Research article

Assessment of coastal erosion and accretion in outer Buenaventura Bay between 1969 and 2023

Evaluación de la erosión y acreción costera en la bahía externa de Buenaventura entre 1969 y 2023

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Abstract

This article presents the results obtained from the analysis of the evolution of the coastline between 1969 and 2023 in the sectors of Soldado Island, Santa Bárbara Island, Bazán Bocana and Piangüita (outer Buenaventura Bay, Colombia). The digitization of the coastline was carried out from a geomorphological and physiographic perspective, and DSAS (Digital Shoreline Analysis System) software was used to quantify the changes. Erosion/accretion rates, net shoreline movements and the greatest distance between all shorelines regardless of dates were calculated, finding that erosion and accretion rates at Bazán Bocana and Piangüita were within the range of ± 2 m/yr, at Soldado Island between 10.7 and -10.74 m/yr, and Santa Bárbara Island between 5.9 and -8.92 m/yr. We therefore classify these shorelines as stable at Bazán Bocana and Piangüita, and with high erosion and accretion on the islands.

Keywords: Shoreline, coastal erosion, accretion, Pacific, Colombia

Resumen

Este artículo presenta los resultados obtenidos del análisis de la evolución de la línea de costa entre 1969 y 2023 en los sectores de isla Soldado, isla Santa Bárbara, Bazán Bocana y Piangüita (bahía externa de Buenaventura). La digitalización de la línea de costa se realizó bajo una perspectiva geomorfológica y fisiográfica, y para la cuantificación de los cambios se utilizó el software Digital Shoreline Analysis System (DSAS, por sus siglas en inglés). Se calcularon las tasas de erosión/acreción, los movimientos netos de la línea de costa y la mayor distancia entre todas las líneas de costa independientemente de las fechas, encontrando que las tasas de erosión y acreción fueron en Bazán Bocana y Piangüita estuvieron dentro del rango ± 2 m/año; en isla Soldado, entre 10.7 y -10.74 m/año, e isla Santa Bárbara, entre 5.9 y -8.92 m/año; clasificando estas líneas de costa como estables en Bocana y Piangüita, y con erosión y acreción alta en las islas.

Palabras claves: *línea de costa, erosión costera, acreción, Pacífico, Colombia.*

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Introduction

Coastal erosion is defined as a retreat of the coastline or the erosion of beaches as a result of the interaction between the materials that make up the coastline, and natural and anthropogenic erosive agents (Ungrd, 2017). The interest that the population has in coastal areas due to its provision of commercial, tourist, transport, resource and communication opportunities (Cohen *et al.* 1997 in Dimar-CCCP, 2013) has exerted strong pressure on these areas, leading to habitat destruction, pollution, erosion and resource depletion, generating conflicts between users and socio-economic problems (MinAmbiente, 2017).

Currently, at a global level, coastal retreat due to erosion is recognized as one of the main threats to coastal areas, and one that is related to sea level rise due to climate change, since rising sea levels increase the threat to coastal areas from natural disasters, with this increase being directly proportional to the magnitude of the disasters, meaning, therefore, that the areas of flooding produced are more extensive (Duncan *et al.*, 2008).

In Colombia, the Caribbean and Pacific coastlines are no strangers to these erosion processes, which are the result of natural forces or human intervention, leading to changes in these coastlines. According to Correa and Vernette (2004), Invemar-GEO (2015), Paniagua (2013) and Vernette *et al.* (2012), these processes have intensified over the last three decades, becoming a problem that leads to the loss of beaches, cliffs and other coastal landforms (Posada *et al.* 2009). With the intention of preserving and/or generating profits in these locations, construction projects have been carried out for coastal protection and recreational purposes without the relevant studies, which in most cases have had the opposite effect to the desired one.

These coastlines have been studied in recent decades by numerous authors, including Cardona (2018), Castañeda (2017), Coca and Ricaurte (2019), Coca and Ricaurte-Villota (2022), Correa *et al.* (2007), Correa and Vernette (2004), Ferrucho-Maloof *et al.* (2022), González and Correa (2001), Paniagua (2013), Posada *et al.* (2009) and Zambrano and Andrade, (2011). The main objective of some of these studies is to examine erosion processes due to their high impact on ecosystems and human settlements, while their effect on socio-economic and environmental areas has been evaluated, as explained by Coca and Ricaurte (2019), who determined the vulnerability of different populations to coastal erosion.

