth, with a footbridge perpendicular to the shoreline and a “T” ending driven into piles (Sector 1) (Figure S1, image from 2003). Subsequently, between 2006 and 2009, an additional breakwater was built to the north of the Manzanares River estuary (termed Sector 2). The last construction, and perhaps the most important one, is the service infrastructure built during 2009–2012 (Figure S1, image from 2009). This infrastructure contained two breakwaters and one seawall mainly comprising quarry rocks (limestone) (Sector 3). These structures aimed at protecting and dissipating wave energy for docking boats. The most outstanding structure is the international marina, with a service infrastructure of 2,201.16 m in length, followed by a 207.73 m pier, and finally the two breakwaters with a length of 147.19 and 137.74 m, respectively (Figure S1, image from 2009 to 2019).

Hard structures have been the first management strategy for coastal erosion issues along the Colombian Caribbean coast. In the first months of 2016, there were 1,484 hard structures, with the highest concentrations in tourist cities (Rangel-Buitrago et al., 2018). As a result of these works,

Santa Marta Bay evidenced irreversible shoreline modifications, with negative visual impacts and the loss of public access to the ocean water area, mainly in Sector 3.

## Shoreline erosion and accretion assessment

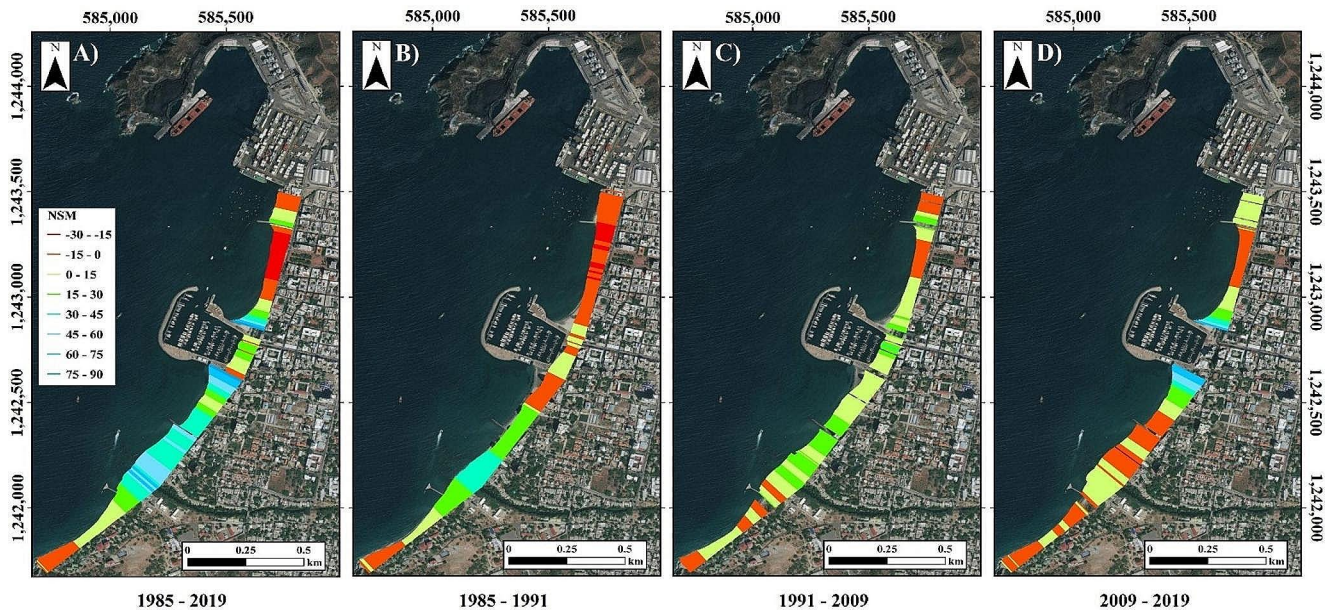
### Long-term shoreline evolution

The main historical shoreline changes along the Colombian Caribbean coast area reflect both erosional and accretion events, with the latter in highly localized areas (Correa et al. 2005). The erosion of the Colombian Caribbean coast seems to have accelerated since the 70s and 80s as the size of coastal cities has also grown (Navarrete-Ramírez 2014). Approximately 50% of this area is suffering erosional processes that cause receding coasts (Rangel-Buitrago et al. 2018). However, erosion rates in the Colombian Caribbean are very varied (Correa and Vernet 2004; Rangel-Buitrago and Posada-Posada 2005; Posada and Henao 2008; Manzolli et al. 2020; Villate et al. 2020). In the Department of Magdalena, where this study is located, maximum rates of  $-15 \text{ m}\cdot\text{y}^{-1}$  have been observed (Ciénaga-Tasajera Sector) (Ingeominas 2008).

The results from the Santa Marta Bay shoreline changes from 1985 to 2019 show a complex spatial evolution, where the periods of accretion and erosion are interspersed and correlated to the different phases of rigid structure installation. The results from our long-term shoreline change assessments (1985–2019) are presented in Fig. 2A and Table S3. The positive EPR and NSM values represent shoreline progradation, and the negative values indicate retrogradation, associated to erosion processes within the sector. The bay was subdivided into four sections depending on the anthropic interventions developed over time. Here, it was possible to detect significant changes along the shoreline. In fact, both in the different periods assessed and among the four sectors defined, accretion processes prevailed.

