Determination of the coastal morphological variation of the bay of Tumaco, from multi-temporal analysis with remote sensing

Determinación de la variación morfológica costera de la Bahía de Tumaco, a partir de análisis multitemporal con sensores remotos

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Abstract

From inputs obtained from remote sensors, a multitemporal analysis of the evolution of the coastal edge of Tumaco Bay has been carried out, in approximately 780 km. The analysis allowed to identify, describe, vectorize and evaluate the changes due to processes of erosion and accretion, and anthropic invasions, to which this coastal edge is subjected, in the south of the Colombian Pacific; using geographic information tools. As a complement, bibliographic information was obtained referring to the oceanic and atmospheric and geological conditions of the bay, allowing relating the influence of these parameters in the processes of erosion and accretion of it. Towards the north of the bay it was found the erosion processes predominate, towards the south the accretion of sediments predominates that gives rise to the formation of fluvio-marine plains and towards the center of the bay there are not so significant changes, showing a relative stability of the terrain. Of the total extension of the coastline of the bay, 24.18 % has been eroding, 31.14 % has accretion, 43.16 % has remained stable or has not undergone significant changes, in 1.52 % the intertidal spaces have been invaded with stilt houses as constructions and in some cases have been filled with different materials to raise the terrain and avoid flooding during high tide. With the delivery of these results, it is sought to generate a base line of research and generation of actions based on the need for detailed knowledge of the evolution of the coastline over time, offering elements of planning, environmental and territorial management of the Colombian Pacific coast.

KEYWORDS: Coastline, coastal edge, remote sensing, GIS, erosion, accretion, litoral.

Resumen

A partir de insumos obtenidos de sensores remotos, se ha realizado el análisis multitemporal de la evolución del borde costero de la bahía de Tumaco, en aproximadamente 780 km, permitiendo identificar, describir, vectorizar y evaluar los cambios debido a procesos de erosión y acreción, e invasiones antrópicas, a los que está sometido este borde costero, en el sur del Pacífico colombiano; empleando herramientas de información geográficas. Como complemento, se obtuvo información bibliográfica referente a las condiciones oceanoatmosféricas y geológicas de la bahía, permitiendo relacionar la influencia de estos parámetros en los procesos de erosión y acreción de la misma. Se encontró que hacia el norte de la bahía predominan los procesos de erosión, hacia el sur predomina la acreción de sedimentos que da lugar a la formación de planicies fluviomarinas y hacia el centro de la bahía no se presentan cambios tan significativos, mostrando una relativa estabilidad del terreno. Del total de la extensión de la línea de costa de la bahía, el 24.18 % se ha estado erosionando, el 31.14 % presenta acreción, el 43.16 % ha permanecido estable o no ha sufrido cambios significativos. El 1.52 % los espacios intermareales han sido invadidos con construcciones palafíticas y en algunos casos han sido rellenados con diferentes materiales

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para elevar el terreno y evitar la inundación durante la marea alta. Como complemento se trató de relacionar estos datos con los parámetros oceanoatmosféricos y geológicos del sector de estudio. Con la entrega de estos resultados se busca generar una línea base de investigación y generación de acciones basadas en la necesidad del conocimiento detallado de la evolución del litoral a través del tiempo, que ofrezca elementos de planificación, gestión ambiental y territorial de la costa pacífica colombiana.

KEY WORDS: *línea de costa, borde costero, sensores remotos, SIG, erosión, acreción, litoral*.

Introduction

Coasts are very dynamic areas due to the convergence of different natural processes of marine and continental origin, and by anthropic processes, making it a fragile system subject to constant variations (Brocal, López & Pardo, 2001). As a consequence of these processes, the coast presents erosion and accretion of its areas. Erosion implies the loss of land due to the sea invasion , in a period of time long enough to rule out temporary or cyclical effects basically due to climate; and coastal accretion implies the accumulation of sediments and the consolidation of land above tidal level (Navarrete, 2014). Accretion processes are typical of low coasts and give rise to the formation of beaches, peninsulas, barrier islands and other forms of coastal accumulation (Carter, 1988 in (Navarrete, 2014), and erosion processes are more associated with high coasts with the presence of cliffs, although they can also occur in low coasts.

Erosion and accretion due to natural processes is intensified by human action, due to the high demographic demand of the coast, its attractive landscape and the resources it offers (Brocal *et al.,* 2001), leading to economic, social and environmental problems, for example: structures of anthropogenic origin, such as roads, houses, jetties, hotels, etc., in addition to making these areas more vulnerable to coastal natural hazards such as storms and tsunamis, erosion also becomes a problem for ecosystems living near the coastline.

The Colombian coasts are currently facing a problem of coastal erosion due to climate change and to the coastal natural dynamics . In the Pacific coast, this situation is aggravated by the continuous sand extraction from beaches to fill and stabilize adjacent areas to the sea and by mangroves felling.

The bay of Tumaco is part of the south zone of the Colombian Pacific coast, and due to its location, it becomes a very dynamic zone due to the geographical conditions in which it is found.

The bay presents a type of coastline composed by the presence of cliffs (to the north) that allows to see sedimentary rock exposed to waves abrasion, product of tectonic lifting. Towards the south and center of the bay, large fluvial-marine plains are observed as a result of the interaction between the sea and the rivers that flow into it.

The climatology of Tumaco is complex due to different oceanic and atmospheric factors that interact in this zone. On one hand, during the first semester of the year the climate of Tumaco is directly influenced by the Intertropical Convergence Zone (ITCZ), which is responsable for having the highest amount of precipitation (between 270 and 380 mm) during the year (Peñaranda, 2012). On the other hand, semi-diurnal macro tides, currents and waves that enter the bay from the SW and SSW (Restrepo, Otero & López, 2009), are responsable of transporting sediments provided by the Mira River (river with the highest average annual flow in the zone 868 m^2 s-1 and which has the greatest influence on it) during the rainy season, when it has its highest flow (MADS-INVEMAR, 2012 in Barajas & García, 2014). These oceanic and atmospheric and geological conditions promote erosion and sedimentation, leading to the formation of different coastal morphologies within the Bay of Tumaco.

