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Morphodynamic and vulnerability analysis of the coastline during the period 1991 - 2023 by means of geotechnologies in Jambelí Island, Santa Rosa Canton, El Oro

Análisis morfodinámico y de vulnerabilidad de la línea de costa durante el periodo 1991 - 2023 mediante geotecnologías en la Isla Jambelí, Cantón Santa Rosa, El Oro

Artículo

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Abstract

Jambelí Island is composed of plains and flatlands of marine sediments and mangrove areas, where cycles of erosion and sedimentation prevail. Over the years, waves, currents, and the El Niño-Southern Oscillation (ENSO) event, along with anthropogenic activity, have influenced the modification of the island's coastline. The reconstruction of coastlines, together with the detailed statistical analysis provided by DSAS, shows variations in the coastal profile from 1991 to 2023, identifying zones of vulnerability and the challenges faced by the island. These variations are due to the geomorphological, hydrogeological, and social conditions present, with the part exposed to the sea being the most vulnerable due to its exposure to these factors. In contrast, the opposite end of the island, surrounded by mangroves, presents more stable areas, as the mangroves stabilize the soil and prevent its loss.

Key words: Jambelí Island, vulnerability, erosion, sedimentation, sea level, currents

Resumen

La Isla Jambelí es una zona conformada por llanuras y planicies de sedimentos marinos y zonas de manglar, en donde prevalecen ciclos de erosión y sedimentación, los cuales con el pasar de los años, las olas, corrientes y el evento del ENOS son características del lugar e incluso actividad antrópica influyen en la modificación la línea de costa de la isla. La reconstrucción de líneas de costa junto con el completo DSAS nos presenta un análisis estadístico de las variaciones que se han presentado en el perfil costero desde 1991 hasta el 2023, y con ello zonas de vulnerabilidad que abordan riesgos y desafíos que enfrenta la isla, las cuales se condicionan por las variables geomorfológicas, hidrogeológicas y sociales presentes en la isla que la ponen en riesgo siendo la parte frente al mar la de mayor vulnerabilidad al estar expuesta y sometida a todos estos factores, pudiendo generar todo tipo de desastres en la isla, a diferencia del otro extremo donde prevalecen zonas estables debido a estar rodeado de manglares que estabilizan el suelo evitando perdida de este.

Palabras Clave: Isla Jambelí, vulnerabilidad, erosión, sedimentación, nivel del mar, corrientes

Introduction

Ecuadorian coasts are distinguished by periods of sand loss followed by periods of sand accumulation. These processes are linked to the history and geomorphological evolution due to agents such as wind, water, waves, and sometimes climatic factors that have formed beaches in the Quaternary. There are also superficial deposits, made up of alluvial estuaries, sand and silt beds, salt flats made up of estuarine mud (mud flats or crab flats), Miocene rocks and dunes characterized by strong wind erosion and the effect of waves.

Núñez (2003) establishes that Ecuador's coastal profile is classified into three types: i) high cliff coasts with small bays such as Manta and Manglar alto; ii) coasts with cliffs and straight beaches such as the Santa Elena Peninsula and Puná Island; and iii) low coasts with mangroves in the vicinity of Valdez and Guayaquil along the southern coast.

Jambelí Island is one of the sectors of the Ecuadorian coast where stationary cycles prevail, in which the beach loses a large amount of sand in one period (six months) and recovers it in another (six months) due to the geodynamic processes of the coast. Soledispa, (2004) suggested that the losses are produced by coastal currents, which are formed due to the angle at which the waves approach the beach, transporting sand parallel to the coast. The coastal current has been recognized as the main destructive and shaping agent of this beach in some sectors.

Coastal studies play a crucial role in understanding dynamic coastal systems, which are open and susceptible to modification. Depending on the circumstances, the movement of water by waves, tides, storms and coastal currents combine and interact with the continent, resulting in a series of erosional or depositional coastal processes (Paul D. Komar, 1983).

Jambelí has an important economic activity based on food production from the shrimp industry and tourism. The communities and coastal ecosystems of the island are the most prone to the negative impacts of these events. These threats can result in property damage, destruction of vital coastal ecosystems and loss of ecosystem services.

It is essential to address and mitigate these vulnerabilities generated by shoreline erosion in order to develop sustainable management of coastal resources, implement climate change adaptation measures, and establish resilient development practices. By doing so, we can reduce the risk of disasters by identifying vulnerable areas and the means to protect these valuable ecosystems.

Jambelí Island is one of the six major islands of the Jambelí Archipelago and is located at the southern end of the coast of Ecuador, in the waters of the Gulf of Guayaquil, in the Santa Rosa canton of the province of El Oro.

The study area, as shown in Figure 1, is bordered to the south by Estero El Bravito, to the north by the Jambelí Channel and to the east by Estero Santa Rosa; its shores are bordered by mangrove areas and shrimp ponds are located in the interior of the island.

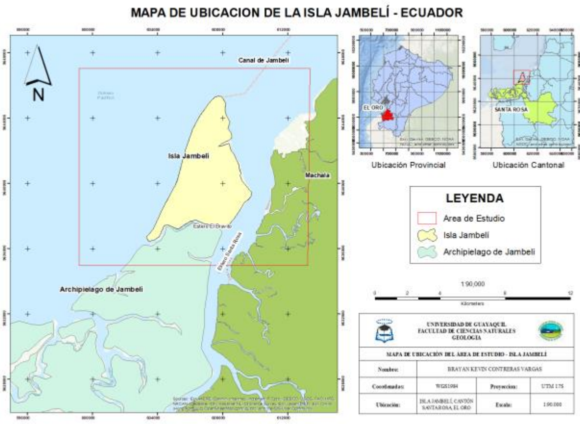

Figure 1. Location map of the study area on Jambelí Island.