In general, Santa Marta Bay experienced shoreline progradation from 1985 to 2019 at an average range of 15.1 m of beach width (NSM) and an average progradation rate of  $0.5 \text{ m}\cdot\text{y}^{-1}$ , thereby being classified into the C4 class of coastal evolution, i.e., it is an area with stable shoreline variations (del Río et al. 2013; Natesan et al. 2015). However, the maximum and minimum rates of 2.6 and  $-0.9 \text{ m}\cdot\text{y}^{-1}$ , respectively, show a moderate long-term accretion trend. Further, approximately 70% of the transects along the shoreline showed a wide beach width, whereas approximately 29% of the transects experienced erosion, and 1% remained stable.

Spatially, long-term changes indicate higher progradation values in the central area of the Santa Marta Bay, in Sector 3. This progradation has been mainly influenced by



**Fig. 2** (A) Long-term (1985–2019) net shoreline movement (NSM). Short-Term Shoreline Changes (B) 1985–1991, (C) 1991–2009, and (D) 2009–2019 assessment periods. The legend in the map A is the same for B, C, and D. Image base: ArcMap® 10.8.1

the disposition of the coastal works in relation to coastal dynamics. Conversely, a process of shoreline transgression was identified, mainly in Sector 4 and the southern margin of Sector 1 (Fig. 2A). In general, in Sectors 1, 2, and 3, the end rate point denotes positive mean values (0.3, 1.2, and 0.5  $\text{m}\cdot\text{y}^{-1}$ , respectively), and only Sector 4 reports average negative values, with a change rate of  $-0.1 \text{ m}\cdot\text{y}^{-1}$  (Fig. 3A and Table S3). Taking the 1985 shoreline as a foundation, we can infer that Santa Marta Bay exhibits stable prograding behavior. However, the bay also evidences different manifestations of coastal movement. For example, Sector 4 reports a net loss of beach area, even with a constant intervention and the installation of rigid structures, whereas Sector 2 has gained area. The other two sectors (1 and 3) have remained more stable, mainly due to engineering works. Sector 2 progradation can be explained through sediment contributions from the Manzanares River, which also influences a part of Sector 1. Nevertheless, in Sector 4, as there is no significant sediment contribution, and due to marine hydrodynamic processes, sediments are distributed to the extremes of the sector adjacent to the rigid structures (Figs. 2 and 3).