Any study based on territorial planning, regardless of its objective, requires the existence of detailed information. This approach, in spite of being expressed in different documents of planning and administration of the territory, is confronted by the sometimes-incomprehensible absence of information on the coast at detailed scales (Díaz, Fernández, Prieto & Ojeda, 2012. In Ojeda Zújar, Díaz Cuevas, Prieto Campos & Álvarez Francoso, 2013).

The determination and characterization of variations in the coastline, especially the identification of changes due to erosion, regardless of whether they are of natural or anthropogenic origin, not only allows the recognition of areas that present natural coastal risks (Zújar, 2000), but are also a necessary reference for environmental and territorial planning and management of these areas (Ojeda Zújar *et al.,* 2013). For this reason, the first step to mitigate coastal erosion and accretion effects is to identify and evaluate the patterns of its cycles during the previous decades, in order to understand and try to predict the coastal edge behavior in order to incorporate these predictions in the coastline planning, management and administration.

Geographic Information Systems (GIS) and the digital treatment of images, become a fundamental tool that facilitates and speeds up this type of analysis, at the same time it allows to generate databases of easy update (Pardo & López Garcia, 1998. In Brocal *et al.,* 2001). This work was aimed at generating technical and scientific information, identifying, characterizing and evaluating changes in the coastal morphology configuration in Tumaco Bay, generated by processes of erosion, accretion and anthropic activity, from orthophotographic and aerial photographs analysis taken in the area from 1958 to 2013, using ArcGIS software, cartographic and bibliographic material.The above in order to obtain a technical input to guide decisions regarding the protection, preservation and restoration of coastlines, in addition to being a baseline study for projects to develop civil structures that mitigate coastal erosion.

Study area

Tumaco Bay is located in the Nariño department, south of the Colombian Pacific, in the municipalities of Francisco Pizarro and Tumaco, between the Salahondita mouth, with coordinates 78º41'45,275'' W and 2º6' 47.481''N, to Bocagrande, with coordinates 78º51' 24,741" W and 1º48' 43,841''N; the study area has a coastal border extension of 780 km and approximately 233 km². The following rivers flow into the bay: Chagüí, Colorado, Curay, Imbilpí, Llanaje, Rosario, Tablones. Currently the bay has several towns located on the coast, being: Llanaje, La Chorrera, Curay, Colorado, La Caleta, Chajal, Trujillo, San Pedro, Albino, Vaquería, Bocagrande and San Andres de Tumaco, the latter the most important within the area with 85,885 inhabitants in the urban area according to the last census of the National Administrative Department of Statistics (DANE) of 2005.

Methodology

Datos

As a basis for the development of this article, a search and compilation of bibliographic material was made to know the geological and ocean-atmospheric characteristics of Tumaco Bay , influential in the configuration of its geomorphology.

For the coastal morphological variation analysis of the bay, 163 IGAC aerial photographs were used, archived by flight number and year in which they were taken (see Table 1). Each photographic package has partial coverage of different areas of the bay, they are at different scales and different levels resolution . Likewise, 315 orthophotographs from 2006 covering the entire bay and 36 orthophotographs covering the urban area of Tumaco and its surroundings, taken in 2013, with a spatial resolution of 25 cm per pixel, were used.

Figure 1. Map of the study area.

Photo-interpretation

Before starting the coastlines vectorization and the coastal edge in general, verification and the aerial photographs georeferencing quality control was carried out, a process that was previously made during the development of the project "Physiographic Zoning of the Pacific Coast, Phase I" in 2013. During that process care was taken on each georeferenced photograph had very good positional exactitude and a low mean quadratic error, to gurantee no distortion (Figure 2).

Figure 2. Example of aerial photograph georeferencing .

Table 1. Inventory of IGAC aerial photographs used for multi-temporal analysis.

Year	Flight	Picture number
1958	C-836	48, 49 y 50
1962	M-1178	22186, 22187 y 22188
1969	C-1243	23, 24, 25, 28, 30, 33, 35, 36, 38
1971	C-1365	114, 115, 116, 117, 118, 119, 120, 124, 125, 126, 127, 130, 131, 132, 136, 137, 138, 139, 140, 143, 144, 145
1976	C-1664	42, 43, 44, 45, 46, 47
1983	C-2076	124, 125, 126, 127
	C-2079	02
1985	C-2191	02, 03, 04, 08, 11, 12, 13, 14, 18, 19, 20, 21, 22, 40
	C-2192	86
	C-2193	221
	C-2194	37
	R-988	39, 40, 41, 43, 44, 45, 46, 53, 55, 57, 59, 60, 61, 63, 68, 70, 71, 73, 75, 76, 77, 78, 79, 81, 85, 86, 88, 89, 90, 92 203, 206, 208, 209, 210, 218, 220, 236 242, 243, 244, 245, 246, 249, 257, 258, 260
1993	C-2509	01, 02, 03, 14, 15, 16, 17, 190, 192, 215, 216
	C-2510	35, 37, 39, 40, 69, 70, 71, 75, 76, 77, 80, 81 146, 148, 150, 165, 167
1998	C-2626	80, 82, 84, 117, 118, 120, 121
2001-2006	C-2788	207, 208, 210, 211, 212, 213, 214, 215, 220, 221, 222, 224, 225, 226, 227, 228

The study in the coast line and coastal edge variations, are very common in the photointerpretation and allow to detect changes between two or more dates (David, College & Beach, 2003) from the recognition and analysis of characteristics such as: shape, tone, color, structure, size, texture, shading, patterns and associations (Bermudez, Álvarez & Niño, 2004). A total of 11 dates were used in this study: 1958, 1962, 1969, 1971, 1983, 1985, 1993, 1998, 2001-2006, and 2014. To identify coastal edge changes, the coastlines of each year were digitalized at a 1:2000 scale, according to the coastline environment observed in the aerial photographs and orthophotographs (Figure 3). The coverage of each of the coastlines is not the same, because the number of aerial photographs per year varies from 3 photographs in the year with the least information (1958), to 64 photographs in the year with the most information (1985). The orthophotos taken in 2006 covered the entire study area, while those taken in 2013 covered the urban area of Tumaco and its surroundings. Because of the above, the coastline analysis of the bay, was carried out by sectors according to the coverage of each photo package.