Jambelí Island has been modified over the years by the coastal dynamics of waves, whose energy could cause damage to the beach. Wind waves predominate in this sector, which attack the coastal areas constantly and permanently, causing erosion (INOCAR 2002). In 2003, El Universo newspaper, in one of its interviews with residents, mentioned that "in 1995, the island's beach was approximately 150 meters wide and 1.6 kilometers long at low tide" (El Universo, 2003). The presence of the El Niño Southern Oscillation Event (ENSO) in 1997-1998 along the coast may have influenced its erosion. That year, the residential sector of the Jambelí beach was affected approximately 50 meters along the beach, in front of which lookout points had been built, which were destroyed.

According to Soledispa (2004), erosion also slightly affected the base of a sector of the roadway that extends along the seawall. The Projects Department of the Municipality of Santa Rosa canton, to which it belongs, calculated that the sea gained an average of 2 meters per year, so in 2003 the residents put up stakes to dam sand and recover the beach (El Universo, 2003).

In response to these events, INOCAR researchers in 2004 established methods to regenerate the beach, such as sand retention with breakwaters, which consisted of modifying the coastal drift, generating beach accretion, since these breakwaters would be perpendicular to the coast (Soledispa P. Bolívar, 2000).

In 2011, five breakwater walls of 100 meters in length were built, with 70 m distance between each one, on the coastal edge and two breakwaters on the sides of the Jambelí beach, with a height of 6 meters, of which 2.20 m would be underwater and 3.80 m would protrude from sea level at low tide, using volcanic rocks of 400 to 600 kilos, extracted from the El Vergel quarry, located in the canton of El Guabo. This project is expected to become a definitive solution to the erosion of Jambelí beach (El Universo, 2011).

In the following years again the El Niño Southern Oscillation Event (ENSO) was present in 2015 and 2016 on the coasts of Ecuador, generating strong winds to the west, which were associated with other factors that caused water warming and sea level rise.

Methodology

The development of the study began with the collection of bibliographic data on the area. As a first step, satellite images were taken at six-year time intervals, from 1991 to 2021 and one from 2023 (see Table 1). They were downloaded from the USGS Earth Explorer Web portal, which corresponds to Landsat Collection 2 Level-2 satellite images and one Landsat Collection 2 Level-1, the first category no longer needs atmospheric correction, while the second does.

Table 1. Satellite image information: Landsat collection 2 level-2 and Landsat collection 2 level-1.

N°	DATE DAY/MM/YEAR	CATEGORY
1	29/04/1991	Landsat 4-5 TM C2 L2
2	06/10/1997	Landsat 4-5 TM C2 L2
3	06/10/1997	Landsat 7 ETM+ C2L2
4	11/07/2009	Landsat 7 ETM+ C2L1
5	25/01/2015	Landsat 8-9 OLI/TIRS C2 L2
6	30/03/2021	Landsat 8-9 OLI/TIRS C2 L2
7	20/03/2023	Landsat 8-9 OLI/TIRS C2 L2

Source: USGS Earth Explorer portal.

Atmospheric correction comprises an attempt to estimate and eliminate atmospheric distortions in the luminance values that reach the probe from the ground surface. While a radiometric correction involves the restoration of damaged lines or pixels that in certain images are presented horizontally, as in the case of Landsat 7 images. The use of different categories of satellites is due to the expiration of their operation. Likewise, to ratify this information at the time of generating the lines, satellite images were also obtained from the Google Earth Pro platform for the years 2015, 2021 and 2023 and an orthophoto from MAG data.

Shorelines have specific ways to identify such as coastal vegetation, the base of dunes or the high tide mark. To achieve an accurate and updated representation of the coastline, it is necessary to determine a consistent criterion to identify them due to the variability of the tide level that distorts the coastlines by their tidal cycles. For this purpose, it has been decided to use a combination of satellite image bands that will allow a delimitation on them.

The combination of SWIR 2 - SWIR 1-NIR bands allows to obtain a better atmospheric penetration, achieving well-defined coastlines and shores. The processing in QGIS was carried out using the SCP complement, in which a set of bands of the satellite images was made. The vegetation is blue, the water is black and the sediments are brown (Annex 1).

Based on the combinations of bands, lines were created along the coastline of Jambelí Island, taking the dry line as a reference. For the elaboration of the 2009 coastline, the satellite image of the web portal was used as a reference, as well as the orthophoto obtained from the geo portal of the Ministry of Agriculture and Livestock (MAG), projecting the two images one on top of the other in the QGIS software with a 25% transparency level.

DSAS is a System developed by the U.S. Geological Survey, which functions as a complement to ArcGIS software, consisting of a process for assessing and calculating shoreline changes over time (Woods Hole Coastal and Marine Science Center, 2022).