In the area of interest, several studies have been conducted on the advances and retreats of the coastline, and to characterize depositional and erosional landforms. One such study is that of Posada *et al.* (2009), which describes the type of coastline, the associated rock type (cohesive and non-cohesive) and the factors involved in sedimentation and erosion processes, as well as a general characterization of the area and 1:100,000 scale maps of geomorphological units, geomorphological features, sedimentary facies and the coastline. Alejandra *et al.* (2017) determined the magnitude of the change in the coastline north of the district of Buenaventura using 30m resolution Landsat satellite images from 1986, 2001 and 2015, finding that at La Bocana and Punta Soldado the erosion/accretion rates were between 5 and -5 m/year; Invemar-GEO (2015), in a technical report describing the recent evolution of the coastal zone of the province of Valle del Cauca, analyzed the coastline of the Punta Soldado sector between 1971 and 2015, finding that between 1971 and 2011 the coastline receded 85 m, and between 2011 and 2015 it receded 47 m. However, there are no studies that characterize the evolution of the coastline in all the study sectors of this publication with high spatial and temporal resolution.

At the time of writing, there are no previous studies on the movements of the coastline in the areas analyzed that use a detailed 1:5,000 scale, nor any with a time series as wide as the one used in this research (1969, 1982, 2006, 2016 and 2023). The aim of this article is to quantify the net movements of the coastline, as well as the erosion and accretion rates in the outer part of Buenaventura Bay. For this reason, we used the DSAS software developed by the United States Geological Survey (USGS), using historic photography from Colombia's Agustín Codazzi Geographical Institute (IGAC), orthophotography and satellite imagery taken between 1969 and 2023. The analysis is focused on the sectors of Soldado Island, Santa Bárbara Island, Bazán Bocana and Piangüita.

Study area

The study area is located in the outer part of Buenaventura Bay. It includes the sectors of Piangüita and Bazán Bocana, as well as Soldado and Santa Bárbara Islands, all part of the municipality of Buenaventura, in the province of Valle del Cauca on the Colombian Pacific coast (Fig. 1). Geomorphologically, Punta Soldado and Santa Bárbara are barrier islands with vegetated intertidal plains and beaches, landforms associated with the interaction of the sea and the rivers that discharge there, such as the Raposo, Dagua and Anchicayá. To the north, at Bazán Bocana and Piangüita there are beaches, coastal plains and hills.