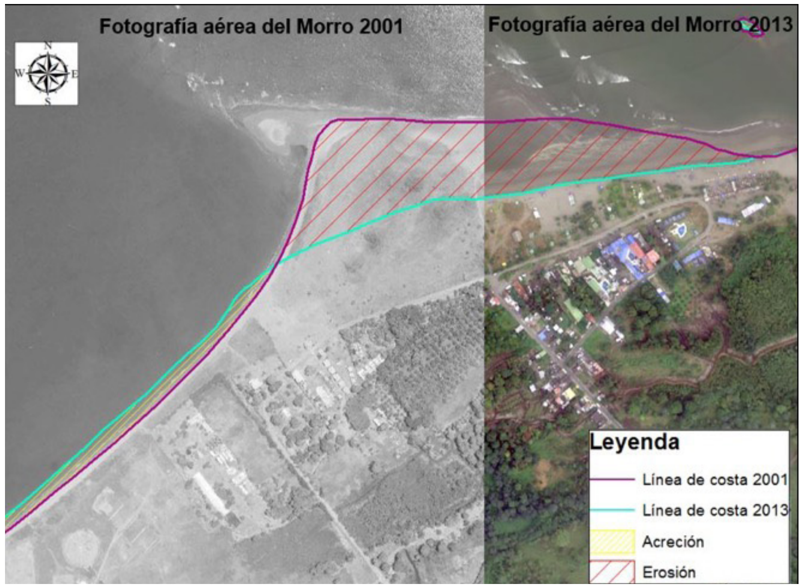


Figure 3. Example of multi-temporal coastline analysis.

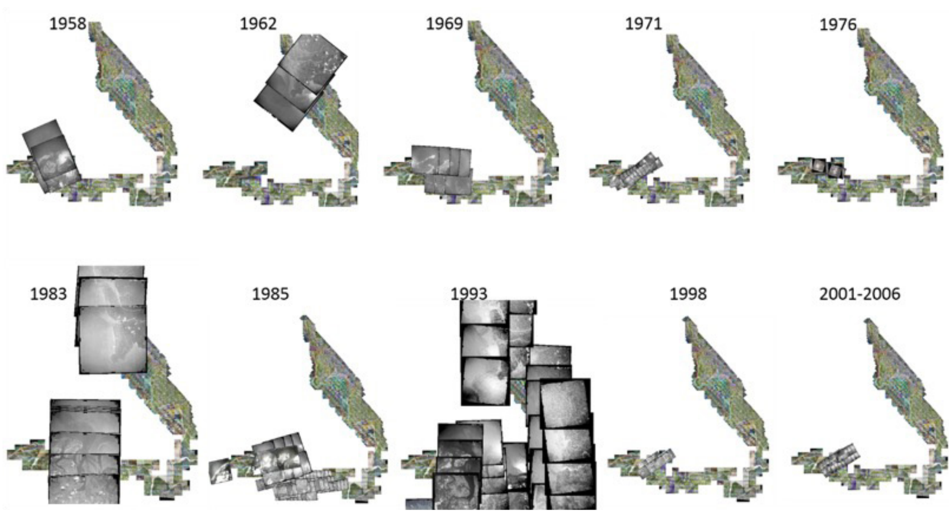


Figure 4. The coverage of old IGAC photographs by year over Tumaco Bay.

The coastline, is the line that forms the limit between land and water (Allen, 1972). Since the study area has semidiurnal macrotides, it is more difficult to define the limit between land and water because it is not just one line, but a transition zone delimited by the low tide and high tide level lines. In that sense, the coastline was defined as follows: where there were sand beaches the maximum water mark in the terrain was taken (Figure 5 a) ergo the high tide line of the moment in the aerial photograph. In low lands vegetated or not vegetated, the line was trazed by the low tide non-vegetated edge, in this case by the mangrove edges, that are covered by the tide daily limiting with the non-vegetated low land (Figure 5 b). In other elevated zones, the line was delineated by the cliff edge (Figure 5 c).

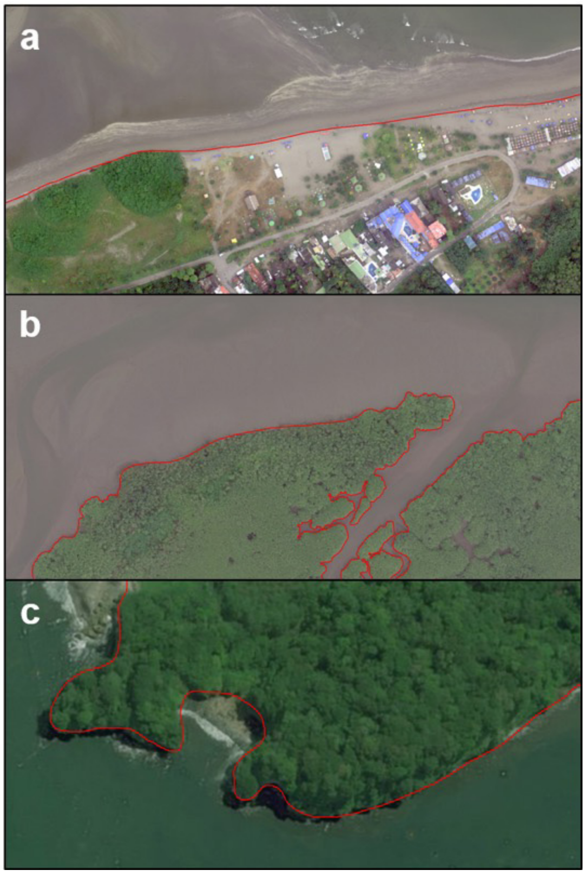
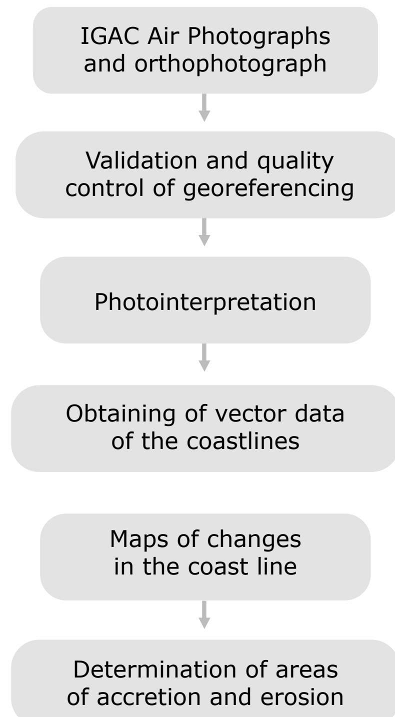


Figura 5. (a) coastline defined from the water mark left by the high tide. (b) coastline defined from the mangrove border inside the intertidal zone (c) coastline defined from a cliff edge.