The information processing includes the use of the sector's coastlines in different years to be compared with a baseline that indicates a starting point for projecting transects perpendicular to it. For the generation of the baseline, the current Nautical Chart of the Jambelí Archipelago generated by the National Oceanographic and Antarctic

Institute of the Navy (INOCAR, 2023), which is the regulatory body for all hydro-oceanographic activities carried out in the jurisdictional and non-jurisdictional maritime areas of national interest in Ecuador, is used as a reference. These surveys are carried out during the winter season (Annex 3).

Vulnerability comprises the degree of damage that a coastline may experience, for which reason models that have been applied to various coastal shorelines were analyzed and compared, thus defining the Coastal Vulnerability Index (CVI), which is based on mostly quantitative variables, of which some types of variables were observed, classifying them into three: 1) Geological/geomorphological, 2) Hydrodynamic and 3) Social (Table 2).

Table 2. Variables considered by the coastal vulnerability index.

Type of variables	Variables	indicators
Geo - Geomorphological	Geomorphology	Modification of coastline.
	Erosion - Sedimentation	Susceptible to flooding.
	Coastal slope.	
Hydrodynamics	Sea level change (cm).	Danger of flooding.
	Mean significant swell (m)	Danger of flooding and erosion.
	Tidal Range (m).	
Social	Land use	Loss of soil stability.
	Population and Developed Area Level of Anthropization	Threat of disaster.
	Priority Sites	

Source: Gornitz,1991.

Upon completing the evaluation of the variables, they were weighted through the Gornitz methodology approach (Gornitz 1991). This methodology addresses the vulnerability of coastal zones and their sequences, identifying prone areas and models to analyze it.

The level of influence of each variable was evaluated individually by tranches and assigned weights ranging from 1, which represents very low vulnerability, to 5, which represents very high vulnerability.

Results

The study area (Fig. 1) was divided into "east" (Fig. 3) and "west" (Fig. 4) sectors. In the comparison analysis of the coastline, particularly between 1991 and 2023 at the west end of the island in a south-north direction, erosion rates were mostly observed, which favor the erosion and removal of sediments due to wave action and other factors.

The baseline used represents the value 0 (Fig. 2) which indicates the starting point. Negative values are those located on the seaward side of the baseline and indicate erosion zones. Positive values are those located on the landward side of the baseline and indicate accumulation zones. The lowest negative values in the southern part of this sector correspond to the first transects where the number of meters of erosion generated by the sea can be observed.

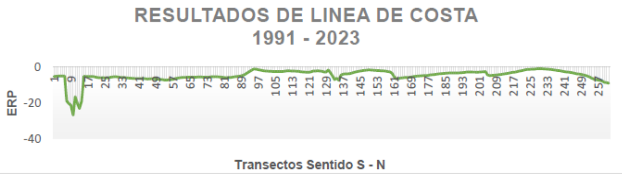

Figure 2. Calculated levels at transects between 1991- 2023 along the west side shoreline.

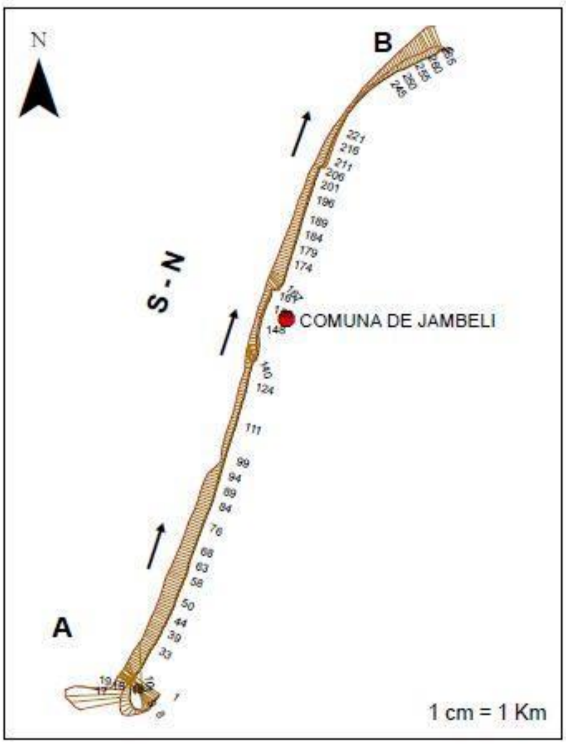

Figure 3. Generated transects of the west side shoreline from 1991 - 2023 .

Stable erosion due to natural processes is visible along this sector (Fig. 3). Upon reaching transect 92, a slight recovery of soil can be seen, while in the stretch between transect 134 and transect 162, where the walls are located to protect the commune, the recovery of the beach can be seen, but also the negative impact on its sides caused by the diversion of wave energy and the loss of up to 10 m of beach.

At the eastern end of Jambelí Island (Fig. 5), where the native mangrove forest areas are located in front of Estero Santa Rosa, variations in the coastline were observed in areas where increased erosion was noted, while in other areas stable levels were observed along the coast, even showing sedimentation levels.

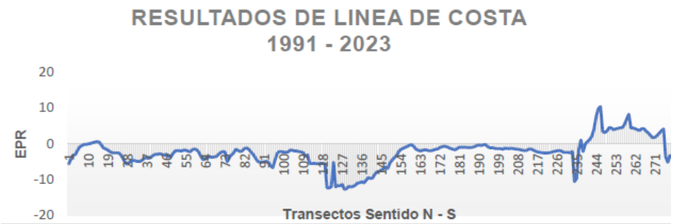

Figure 4 Calculated levels at transects between 1991-2023 along the east side shoreline.