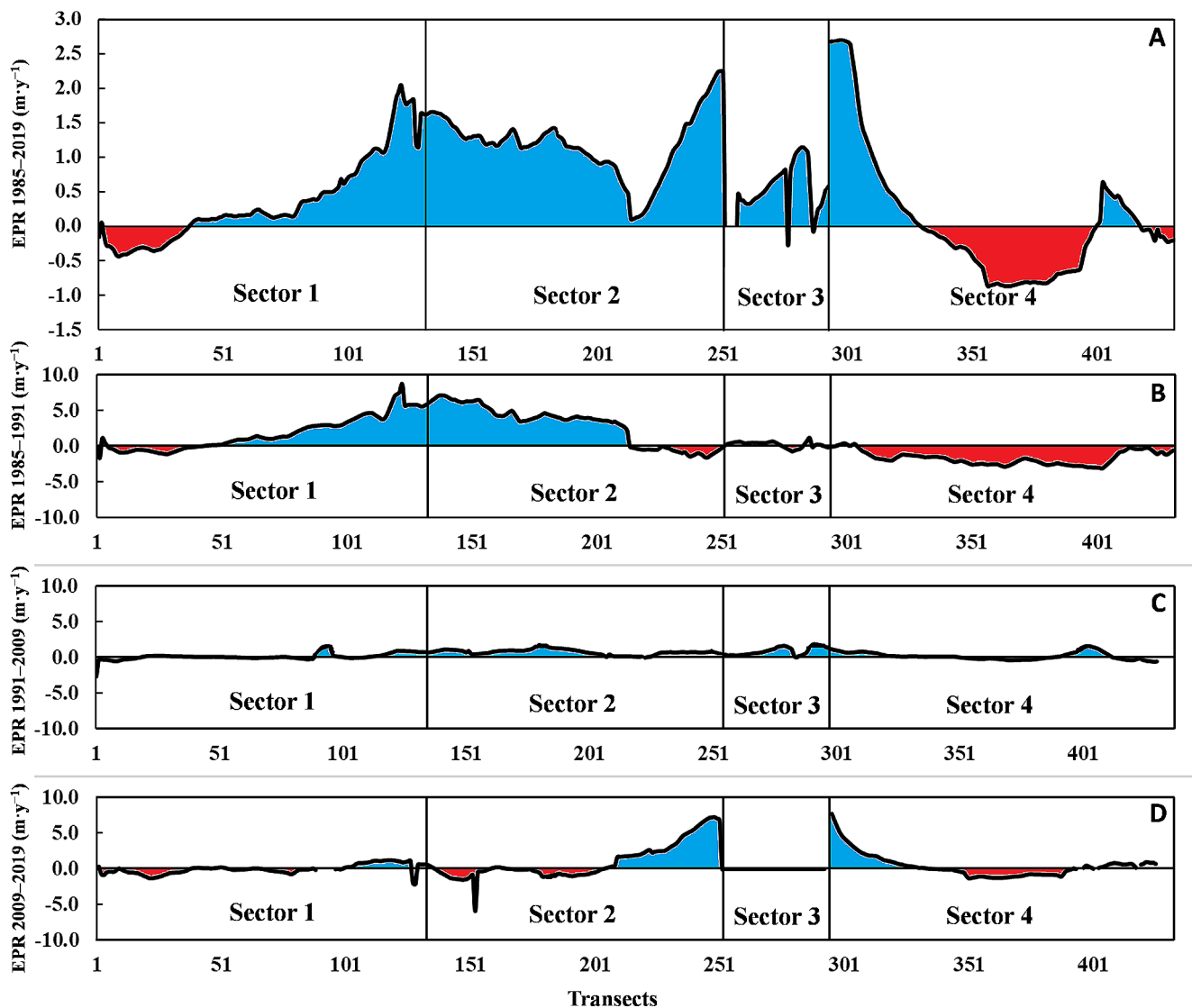
The behavior of different sectors regarding accretion, erosion, or stability processes is basically influenced by how anthropic structures interact with local hydrodynamics. This influence has already been discussed in different studies, such as (Di Paola et al. 2020; Manno et al. 2016; Pranzini 2018; Rangel-Buitrago et al., 2018). In the past century, the Colombian Caribbean coast has experienced a population increase, with intense development and urbanization, in addition to the drastic increase in the number of tourists

on vacation (Rangel-Buitrago et al. 2018). The increase in the use and occupation of these sectors has required a larger number of coastal protective measures to mitigate coastal hazards, such as erosion processes, and the construction of service structures to meet the ever-increasing demands.