Once each one of the coastlines was obtained, it was proceeded to identify and evaluate the areas that during this period of time (1958-2014) have suffered erosion, sediment accretion processes, or areas in which there is a relative "stability" of the coastal edge, in addition to the analysis of urban areas expansion, due to the invasion mainly of stilts buildings. To establish if there was a sector suffering erosion or acression or if it was "stable", a 10-year of coastline analysis was made in the complete Bay depending on the photographic coverage. Areas of erosion/ acression were also quantified and changes in the main populated islands of the Bay. For this purpose polygons were generated and the lost/gain area for each polygon was determined. The process for validation for the IGAC aerial photographs georeferencing quality control; the obtaining of vectorial data of the different coastlines variation analysis; and in general the geoprocessing, was carried out using ESRI ArcGIS software version 10.3.

Flowchart of the research methodology:



Geology

The bay is part of the Tumaco basin, which extends from the Garrapatas fault system (North) to the Ecuadorian border (South) (Ortiz & Valencia, 2013), and this in turn is part of the South Colombian Pacific within the Atrato - San Juan – Tumaco's high Terrain (Etayo-Serna et al., 1983). This basin represents an Forearc Basin associated with a tertiary subduction system, due to the collision and subduction of the oceanic and continental plates in which rocks from the Upper Cretaceous that constitute the basement and Cenozoic sedimentary rocks, from the Eocene to the Pliocene, formed in deep marine environments, emerge (Ortiz & Valencia, 2013).

The lithological formations in the bay consist mainly of sedimentary rock of marine and fluvial origin (Posada, Henao & Guzmán, 2009), in which conglomerates, claystones and mudstones predominate, frequently with small layers of dicotyledonous leaves, from the Naya (Miocene) and Guapi (Pliocene) formations (Etayo-Serna *et al.,* 1983). The rocky outcrops along the coastline of the bay (Punta Cascajal in Isla del Gallo, Punta Laura and El Morro), are part of the remains of a series of anticlines elongated in the Northeast and formed by tectonic movements of the Andes towards the end of the Lower Pleistocene (Van der Hammen, 1958. In Muñoz, Cossio, Salazar & Rodríguez, 2003). The deposits of the recent Tumaco Bay Quaternary are associated with the deltaic plain of Nariño, framed within a coastal environment associated with the marine and fluvial dynamics characterized by the development of the Patía and Mira rivers, the main ones in this area (Tejada *et al.,* 2003).

The Bay geomorphology is associated with erosive and depositional geoforms. Erosive geoforms are presented as cliffs, pillars, arches, caverns and fallen blocks along the Bay hills. Depositional geoforms of fluvial-marine origin, are constituted mainly by sands and silts, present as sand barriers, barrier islands, plains and beaches, located parallel to the coastline due to the littoral drift direction (Muñoz *et al.,* 2003).

Ocean-atmospheric parameters that influence in the dynamics of the morphology of Tumaco bay

The climate of Tumaco Bay is directly influenced by the Intertropical Convergence Zone (ITCZ), due to the fact that during its North-South-North movement, it affects the precipitation processes in the South of the Colombian Pacific during the months of January, February and March (Gómez & Peñaranda, 2012), presenting a rainy season during the first semester of the year (Barajas & García, 2014). This phenomenon occurs when the Northern Hemisphere trade winds converge with the Southern Hemisphere trade winds, generating a low pressure and, as a consequence, an increase in cloud cover, rains, the presence of variable and weak winds, and storms (Barajas & García, 2014). According to the multiannual monthly average values for the CCCP weather station during the period 1958-2010 (Gómez & Peñaranda, 2012), precipitation peaks in May at 310 mm, drops to 250 and 145 mm between June and July, reaching the lowest values between August and November with a minimum in November and October of 110 mm. The values increase between December and April, rising from 165 to 295 mm, with a peak in January of 300 mm (Figure 6).

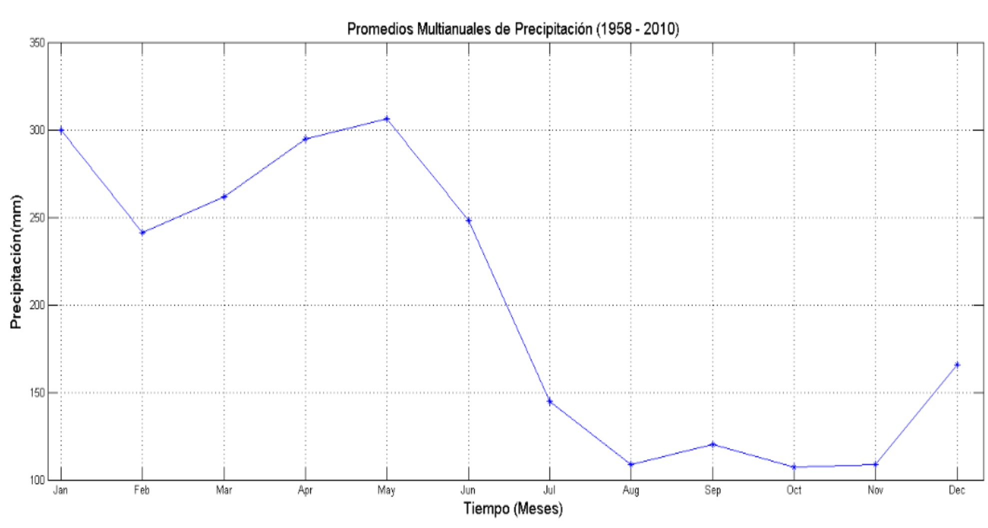


Figure 6. Multi-year average monthly rainfall, period 1958-2010 (Gómez & Peñaranda, 2012)