Erosion was observed in front of the entrance of Estero Jambelí, reaching approximately 15 meters, then remaining stable until reaching the south, showing erosion and sedimentation processes due to periods of calm and the influence of the gentle currents that enter through the estuary.

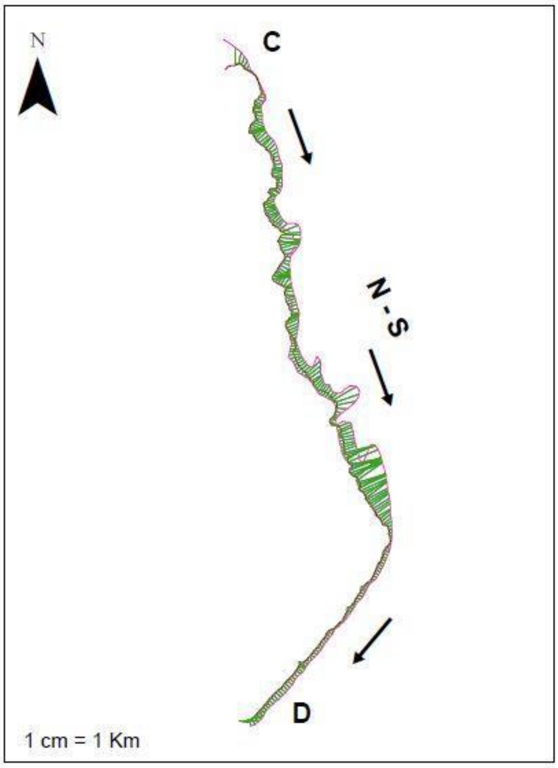

Figure 5. Transects generated from the east side shoreline from 1991 - 2023.

For the coastal vulnerability assessment, the 10 variables considered in Annex 6 were taken into account. These variables were analyzed in 6 sections located along the coastal profile of the northern end of Jambelí Island. Figure 6 shows the map of the six stretches, which in turn are enclosed and combined with color in a rectangle each one of them for a better appreciation.

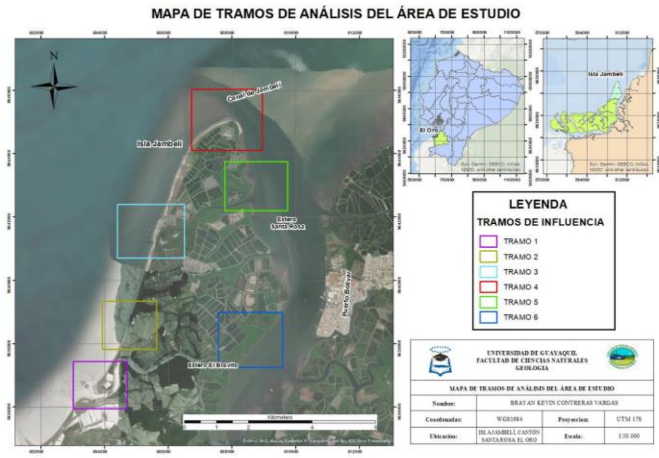

Figure 6. Map of analysis sections.

Once the vulnerability variables (Annex 7) had been identified in each section of the coastal sector, they were assigned a numerical value ranging from 1, which represents very low vulnerability, to 5, which represents very high vulnerability.

Table 3. Vulnerability by sections with their respective ranges.

	VULNERABILIDAD									
ZONA	Geomorfología	Erosión	Pendiente	Nivel Del Mar	Altura De Ola	Rango Mareal	Cobertura Vegetal	A. Desarrollo	N. antrópico	Sitios Prioritarios
TRAMO 1	5	5	5	5	1	3	4		3	3
TRAMO 2	5	5	5	5	1	3	4		3	3
TRAMO 3	5	5	5	5	1	3	3	1	1	5
TRAMO 4	5	5	5	5	1	3	4	1	3	5
TRAMO 5	5	3	4	5	1	3	4		3	5
TRAMO 6	5	2	5	5	1	3	4		3	5

Figure. 7 Shows the degree of vulnerability of each reach according to a color chart. The red color represents extreme coastal vulnerability, which includes section 4; the orange color represents the high vulnerability sections, which include sections 1 and 2; the yellow color represents moderate vulnerability and corresponds to section 5, while the green color

represents low vulnerability and can be observed in sections 3 and 6, this low vulnerability is due to anthropic influences present in section 3 and the presence of mangroves and gentle currents that generate deposits in section 6.