In Santa Marta Bay, shoreline change trends have intensified since the port construction. Subsequently, several other works (i.e. breakwaters, seawall, and beach nourishment) have been incorporated to mitigate erosional processes. Since then, the urban beach adjacent to the port structure has faced continuous erosion processes, up to the intervention from authorities through mitigation measures, such as building hard coastal protection structures throughout the affected area. These efforts were aimed at protecting beaches, stabilizing beach profiles, attenuating wave energy, and sustaining tourism structures.

### Short-term shoreline changes

Shoreline movement data show significant mobility in the short-term analyzed periods. The different sectors exhibit shoreline changes, both in the sense of beach area loss and expansion. The division of analysis periods is linked to anthropic interventions. For each period, i.e., 1985–1991, 1991–2009, and 2009–2019, we identified shoreline variability averages for each transect, observing that variations were closely related to the engineering works conducted in the three anthropic intervention cycles for rigid structures. The NSM and EPR are expressed for each period assessed in Figs. 3 and 4. Table S3 provides detailed information



**Fig. 3** (A) Long-term shoreline change (1985–2019) (EPR method). Short-term shoreline change (EPR method) (B) 1985–1991, (C) 1991–2009, and (D) 2009–2019

about the mean, median, maximum, and minimum for each sector and period.

**1985–1991 Period.** In this first period, which represents a 6-year, the only rigid structure was the promenade Rodrigo de Bastidas State Park (Sector 4). In 1985, a part of its structure (south of Sector 4) became exposed without the presence of a beach area. The rest of the sector reported an average beach width of 17 m. In the following years (1987 to 1991), the shoreline experienced multiple transgressions, which reduced the sandy area in this sector. The average annual land loss in this sector was  $-1.6$  m per year, with a mean retrograde loss of  $-9.8$  m.

According to the statistical comparative analysis conducted based on the NSM values from 1985 to 1991, the

shoreline exhibited stability with the mean NSM values of 5.3 m, an EPR value of  $0.9$   $\text{m}\cdot\text{y}^{-1}$ , and the maximum and minimum rates of 8.7 (Sector 1) and  $-3.1$  (Sector 4)  $\text{m}\cdot\text{y}^{-1}$ . Sector 3 evidenced a slight predisposition to progradation with an average gain of 1.6 m. Even when the entire Sector 3 was evaluated (Fig. 3), we could detect small areas in which erosional processes were present. Moreover, in Sectors 1 and 2, shoreline progradation was clearly present, with an average shoreline progress rate of 1.6 and  $3.1$   $\text{m}\cdot\text{y}^{-1}$ , respectively. Here, Sector 2 reports a larger shoreline progradation with an average gain of 18.8 m. These two sectors are directly influenced by the mouth of the Manzanares River, which is the only sediment source in the bay. However, small shoreline transgression segments are observed in the southern border of Sector 1 and in the northern area of Sector 2 (Fig. 3). Unlike the other three sectors, Sector

4 evidenced an intense erosion from 1985 to 1991, with a maximum shoreline transgression rate of  $-3.1 \text{ m}\cdot\text{y}^{-1}$ . Here, 42% of the transects in this sector report shoreline dislocation rates exceeding  $-2 \text{ m}\cdot\text{y}^{-1}$ , which imply that this sector is classified as C3 (moderate erosion) in the coastal evolution for this period.

**1991–2009 Period.** (Containment Work Construction Period). The second period is the longest as it spans 18 y. In this period, an average progradation rate of  $0.3 \text{ m}\cdot\text{y}^{-1}$  was recorded, with the maximum and minimum rates of  $1.6$  and  $-2.6 \text{ m}\cdot\text{y}^{-1}$ , respectively. In general, it is more stable than the first period, evidencing variations among the different sectors assessed. In this period, Sector 1 reduced its progradation rates from  $1.6$  to  $0.3 \text{ m}\cdot\text{y}^{-1}$  because of the installation of some structures in its northern area. For Sector 2, the trend of positive shoreline advancement was sustained, but at a lower average progradation rate ( $0.6 \text{ m}\cdot\text{y}^{-1}$ ), despite not presenting any transects with erosion. Sector 3 remained quite stable at an average progradation rate of  $0.7 \text{ m}\cdot\text{y}^{-1}$ . This shoreline gain rate occurred before anthropic interventions. However, as of the 2009 construction of the International Marina of Santa Marta, this bay sector has not experienced any further changes. In contrast to the first period, Sector 4 reversed the erosional trend and reported the largest number of shoreline gain transects (59%). The average progradation rate was  $0.2 \text{ m}\cdot\text{y}^{-1}$ . Figures 2 and 3 depict sectors with some erosional processes, mainly in the central portion, and progradation near coastal works. The construction of seawalls provided larger shoreline stability, with a higher tendency for erosion in the central part of the sector.