The main rivers that flow into and around the study area are the Mira and Patía Rivers. However, the Mira River is the one that provides the most suspended sediments and has the greatest influence on the bay. It is located approximately 24 nautical miles southwest of the southern end of the bay (Barajas & García, 2014), its delta has a subarea area of 520 km², which extends from its peak to approximately 20 km from the coastline (Restrepo *et al.,* 2009), its average annual flow is 868 m³/s and its suspended sediment concentration, , according to the average flow range, is 0.35 kg/m³ (Restrepo & López, 2008). The river basin has a bimodal hydrological regime, where the maximum flows are in the months of April-May (maximum in May of 1105 m³/s) and November-January; the period of minimum flow in the months of July to September (minimum in August with 553 m³/s) and a transition season during the other months of the year (Barajas & García, 2014) (MADS-Invemar, 2012. In Barajas & García, 2014).

The waves and currents that enter the bay come from the SW and SSW, with heights between 0.29 and 2.23 m, and periods that vary between 5.0 and 23.0 s, in deep waters (Restrepo, 2007). The waves during their transit towards shallow waters and after suffering the effects of wave shoaling, refraction-diffraction, dissipation with the bottom and waves breakage, cause significant changes in the wave height , generating areas of increased wave energy with heights greater than 3 m near the coastline (MADS-INVEMAR, 2012. In Barajas & García, 2014), in sectors of Punta Cascajal in Isla del Gallo and in general to the north of the bay. In the south zone of the bay, waves enter with direction W - NW and significant wave height of 0.2 and 1.2 m. Towards the E and center of the bay, the wave enters in WSW direction and significant wave height of 0.2 to 0.8 m approximately.

Another important aspect of the Tumaco Bay morphology is the tides. The Colombian Pacific have semi-diurnal macro-tides with mean amplitudes of around 4.5 m (IDEAM, 2007). Beginning with a maximum level (high tide) follow a retirement flow during the following six hours when the low tide level is reached and then there is a filling up flow rising the levels until the next high tide. The Colombian Pacific has regular semi-diurnal tides since there are two high tides and two low tides with a period of 12.25 hours (Gidhagen, 1982 in IDEAM, 2007).

RESULTS AND DISCUSSION

The use and analysis of remote sensing in a Geographic Information System (GIS), allows the determination of changes in the coastline, in a precise and detailed form (Rangel-Buitrago & Posada-Posada, 2013) , in this case for the period 1958 – 2014. The obtained data were useful to show the variability of the changes in different points of the bay, allowing the establishment of possible erosion and / or accretion patterns .

The outcrops of sedimentary rocks of the Miocene and Pliocene, are non-cohesive rocks that are characterized by being little resistant to the impact of waves at the base of the cliffs (Martínez, 1993. In Posada *et al.,* 2009), fragile little consolidated, highly deleterious and affected by fractures (Posada *et al.,* 2009), which facilitate the erosion of the cliff areas present in the sectors of Punta Cascajal in Isla del Gallo, Punta Laura near the mouth of Curay River, Colorado near the mouth of the Colorado River and in El Morro (Rangel & Posada, 2013). The plains of fluvial-marine origin are mainly located in the south and center of the bay. They are product of the sediment transport of the interaction of the sea with the rivers that end there; nevertheless, these plains present some degree of erosion in some sectors.

As shown in Figure 7, the bay presents zones where erosion processes have predominated, sediment accretion or where there is a relative "stability" of the coastal edge, that is, zones in which the line of the coast varies very little, because there is a slight erosion cyclically followed by a slight accretion of sediments, thus avoiding abrupt changes in the regression or transgression of the coastline.

Of the 780 km of coastline that were analyzed in the bay of Tumaco, it was found that, 24,18 % of erosion processes have predominated; 31,14 %

of sediment accretion predominated; 43,16 % of the coast has maintained relative stability during the period from 1993 to 2006; and the 1, 2 % of the coastline has presented regression, due to the fact that the invasions of anthropic structures have gained ground to the sea.

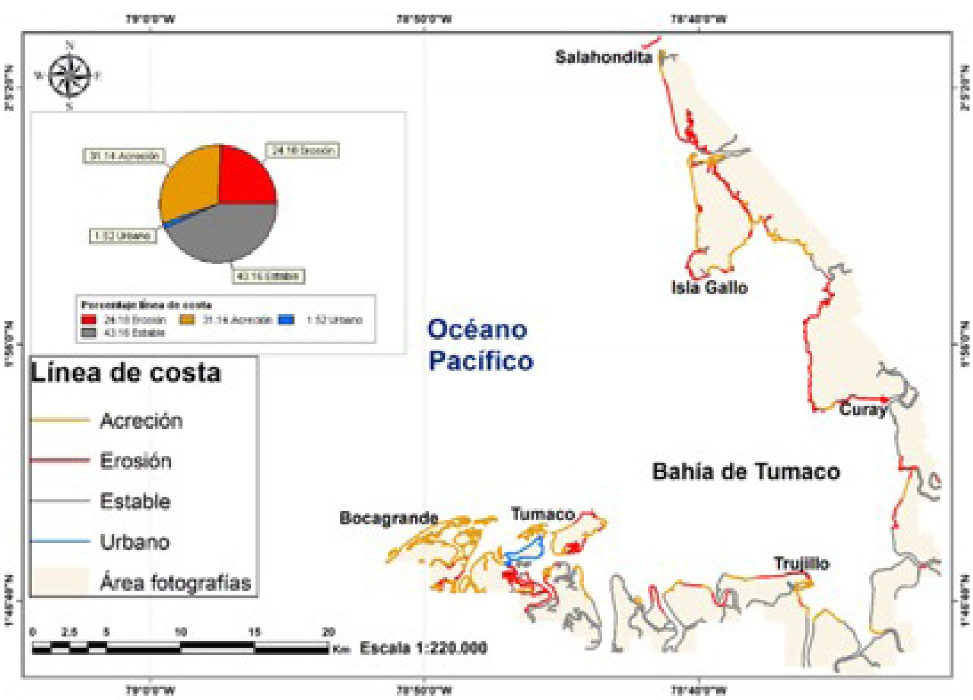


Figure 7. Erosion and coastal accretion in Tumaco Bay.