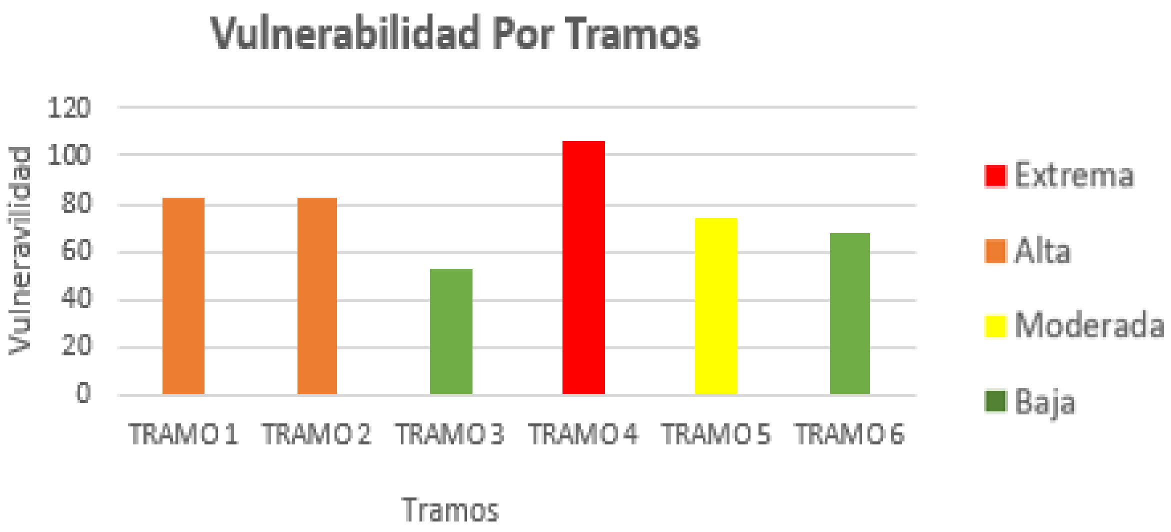

Figure 7. Vulnerability analyzed by sections.

The following figure (Figure 8) shows the general average range of each variable analyzed in the northern end of Jambelí Island. This graph shows that the highest vulnerability variables present in the northern part of the island are erosion or soil loss due to its very low slopes and the geomorphology of the site.

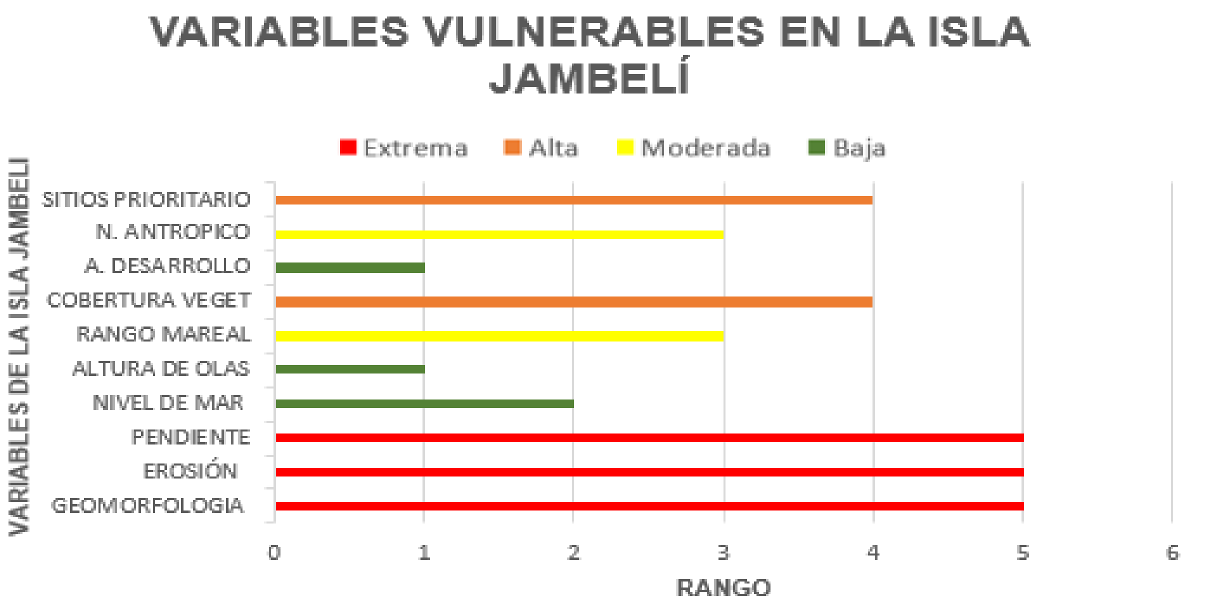

Figure 8. Variables considered for the calculation of vulnerability for Jambelí Island.

Jambelí Island has experienced significant changes in its coastline from 1991 to 2023, due to natural factors (wave dynamics and El Niño events) and anthropogenic factors (construction of stakes and gabion walls). Fuentes and Moncada (2021) state that the analysis carried out from 1985 - 2020 in the Jambelí Archipelago shows that the greatest changes occur on Jambelí Island. The presence of the El Niño Southern Oscillation Event is a phenomenon that has a strong impact on the coasts because it causes an increase in sea temperature, a significant increase in sea level, and an increase in winds and currents that crash against the coasts with greater frequency, generating wear on the coastal profile, increasing the loss of coastline more rapidly due to erosion parallel to the coast, presenting variations in the coastal edge. In response to this action, the local inhabitants-built walls of stakes on the edge of the beach in order to stop and recover sand, but to no avail.

However, the walls in front of the town of Jambelí fulfill their function of avoiding the collision of waves against the coastal edge, generating sedimentation in front of them. On the other hand, when the walls receive these shocks, they generate a deviation in the direction of the waves, sending them towards the sides, generating a double impact on the lateral sides of the coast where the walls are not located. Due to this deflection, the phenomenon of superposition of waves in the swell is produced, increasing their energy and decreasing the period between each one of them. However, despite these interventions, erosion persists, exacerbated by rising sea levels due to climate change and other factors.