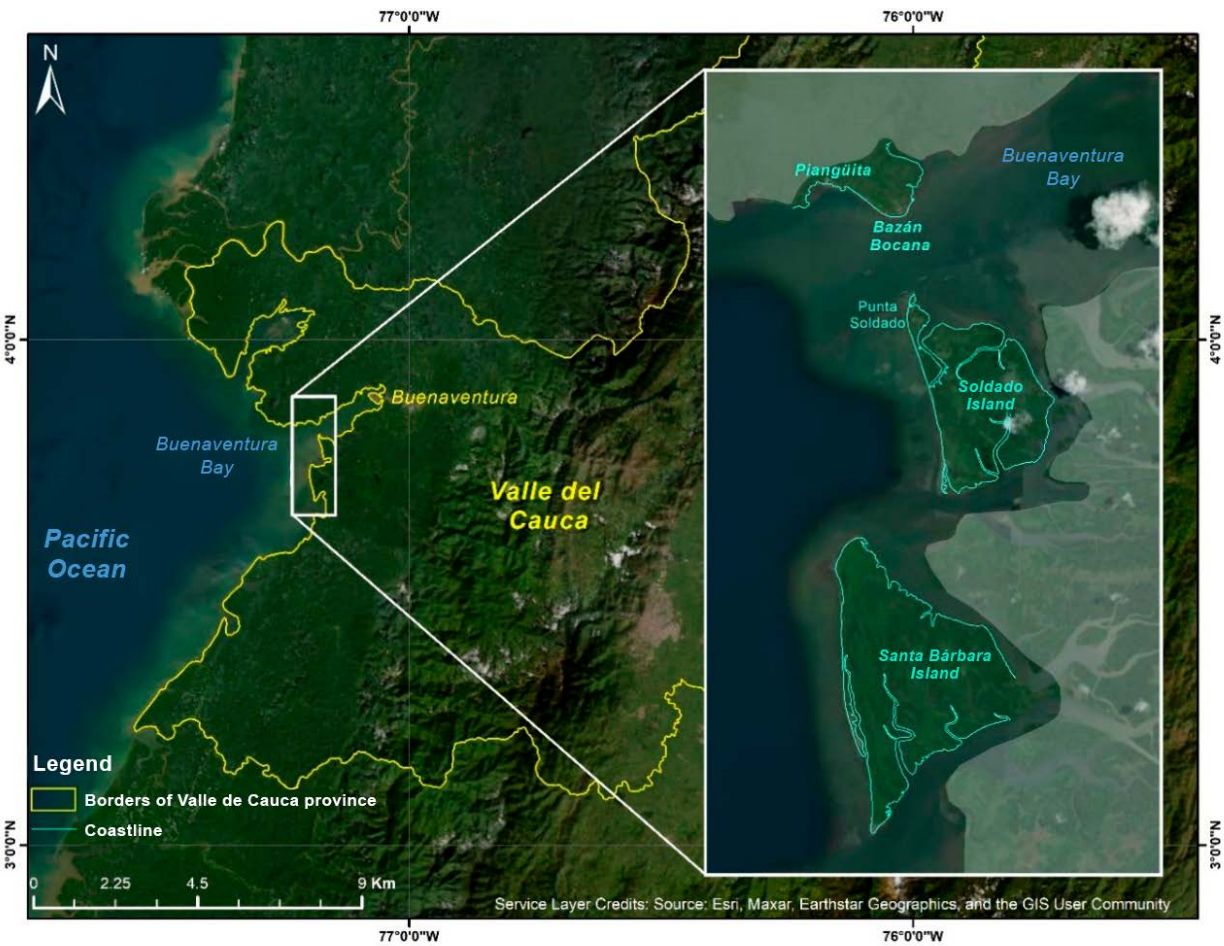

Figure 1. Location of the study area

Methodology

Data

The coastlines were extracted using aerial photographs from the IGAC, orthophotographs and satellite images from different dates, as shown in Table 1:

Table 1. Remote sensors

Remote sensor	Resolution	Year	Observations
IGAC Photography	0.9 meters/pixel	1969 y 1982	Dimar database
Orthophotographs	0.25 meters/pixel	2006	Dimar database
Satellite images	0.3 meters/pixel	2016	Maxar constellation – Dimar database
Satellite images	5 meters/pixel	2023	Sentinel 2 satellites downloaded from LandViewer

Criteria for defining the coastline and digitization process

The coastline was digitized at a 1:5,000 scale to suit the photo-interpretation that was made with the lowest resolution satellite images (5 m resolution from Sentinel 2), complemented in some sections by higher resolution images without reduction, in order to preserve relevant geomorphological details. The criteria used in this digitization process were defined from the following geomorphological and physiographical perspective (Fig. 2):

- **Rocky coasts:** directly connected with the sea, the coastline is defined using the base of the cliff or the edge of the rocky outcrop (Ojeda Zújar *et al.*, 2013) (Fig. 2a).
- **Mangroves:** these grow in intertidal zones and one of their main ecosystem services is to protect the coast from erosion. In this case, the coastline is defined by the coastal edge of the mangrove (Fig. 2b).
- **Beaches:** defined by the internal boundary between the dry beach (backshore) and the permanent vegetation or coastal dune, if there is one (Fig. 2c).
- **Infrastructure in direct contact with the sea:** defined by the external edge of the infrastructure that is in contact with the sea (Fig. 2d).