**2009–2019 Period.** (Post Structure Construction Period). Average shoreline progradation rates increased with the completion of the coastal structures, remaining stable at  $0.4 \text{ m}\cdot\text{y}^{-1}$  from 2009 to 2019, with the maximum and minimum rates of  $7.8$  and  $-5.9 \text{ m}\cdot\text{y}^{-1}$ , respectively. Furthermore, when the different sections are assessed individually, an increase may be observed in the number of erosion process profiles from the previous period. Although several profiles reported negative values, accretion rates remained stable ( $\text{EPR}=0 \text{ m}\cdot\text{y}^{-1}$ ) for Sector 1. In this period, accretion rates are expected to increase again at a mean progradation rate of  $1.0 \text{ m}\cdot\text{y}^{-1}$ , which is higher than the previous period, owing to the installation of the marina structure. This mainly favored an accumulation of sediment next to the S structure (Figs. 3 and 4). The construction of the marina in Sector 3 eliminated this stretch of beach and became significant for the  $0.4 \text{ m}\cdot\text{y}^{-1}$  accretion rates of Sector 4. The main accretion profiles were located next to the marina structure.

During the various phases of construction for these coastal projects, the primary feature observed was the preservation of the beach area, as evidenced by the overall shoreline stability presented in Table S3. The results revealed substantial shoreline fluctuations, underscoring the area's high susceptibility to coastal erosion.

In retrospect, the erosional or negative variability condition was mitigated with the construction of breakwaters and service infrastructure that generated an accretion condition that remained active until 2019, without ignoring the specific areas wherein a negative variability trend may still be observed. For example, we can mention the area next to the breakwater in Sector N (Sector 4), without affecting the width of the beach, which required 16 y to recover supported by sediment deposits between the protective and service structures erected.

The results obtained show similar accretion and erosion patterns, as found in other studies that have also used this approach. A study conducted in Puducherry, India (Misra and Ramakrishnan 2020) assessed the coastal geomorphological impact of a beach restoration project to contain coastal erosion by constructing artificial reefs and beach nourishment. The results show the growth of a small stretch of beach, as well as the subsequent coastal stabilization, with approximately 76% of the coast in accretion. Similar to our study, this paper also observed accretion and erosion patterns, and considered this mitigation measure as beneficial for protecting this eroded shoreline. Zulfakar et al. (2020) also found similar results with accretion and erosion sectors in Kuala Nerus, Terengganu (Malaysia). In 2016, coastal protective structures were built after several erosion events had taken place. The results indicated that most of the shoreline eroded during preconstruction had been recovered after the structure had been constructed.

## Coastal zone management

As coastal erosion is essentially generated by the conflict among natural processes, retreat of the shoreline, and human activities, its solution necessarily involves a comprehensive management of the coastal zone. Attempts to stabilize the position of the shoreline through coastal works have proven to be ineffective to control the phenomenon and often generate negative long-term impacts. However, in some extreme cases, this is the fastest and most efficient way to defend public or private assets. Although it is common for hard engineering structures, such as breakwaters and piers, to actually promote erosion (Phillips and Jones 2006; Rangel-Buitrago et al. 2018; Manzolli et al. 2024), in Santa Marta Bay, this was not the case because the assessments conducted in the last 34-year evidence a clear favoring of dynamics after the works had been completed.