Velásquez Barrionuevo, 2021, indicates that the rise in sea level caused by climate change has generated modifications in the coasts, with the sea taking more and more space on the coasts, thus surpassing reference lines of tidal ranges, this gradual increase, at a global level, is reflected in Jambelí Island where one of the walls located parallel to the coast is almost covered by the sea in normal conditions, being completely covered in high tides and storm surges. This is also evident in section 1, where the sea connects with the El Bravito estuary; the tidal regime pushes sand towards the mangrove roots, covering crab and shrimp larvae breeding holes and affecting different areas.

On the other hand, the evaluation of coastal vulnerability in this sector considered geomorphological, hydrogeological and social variables. It was observed that erosion is more pronounced in the western section with low slopes, which increases the potential vulnerability of the area to flooding. In contrast, the eastern end, surrounded by mangroves, is less vulnerable due to its natural coastal protection. However, the clearing of mangroves for shrimp farms has diminished this protection, increasing erosion in the long term.

Conclusions

Between 1991 and 2023, Jambeli Island has experienced significant variations in its coastline, especially at the western end, where erosion has predominated over sedimentation due to both natural and anthropogenic factors.

Waves have caused slight and balanced changes in the coast over six years. However, events such as El Niño Southern Oscillation (ENSO) have generated high levels of erosion due to increases in winds, currents and sea level.

However, the protective structures built, such as breakwater walls and stakes, have generated sedimentation in front of them, but have also caused significant damage to the sides by deflecting waves.

The eastern part of the island shows moderate to low erosion and sedimentation due to weak currents that mostly transport sediments.

The highest vulnerability was found in section 4 (where the lighthouse is located) due to geomorphological and social variables, and in section 1, where sea level rise puts a large part of the island at risk. Erosion, slopes and geomorphology were also the most influential variables, with the greatest threats in the western zone exposed to the sea.

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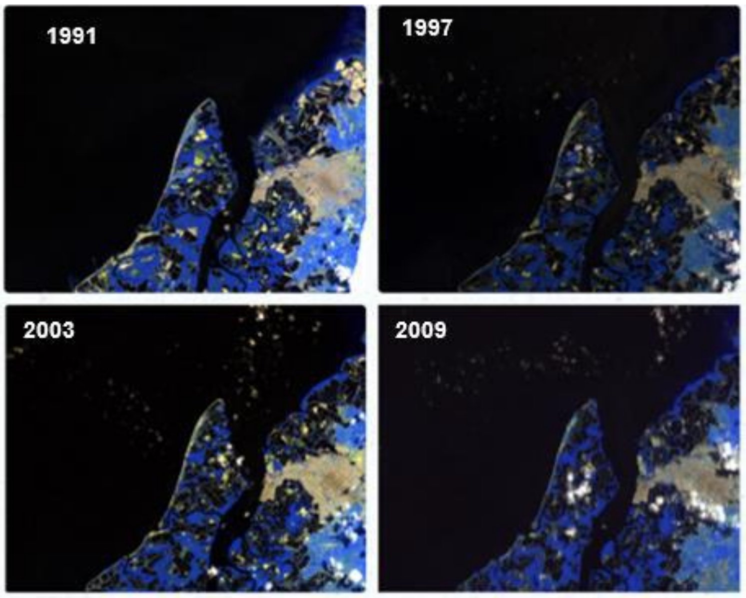
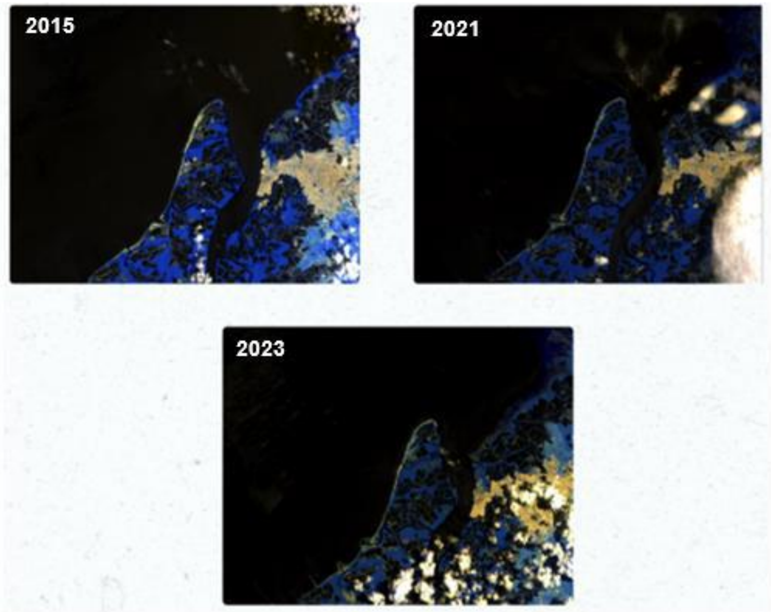
ANNEX:

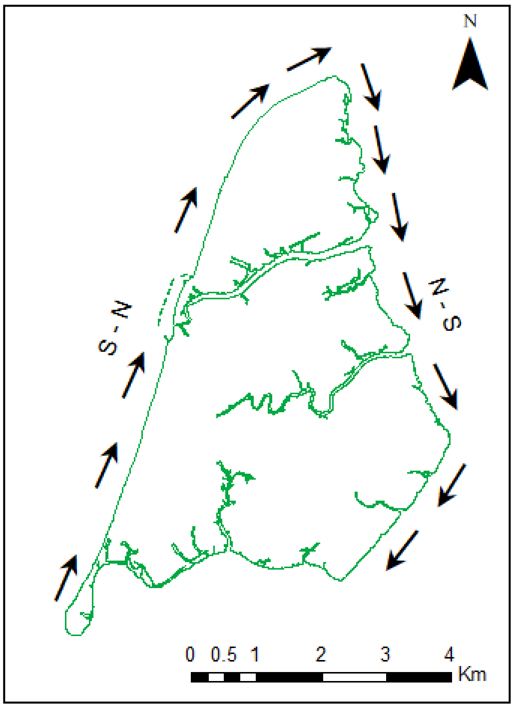


Annex 1. Combination of bands on satellite images downloaded through the Usgs Earth Explorer web page.

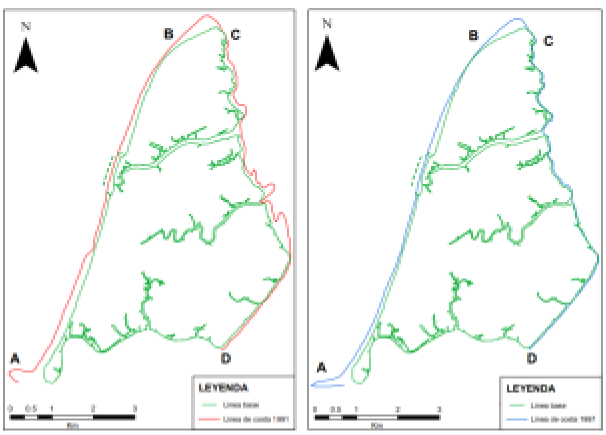


Annex 2.. Combination of bands on satellite images downloaded through the Usgs Earth Explorer web page.

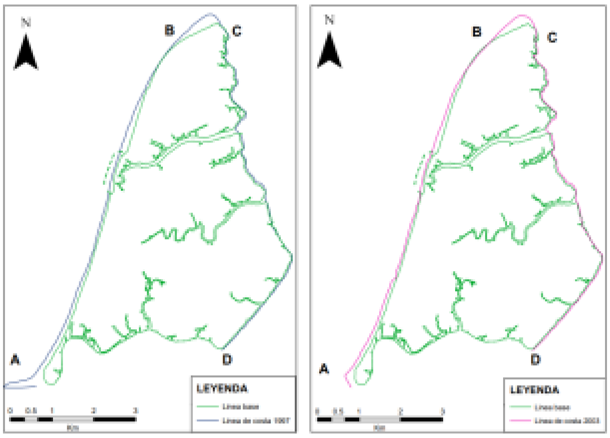
Annex 3. Orthophoto provided by sig tierras



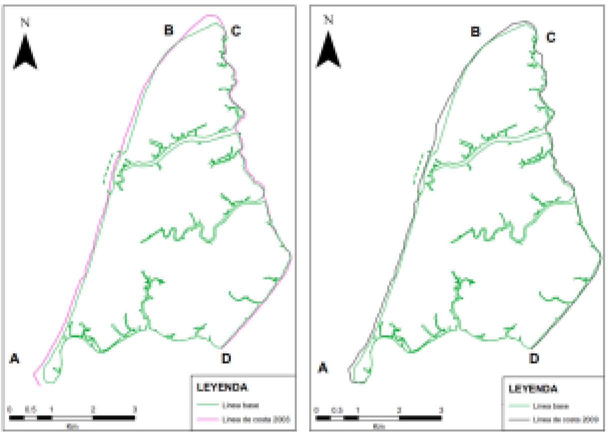
Annex 4. Baseline for Jambelí Island (information provided by INOCAR, 2023).