The coastlines were digitized by a single person who is an expert in the field in order to minimize the inevitable subjectivity in the photo-interpretation process, and always at the same scale (1:5,000) in order to guarantee geometric coherence (Ojeda Zújar *et al.*, 2013)

Measuring change and calculating erosion rates

To measure the net changes in the coastline and calculate the rates of erosion, we used DSAS, a piece of software that is compatible with ArcGIS. To use this software, the user must create a coastline for each year for which measurements will be made, and a digitized baseline approximately parallel to and at a prudent distance the coastline, which serves as the starting point for the different orthogonal transects that intersect the coastlines. The tool generates semi-automatic transects once the analyst has designated the distance between them (Fernández de la Torre, s.f.). For this study, the distance between transects was set at 50 m, a reasonable separation given the scale of the work. The statistics calculated by the DSAS software during this process were:

- **Net Shoreline Movement (NSM):** calculates the net movement of the coastline, that is the movement between the oldest coastline and the most recent one.
- **End Point Rate (EPR):** calculates the rate of change in the coastline in meters per year, in other words the ratio of NSM divided by the time elapsed.
- **Shoreline Change Envelope (SCE):** calculates the greatest distance between all the coastlines registered, independently of the dates (Himmelstoss *et al.*, 2021).

To classify the level of coastal erosion and accretion, we adapted the categories of coastal evolution proposed by Del Río *et al.* (2013), which are presented in Table 2:

Figure 2. Criteria for digitizing the coast lines. a. Coastline defined by the cliff base; b. Coastline defined by the coastal edge of the mangrove in intertidal zones; c. Coastline defined by the landward boundary of a beach; d. Coastline defined by the edge of infrastructure.

Table 2. Classification of the level of accretion and erosion [Taken from: Del Río *et al.* (2013)]

Range of EPR (m/year)	Classification of the coastline change processes
< -15	Very high erosion
-5 to -15	High erosion
-2 to -5	Moderate erosion
-2 to 2	Stable
2 to 5	Moderate accretion
5 to 15	High accretion
>15	Very high accretion

Results

Bazán Bocana and Piangüita

The results obtained from the DSAS software show that the coastlines at Bazán Bocana and Piangüita have remained stable, since the EPR is within the range of -2 to 2 m/year. There have been negative NSM movements (erosion) of up to -86.2 m, and positive movements (accretion) of up to 87.1 m. The SCE calculation shows that the greatest movement in the coastline was 87.1 m (Fig. 3). In general, of the 4.07 km of coastline analyzed in this study, 35.44 % have eroded and 64.56 % have accreted; however, these processes have been slow, since the EPR values have been within the range for a stable coastline (-2 to 2 m/year) (Table 2).