The areas of Tumaco Bay that have been most affected due to erosion and accretion processes are described below.

Bocagrande and Vaquería Island Sector

Figure 8 shows the evolution of the coastline of the Bocagrande peninsula, Vaquería Island and the surroundings of this sector, during the period 1969-2006. The Bocagrande peninsula in 1969 (light green line), had an area of 91.45 ha., was not firmly attached to the shallow and was approximately 400 m NW of its position in 2006. In 1985 (yellow line), the peninsula becomes thinner, splits in two and extends more towards the NE. For 1993 (red line), the peninsula increases its thickness and moves towards the SW, being again about 400 m towards the NW of the position it takes for the year 2006.

In 2006, the peninsula again moves towards the SE, increases its area to 193.86 ha. due to the accretion, decreases its thickness while increasing its length in NE direction. It can be observed that the behavior of the peninsula during this period of time, is to thicken and therefore to move approximately 400 m towards NW, at the same time that its length decreases, followed by the previous pattern, it thins moving approximately 400 m towards the SE and increasing its length in NE direction. In Vaquería Island and in general in the other areas shown in Figure 6, processes of sediment accretion have been presented, causing for example Vaquería Island to go from an area of 139.77 ha. in 1969 to 172.15 ha. in 2006.

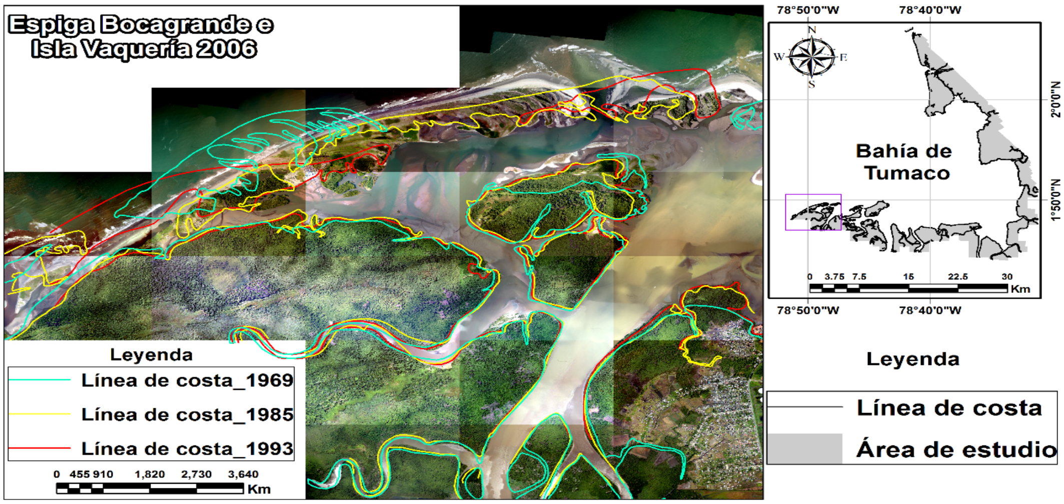


Figure 8. Evolution of the southwestern coastline of Tumaco Bay, period 1969- 2006.

Table 2 evaluates the changes in the areas of the Bocagrande and Isla Vaquería peninsulas, and shows what is the annual accretion or erosion rate during the 37 years of the 1969-2006 period.

Table 2. Quantification of changes in the Bocagrande peninsula area and Vaquería Island of Tumaco Bay due to coastal erosion and accretion.

Zone	Area (ha)	Rate of erosion or accretion (ha/year)
Bocagrande	From 91.45 to 193.86	Accretion of 2.77
Isla Vaquería	From 139.77 to 172.15	Accretion of 0.88

El Guano, Tumaco and Viciosa Islands

The position and form of Guano Island in 1958 and the displacement that had in approximately a decade towards the SE going from occupying 68.46 ha. to 59.92 ha. in 1969 (clear green line) are observed in Figure 9, evidencing an erosion of 0.78 ha/year during this period. Subsequently, in 1979 this island disappeared completely due to the tsunami generated after the 7.9 magnitude, Richter scale earthquake. Figure 7 also shows Tumaco Island in 1958, year in which the accretion of what is known today as La Viciosa Island begins, which is currently adjacent to that one of Tumaco. The aerial photography and the superimposition of the green, red and blue lines represent the change that these three islands, Tumaco, La Viciosa and El Guano, had during the period 1958 - 1983. Guano Island shows a behavior similar to that of the peninsula of Bocagrande, decreasing its thickness and moving towards the SE. In La Viciosa Island, the processes that predominated during this period were the accretion of sediments, due to its formation and increase, going from an area of 27.25 ha. in 1958 to 30.20 ha. in 1983. As for the island of Tumaco, it also increased its area, but in this case, it was due to anthropogenic invasions in the periphery of the island, going from an area of 101,57 ha. in 1958 to 143.05 ha. in 1983.

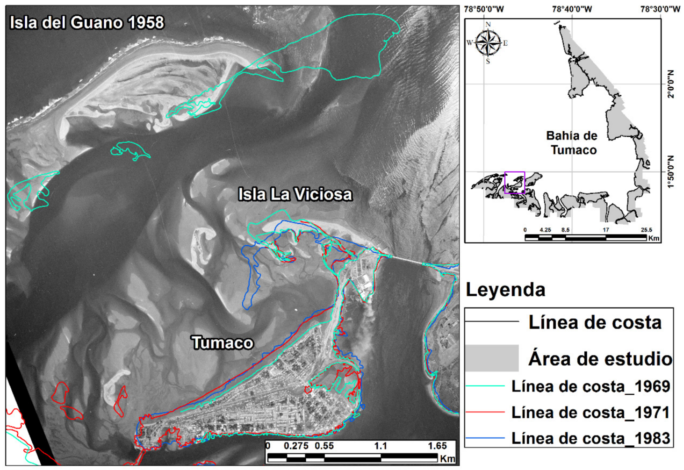


Figure 9. Evolution of the coastline of the islands Tumaco, La Viciosa and the Guano in Tumaco Bay, period 1958-1983.