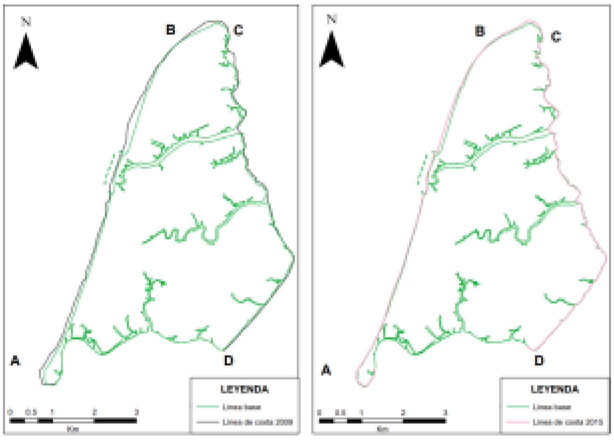
1991 - 1997



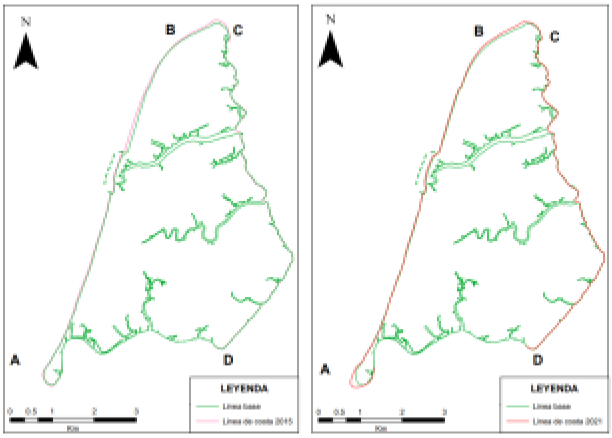
1997 - 2003



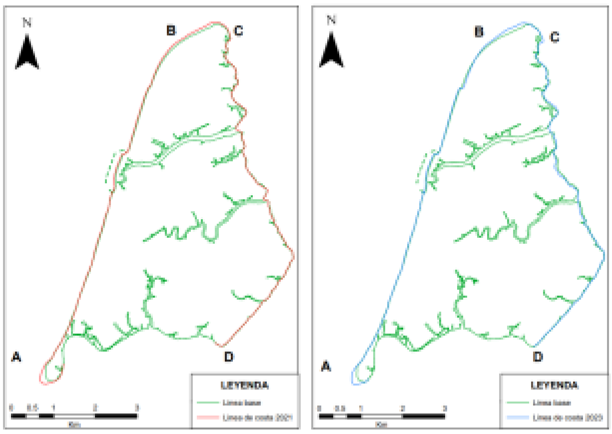
2003 - 2009



2009 - 2015



2015 - 2021



2021 - 2023

Annex 5. Shorelines along with their baseline**.**

		RANGO				
N°	**VARIABLE**	**MUY BAJA (1)**	**BAJA (2)**	**MODERADA (3)**	**ALTA (4)**	**MUY ALTA (5)**
1	**Geomorfología**	Acantilados altos (+4m)	Acantilados medios y bajo (-4m)	Barreras, deltas, Terrazas marinas	Llanura aluvial, Laguna costera	Playa, campos de dunas, Espigas, Pantanos de manglar
2	**Erosión**	Acumulación	Estabilidad	Erosión baja (Menos de 0,5 m/año)	Erosión media (0,5 – m/año	Erosión alta (Mas de 1m/ año)
3	**Pendiente costera %**	Mas o igual 8º	Entre 6 y 8	Entre 4 y 6	Entre 2 y 4	Entre 0 y 2
4	**Cambio del nivel del Mar**	Descenso 1mm/año	Estabilidad relativa	Aumento de hasta 0.5 mm/año	Aumento entre 0.5-1 mm/año	Aumento mayor de 1 mm/año
5	**Altura de la ola**	Entre 0 y 1 m	x	Entre 1 y 2 m	x	Mayor a 2 m
6	**Rango Mareal**	Micromareal Menor a 2 metros	x	Mesomareal Desde los 2 a los 4 metros.	x	Macromareal Superior a los 4 metros.
7	**Uso y Cobertura Vegetal**	Arbusto y matorrales	Pastos arbolados, Pastos enmalezados	Marismas costeras, Lagunas, Zonas pantanosas	Bosques de mangle Agricultura Cultivos	Bosques de manglares, Áreas protegidas, camaroneras
8	**% Población y área desarrollada**	Menor al 20 %	Entre 20 y 40 %	Entre 40 y 60%	Entre 60 y 80 %	Mayor al 80%
9	**Nivel de Antropización**	Puertos, espigones, rompeolas, Rellenos	Rellenos blandos	Costas Naturales Muelles	Deforestación, extracción de áridos, edificios altos	Drenaje urbano, comuna
10	**Sitios Prioritarios**	Área excluida	x	Área Agrícola, Área de Acuicultura	x	Área Industrial, comercial, Tejido urbano, zonas recreativas, Bosques Nativos

Annex 6. Variables considered for the calculation of CVI and their ranges of values (Gornitz, 1991).

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VULNERABILIDAD POR TRAMOS										
Zona	**Geomorfología**	**Erosión**	**Pendiente**	**Nivel Del Mar**	**Altura De Olas (m)**	**Rango**	**Cobertura Vegetal**	**Área**	**Nivel De Antropización**	**Sitios Prioritarios**
Tramo 1	Playa, campos de dunas	4.5 m/añ	5.8%	3.5 mm	0.37 m	2.6	Camaroneras, Pastos, Bosques de manglar	/	Costas Naturales	Áreas de acuicultura
Tramo 2	Playa, campos de dunas	1.3 m/añ	7.8%	3.5 mm	0.37 m	2.6	Bosques de manglar	/	Costas Naturales	Áreas de acuicultura
Tramo 3	Playa	2.4 m/añ	12.2 %	3.5 mm	0.37 m	2.6	Pasto	13. 7 %	Rompeolas Espigones	Comuna, zonas recreativas
Tramo 4	Playa, campos de dunas, espiga	3 m/añ	12.8 %	3.5 mm	0.37 m	2.6	Arbustos matorrales, Bosque manglar	5.6 %	Costas Naturales, Muelles	Área de acuicultura, Comuna
Tramo 5	Playa, Pantanos de manglar	0.9 m/añ	23.6 %	3.5 mm	0.37 m	2.6	Bosques de mangle, zonas pantanosas	/	Costas Naturales	Bosques Nativos
Tramo 6	Pantanos de manglar	0.9 m/añ	11.1 %	3.5 mm	0.37 m	2.6	Bosques de mangles, zonas pantanosas	/	Costas Naturales	Bosques Nativos

Annex 7. Analysis of vulnerability variables by sections