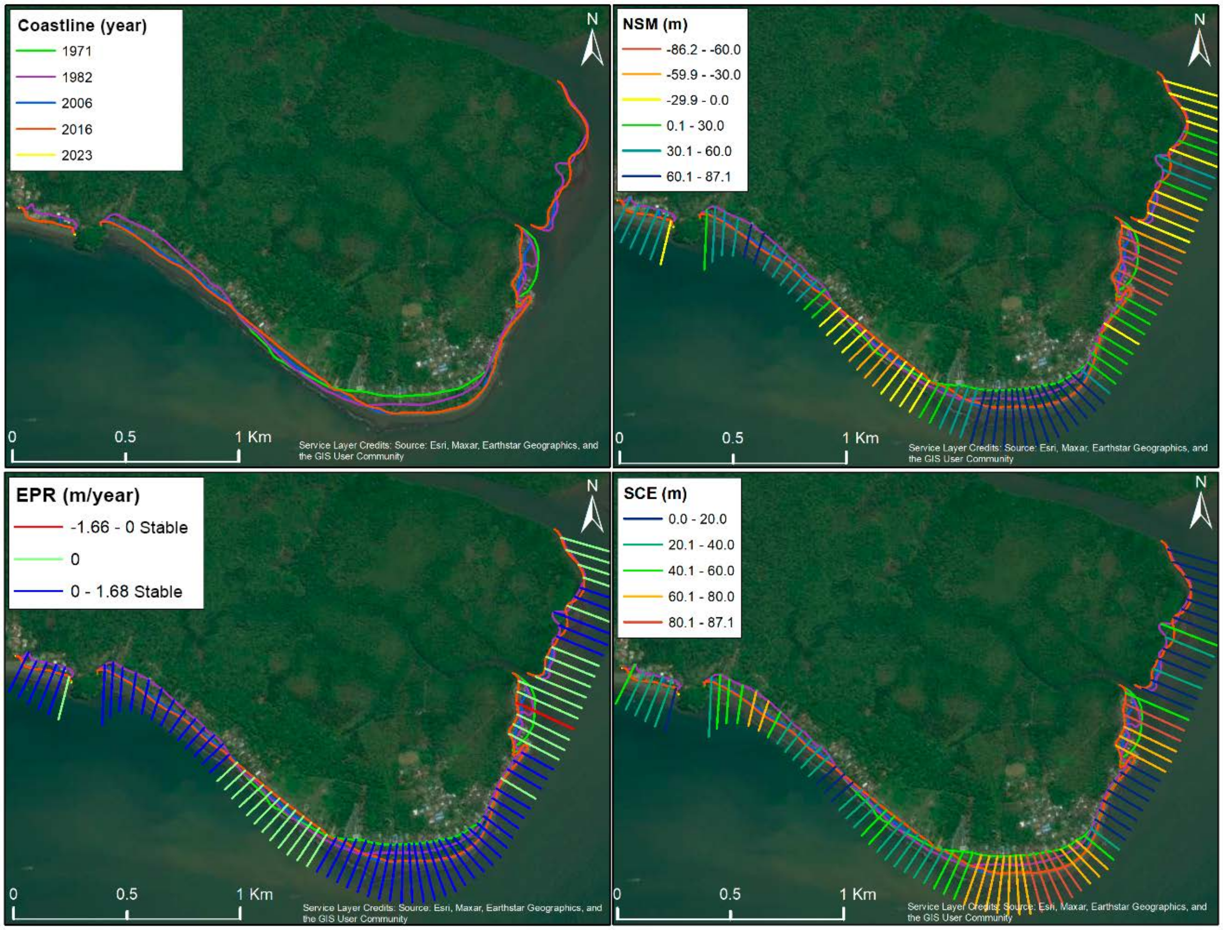

Figure 3. Evolution of the coastline in the Bazán Bocana and Piangüita sector, and results of the NSM, EPR and SCE statistics.

Soldado Island

The results obtained for Soldado Island show that the coastline has experienced high erosion, with EPR values that reach -10.7 m/year, and high accretion of up to 10.7 m/year. The NSM values show that the coastline has had negative net movements (erosion) of up to -558.5 m and positive ones (accretion) of up to 556.4 m. The SCE figures show that the greatest difference between coastlines in this sector was 620 m (Fig. 4). In general, of the 10.36 km of coastline analyzed in this sector, 77.6 % have eroded and 22.4 % have accreted (Table 3).