Table 3 evaluates the change in the extent of the area of the islands Tumaco and La Viciosa, as well as the annual rate of accretion or erosion during the 25 years of the period 1958 - 1983.

Table 3. Quantification of changes in the Tumaco and La Viciosa islands of the bay due to coastal erosion and accretion between1958-1983.

Zone	Area (ha)	Rate of erosion or accretion (ha/year)
Tumaco	From 101.57 to 143.05	Accretion of 1.65
La Viciosa	From 27.25 to 30.20	Accretion of 0.118

Figure 10 shows the evolution of the Tumaco and La Viciosa Islands during the past period of 1985- 2014. The increase due to accretion in La Viciosa is considerable, since during this period its area increased from 49.76 ha. to 73.89 ha, although in one sector of the same, this increase is due to anthropogenic invasions. During this period, the island of Tumaco increases its area, but in smaller proportion to the period 1958-1983, also as a consequence of invasions of an anthropogenic nature, and goes from occupying an area of 149.32 ha. to 174.81 ha. in 2014.

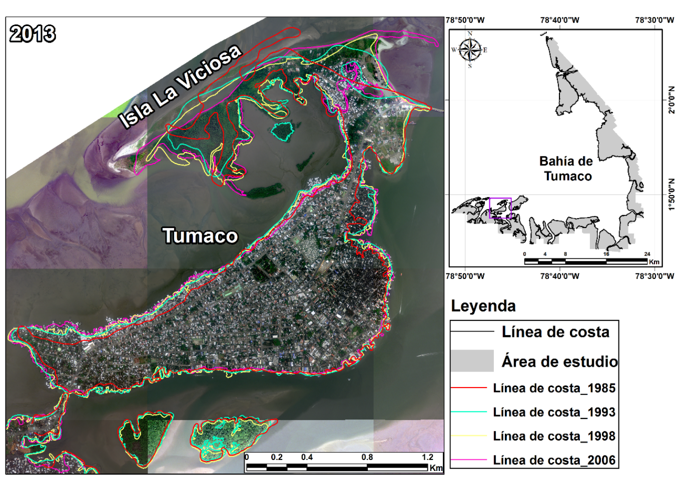


Figura 10. Evolution of the coastline of the Tumaco islands and La Viciosa in Tumaco Bay, period 1985-2014.

Table 4 evaluates the change in the extent of the Tumaco and La Viciosa Islands area, as well as the annual rate of accretion or erosion during the 28 years of the 1985-2014 period.

Table 4. Quantification of changes in the Tumaco and La Viciosa islands of the bay due to coastal erosion and accretion between 1985-2014.

Zone	Area (ha)	Rate of erosion or accretion (ha/year)
Tumaco	From 149.32 to 174.81	Accretion of 0.91
La Viciosa	From 49.76 to 73.89	Accretion of 0.86

El Morro

Figure 11 shows the state of El Morro Island in 1958. The red, green and yellow lines represent the coastlines of El Morro in 1969, 1971 and 1983, respectively. During this period, the main changes occurred in the northeastern tip of the island with an erosion of 36.37 ha. and accretion towards the eastern part of the island, behind the hill, of 19.64 ha. The rest of the island presents no major changes. During this period, the entire island went from occupying an area of 496.61 ha. in 1958 to 468.48 ha. in 1983.

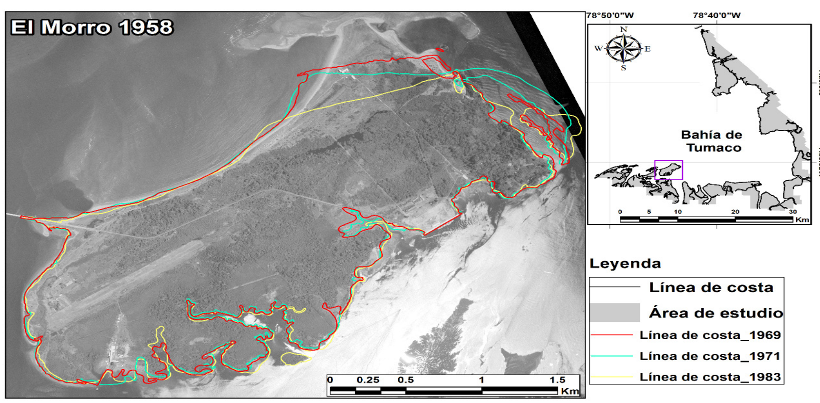


Figure 11. Evolution of the coastline of the island El Morro in the bay of Tumaco, period 1958 – 1983.

Table 5 evaluates the change in the extent of the El Morro Island area, as well as the annual erosion rate during the 25 years of the 1958-1983 period.

Table 5. Quantification of changes in El Morro Island of the bay, due to erosion and coastal accretion between 1958-1983.

Zone	Area (ha)	Rate of erosion or accretion (ha/year)
El Morro	From 496.61 to 468.48	Erosion of 1.13

Figure 12 shows an orthophotograph of El Morro, taken in 2014 and the coastlines of this island in 1985, 1993, 1998 and 2006. It can be observed that from 1985 to 1993 the northern part of the island was eroded to the maximum point of transgression of the coastline, followed by an accretion period until 2006 and again an erosion period until 2014, but in the northeastern tip of the island only. The eastern tip of the island, behind the hill, had an accretion period from 1985 to 1993, followed by erosion until 2014. During this period (1985-2014) the islands passed from occupying an area of 484.86 ha. in 1985 to 500.26 ha. in 2014.