Even considering the importance of structures in reducing erosion rates at a local scale, the impacts related to changes in beach dynamics with the installation of rigid structures must be assessed (Molina et al. 2019) observed erosion areas downstream ports and breakwaters and matching linings/seawalls, because of sediment interruptions caused by these structures. Consequently, rigid interventions have been conducted throughout Santa Marta Bay to contain the initial natural erosion of the northern sector and then reduce the effects from these structures. Commonly, the development of the erosion processes in adjacent areas (driftward) leads to the establishment of new structures (Cooper et al. 2009). This effect seems to be the best explanation for why a total of 1,484 hard structures were identified along the Colombian Caribbean coast in 2016, with the highest concentrations located in tourist cities (Rangel-Buitrago et al. 2018).

Another important factor that must be considered is the changes in the local wind dynamics. Large buildings, port structures, or engineering works, whether onshore or offshore, serve as a wind screen, thus changing current and wave train circulation (Posada-Posada and Henao 2008). This section of Santa Marta Bay is the most urbanized in the department and exhibits a large number of alterations resulting in a high shoreline hardening rate. Anthropogenic structures locally constrain sand circulation and limit contribution areas owing to the occupation of beaches and their surrounding areas, wherein sandbanks may often be found, such as the presence of boardwalks and seawalls. Unfortunately, from a governance standpoint, coastal erosion management in Colombia fails due to a weak institutional framework coupled with diluted and compromised coastal erosion management regulations (Rangel-Buitrago et al. 2018). Finally, the literature agrees that shoreline intervention must be preceded by protocols that guarantee their effectiveness and longevity, requiring studies on their positive and negative impacts, duly measured both in magnitude and scope.

Recent studies also highlight the global importance of using Nature-Based Solutions (NBS) for coastal management (Kumar et al. 2021; Inácio et al. 2023; Unguendoli et al. 2023). NBS, as demonstrated by these studies, provide a sustainable and environmentally friendly approach to mitigating coastal erosion while enhancing coastal resilience. Embracing NBS on a broader scale can contribute to the protection and preservation of vulnerable coastlines worldwide, making them more resilient in the face of increasing coastal challenges.

## Conclusions

This study assessed the spatiotemporal behavior of the short and long-term characteristics of shoreline changes at Santa Marta Bay and their relationship with coastal protective structures for the past 34 years (1985–2019). Considering different interventions conducted to reduce shoreline erosional processes, the study observed a relatively stable coastal behavior throughout the study period (1985–2019).

The short-term assessment showed that the intense erosion evidenced from 1985 to 1991, with an average retreat speed of  $-1.6 \text{ m}\cdot\text{y}^{-1}$  in Sector 4 (north), changed gradually since 2003 with the construction of rigid structures and beach nourishment. Consequently, shoreline retreat decreased and a progradation of  $0.2 \text{ m}\cdot\text{y}^{-1}$  was observed at the beach. In this study, a cyclical erosion and accretion behavior was identified throughout the period assessed as a response to anthropic interventions. Further, although the highest progradation rates are adjacent to these structures, a significant percentage of transects reported negative values during this period.

The 2009–2019 (most recent) period, despite recording a positive average value, exhibited a high percentage of erosion profiles, thus indicating that engineering works, in spite of presenting positive results in the short term, require new long-term interventions.

The application of DSAS has played a fundamental role in understanding the beach evolution, capable of indicating the evolution of beach systems in the short and long term. However, it is important to note that although DSAS has been a valuable tool for analyzing data and extracting distances and statistics, its use is not exclusive, as there are several other approaches and tools available.

Finally, the study concludes that shoreline changes are influenced by anthropic interventions, which play an important role in landscape configuration and managing coastal hydrodynamics. Coastal erosion is not uniform along the coast, the anthropic structures also contribute to coastal erosion by altering natural sediment transport processes and changing the shape of the beach and nearshore environment. The use of rigid structures leads to the transfer of erosion from one location to another and cause long-term impacts on shoreline retreat and beach loss. These processes resulted in a recurrent intervention in the study area. Therefore, quantifying the scale and rate of shoreline changes and correlating them with anthropogenic structures is an essential step in assessing shoreline vulnerability. Moreover, the study provides a solid foundation and results that help increase the knowledge and understanding of the coastal erosion issues observed throughout Santa Marta Bay and their interaction with hard structures.

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## Declarations

**Conflicts of interest** The authors declare no conflict of interest.

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