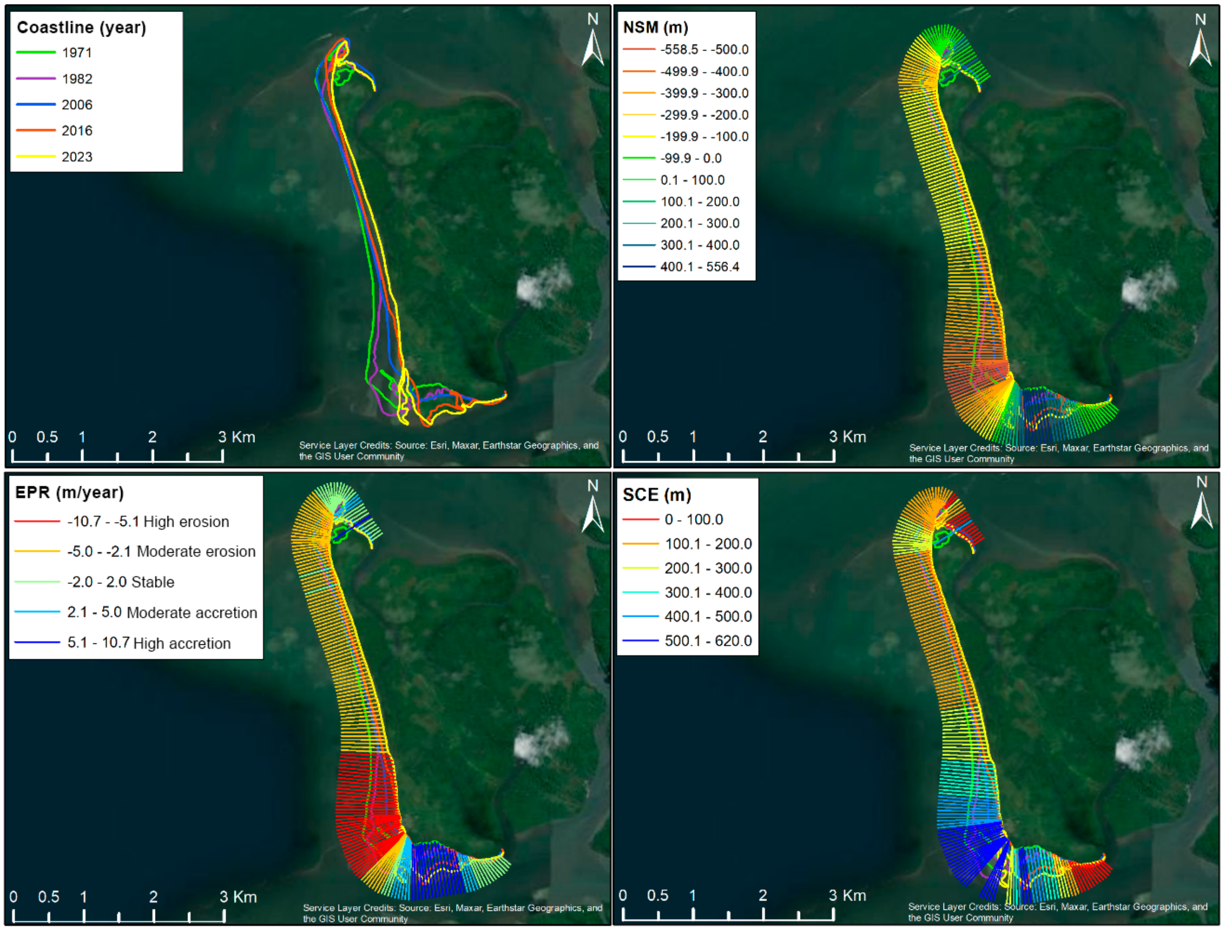

Figure 4. Evolution of the coastline in the Soldado Island sector, and the results of the NSM, EPR and SCE statistics

Santa Bárbara Island

The results obtained for Santa Bárbara Island demonstrate that the coast line has experienced both high erosion, with EPR figures that reached as much as -8.9 m/year, and high accretion, with values of up to 5.9 m/year. The NSM values show that there have been net negative coastline movements (erosion) of up to -233.9 m/year and net positive movements (accretion) as high as 306.8 m. The SCE figure shows that the greatest difference between coastlines in different years was 373.1 m (Fig. 5). In general, 35.5 % of the 12.6 km of coastline in this sector has eroded and 64.5 % has accreted (Table 3).