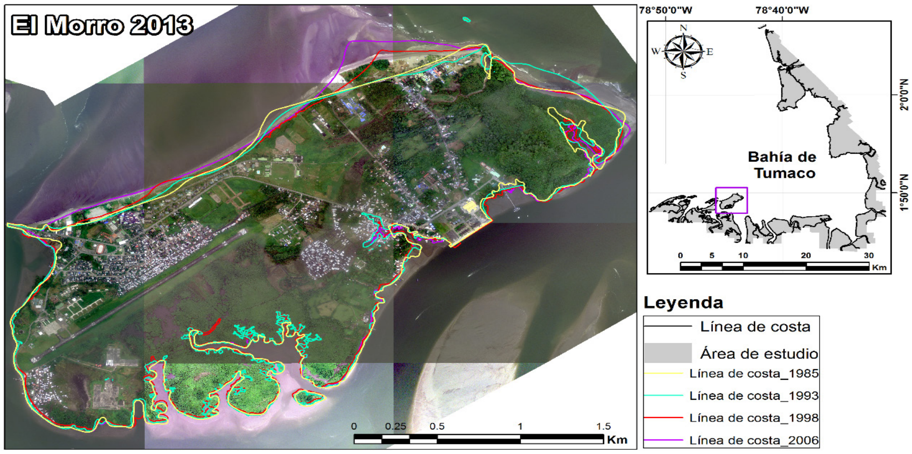


Figure 12. El Morro island coastline evolution in Tumaco Bay, period 1985-2014.

Table 6 evaluates the change in the size of the El Morro island area, as well as the annual rate of accretion during the 28 years of the 1985-2014 period.

Table 6. Quantification of the changes in the El Morro island of the bay, due to coastal accretion between 1985-2014.

Zone	Area (ha)	Rate of erosion or accretion (ha/year)
El Morro	From 484.86 to 500.26	Accretion of 0.55

North of the bay: Salahondita and Gallo Island

As can be seen in Figure 13, northwards of the mouth of Salahondita, from 1983 to 2006, there was erosion and therefore retreat of the coastline, while towards the south of the mouth and in the surroundings of Salahondita there was accretion allowing the formation of new areas and the spigot. The southernmost zone of Salahondita presented accretion from 1983 to 1993, followed by erosion until 2006. In Isla del Gallo, it can be observed that there was a period of erosion from 1962 to 1993, followed by a period of strong accretion until 2006. This island went from occupying 1990.59 ha. in 1962 to 2060.30 ha. in 2006.

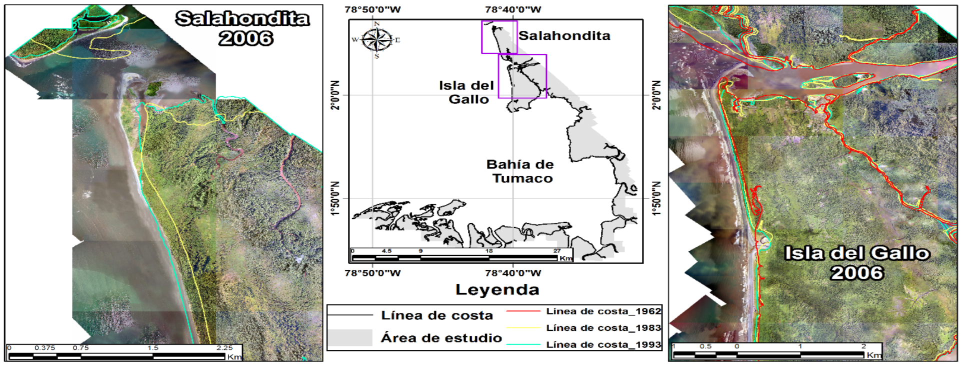


Figure 13. Coastline evolution in Salahondita sectors and Gallo Island north of Tumaco Bay , period 1962-2006.

Table 7 shows the total area changes by erosion and accretion processes in the most affected sectors in Tumaco Bay in certain periods of time and the average erosion or accretion rate per year, assuming that these changes were homogeneous from one year to the next.

Table 7. Quantification of changes in the most affected areas by erosion and accretion processes of the bay.

Zone	Period	Area (ha)	Erosion/accretion rate (ha/year)
Tumaco	From 1958 to 2013	From 101.57 to 174.81	Accretion of 1.33
La Viciosa	From 1958 to 2013	From 27.25 to 73.89	Accretion of 0.848
El Morro	From 1958 to 2013	From 496.61 to 501.79	Accretion of 0.0941
Bocagrande	From 1969 to 2006	From 91.45 to 193.86	Accretion of 2.77
Isla El Guano	From 1958 to 1969	From 68.46 to 59.92	Accretion of 0.78
Isla Vaquería	From 1969 to 2006	From 139.77 to 172.15	Accretion of 0.88
Isla del Gallo	From 1962 to 2006	From 1990.59 to 2060.30	Accretion of 1.58

The loss or gain calculation in the area of each of the islands that are part of the bay, showed that most of them, have experienced an increase in their area due to the accretion of sediments during the period 1958-2013, except the island of Guano, which during the period 1958-1969 was eroded with an average rate of 0.78 ha. per year. The accretion rate of other islands varied from 0.0941 ha. to 2.77 ha. per year.

Conclusions

Analysis of the coastlines in different years, allowed knowing the areas in which erosion, accretion processes have predominated or have been relatively stable over time. In the bay, erosion occurs mainly to the north in the cliff areas and on the beaches south of Salahondita. The accretion is strong in the southwest of the bay in the sectors of Bocagrande, Isla Vaquería, La Viciosa, El Morro and surrounding areas.

Annual rates corresponding to the different periods of time used in the analysis of the different islands, report accretion rates between 0.55 and 2.77 ha. / year, and erosion between 0.78 and 1.13 ha. / year.

According to the consulted literature, the oceano-atmospheric and geological conditions promote erosion and sedimentation, allowing the formation of different coastal morphologies within Tumaco Bay. On one hand, the ITCZ affects the climate in the area, creating a rainy season during the first half of the year, which increases the Mira River flow and in turn the amount of suspended sediment, which are transported by the direction of the swell in the SW SSW direction towards the bay, promoting the deposition of sediments in the S and E of it. On the other hand, the wave that arrives in SW direction towards the N of the bay with greater energy and waves of up to 3 m, promotes the erosion of little cohesive rocks that emerge in this area.

The sifting invasions of the low tide areas adjacent to Tumaco Island, increased the area by 72 %, because it happened to have an extension of 101.57 ha. in 1958 and of 174.81 ha. in 2013, with an annual increase rate in 1.33 ha/year.

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