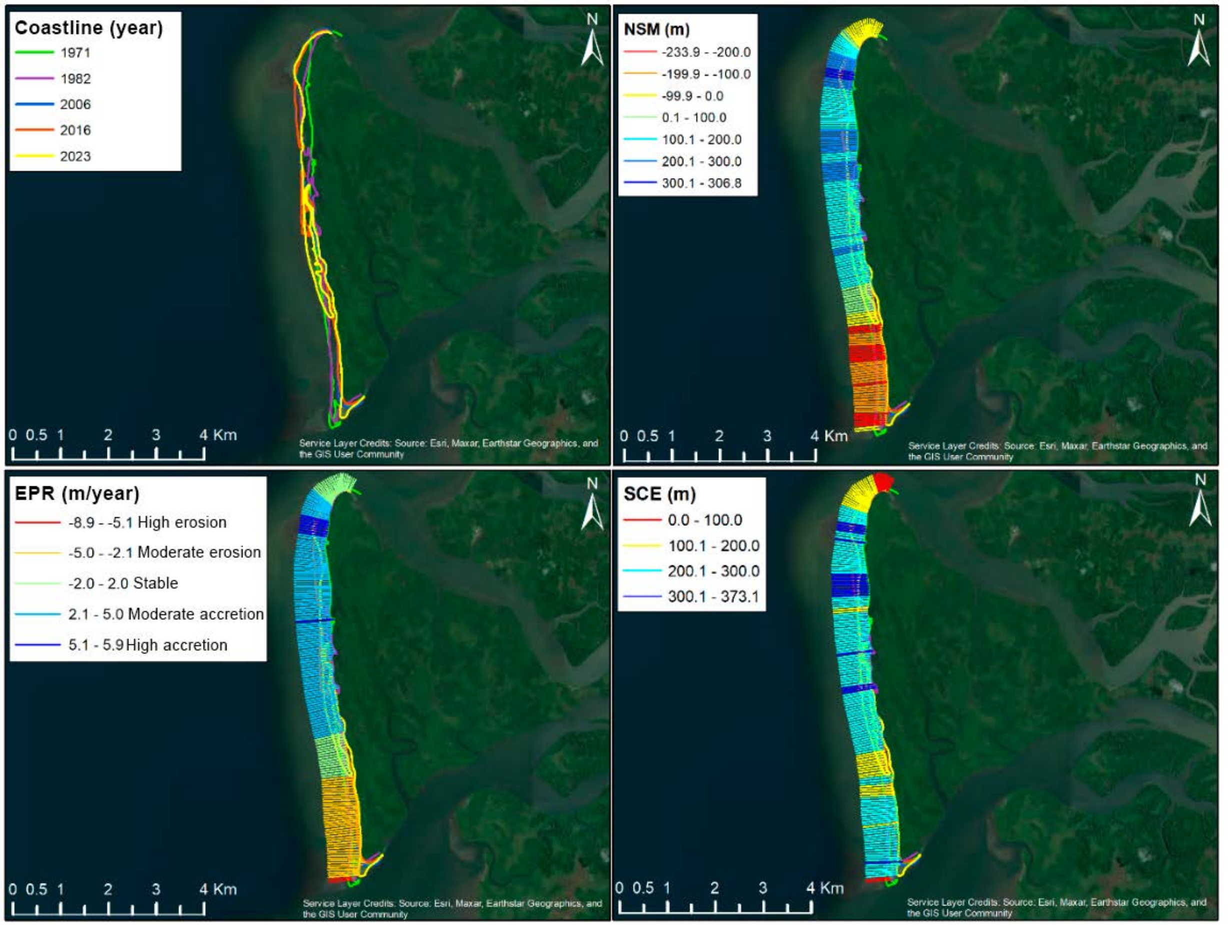

Figure 5. Evolution of the coastline of Santa Bárbara Island, and the results of the NSM, EPR and SCE statistics

Table 3. Results of the EPR, NSM and SCE statistics around the study area

Statistic	Bazán Bocana and Piangüita	Soldado Island	Santa Bárbara Island
% of the coastline that has eroded	35.44	77.6	35.45
% of the coastline that has accreted	64.56	22.4	64.55
Maximum accretion NSM (m)	87.11	556.37	306.76
Average accretion NSM (m)	43.67	216.4	168.08
Maximum erosion NSM (m)	-86.18	-558.51	-233.93
Average erosion NSM (m)	-30.45	-210.6	-138.06
Maximum accretion EPR (m/year)	1.68	10.7	5.9
Average accretion EPR (m/year)	0.84	4.16	3.23
Maximum erosion EPR (m/year)	-1.66	-10.74	-8.92
Average erosion EPR (m/year)	-0.59	-4.05	-2.83
Maximum SCE (m)	87.11	620.47	373.14
Mean SCE (m)	41.21	263.22	226.96

Discussion

The evolution of the coastline in Buenaventura Bay in recent years has been conditioned by its geomorphology, which, in turn, depends on the lithological characteristics of the zone and its interaction with the exogenic and endogenic processes that shape it, for example, marine meteorology and tectonics. The geomorphology of the northern section of the outer bay is characterized by hills and slopes in the main, with some smaller beaches (Bazán Bocana and Piangüita). Hills and slopes formed by a poorly lithified sedimentary sequence of sandstones, conglomerates and shales of continental and marine origin (SGC and UNAL, 2015) surround some of the beaches in the area, providing them with some protection from the hydrodynamics of the area, as evidenced by the beaches of Bazán Bocana and Piangüita, which have been classified as stable, since the rates of change in the coastline when the sea has advanced or retreated have not exceeded ± 2 m/year.

On the other hand, in the southern part of the bay, Soldado Island and Santa Bárbara Island are characterized by being low plains directly exposed to fluvial-marine dynamics and anthropogenic activities. These characteristics explain the more pronounced changes in the coastline here than in other parts of the bay.

On Soldado Island, the highest erosion rates (-10.74 m/year) were observed in the south, around the settlement that gives the island its name, and the highest accretion rates (10.70 m/year) were observed at the southern tip of the island. It can therefore be inferred that the sediment lost in the sector where the coastline receded the most was redeposited at the southernmost tip of the island, possibly influenced by wave dynamics. Erosion and accretion rates are moderate (± 2 to 5 m/year) towards the north-central and northern parts of the island; however, the same pattern of sediment rearrangement can be seen: a decrease in the width of Soldado Island (due to coastline retreat) and an increase in its length due to sediment rearrangement towards the northern and southern tips. This study quantified changes in the coastline by averaging them over a period of 52 years; however, the results in the Invemar-GEO (2015) and Eisinguer (2023) studies show that between 2011 and 2021 the erosion rates on the island have reached levels of between -19.25 and -22.10 m/year. In the last decade, the most significant coastline retreats were observed between 2014 and 2016. According to the National Oceanic and Atmospheric Administration (NOAA), the El Niño event in 2015-2016, classified as "very strong", may have been associated with the coastline retreat in those years.

In the case of Santa Bárbara Island, there has been mainly moderate erosion in the south, with coastline retreats of between -2 and -5 m/year, plus a few areas of high erosion, with values reaching -8.9 m/year. Towards the centre and north of the island, moderate accretion has predominated, with coastline advances of between 2 and 5 m/year, although there are some zones where it has remained stable (± 2 m/year) or experienced high accretion (between 5 and 5.9 m/year). Compared to Soldado Island, this island has undergone fewer changes in its coastline, and its length has remained relatively stable.

Conclusions

The northern part of outer Buenaventura Bay, Bazán Bocana and Piangüita, is where the coastline has receded or advanced the least in the last 54 years, while on Soldado Island these changes have been very significant in terms of land loss and gain.

At Bazán Bocana and Piangüita, during the study period, 35.44% of the coastline receded (erosion) and 64.56% advanced (accretion). However, according to the results, erosion and accretion rates range from 1.68 to -1.66 m/year, so the coastline in this sector was classified as stable. As the maximum erosion/accretion rates are so similar, as are their averages (0.84 and -0.59 m/year), it can be concluded that sediment has been rearranging itself along the coastline in this sector.

On Soldado Island, 77.6% of the coastline receded due to erosion processes and 22.4% advanced as a result of accretion processes. Erosion/accretion rates range from 10.70 to -10.74 m/year, so the coastline was classified as having high erosion and accretion. Like in the north of the study area, the maximum erosion/accretion rates were very similar to each other, as were the averages (4.16 and -4.05 m/year), so it can be inferred that the sediment was rearranged along its coastline.

On Santa Bárbara Island, 35.45% of the coastline receded and 64.55% advanced. The range of erosion/accretion rates was 5.9 to -8.92 m/year, which is why the coastline was classified as having high erosion and accretion. The maximum erosion rate is higher than the maximum accretion rate, but the averages of these rates were very similar, 3.23 and -2.87 m/year, and the percentage of coastline that advanced was much higher than that which receded; therefore, it can be concluded that there was a slight gain in sediment accumulation on the beaches of this island.

Authors' contributions

Abstract: K. A. E. V.; Introduction: K. A. E. V.; Study area: K. A. E. V.; Methodology: K. A. E. V. - D. C. N. P.; Results: D. C. N. P.; Discussion: D. C. N. P.; Conclusions: D. C. N. P.

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