Magnitude and Causes of Beach Accretion on the Eastern Margin of the Tayrona National Natural Park (Colombian Caribbean)

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ABSTRACT

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Beaches on the eastern margin of Tayrona National Natural Park experienced stability and even accretion over the last decade, in contrast to general erosion along the Colombian Caribbean coast. The objective of this study is to characterize shoreline change and analyze the factors contributing to the accretionary trend. Ortho-rectified satellite images, combined with topography from both drone images and RTK-DGPS measurements, were used to map successive shorelines from 2002-2008. Net shoreline movement and shoreline migration rates revealed these beaches had an accretionary trend, with the exception of Piscina Beach that eroded during the time period. The maintenance of natural inputs of sediment from local rivers, redistributed by littoral drift with sediment bypassing across the small headlands limiting the beaches, the resilience of the beaches to the impact of hurricanes and low human pressure allows for a positive sedimentary budget for the beaches. Piscinas Beach is the most cut off from fluvial sediment input, and despite it has a coral reef barrier, its dissipative profile indicate that it is the most exposed to wave impact.

ADDITIONAL INDEX WORDS: Shoreline migration, DSAS, sediment input, littoral drift, hurricanes, tourist pressure.

INTRODUCTION

Beaches are wave-deposited accumulations of sediment located at the shoreline. They require sandy or coarser sediment to form them, a base to reside on, usually the bedrock geology, and waves to shape them (Short, 2012). Moreover, they have important ecologic and socio-economic roles. Beaches are places of great tourist attraction; beaches also provide protection from the sea, dampening the waves and eliminating the energy of storm surges, keeping the coastline constantly changing.

Beach morphodynamics is characterized by natural cycles of erosion and accretion events. Geomorphological changes can take minutes (episodic events), hours or days (short term), months (medium term), decades (long term), or centuries (very long term). The magnitude, duration and speed of beach morphodynamics changes is controlled by both the natural processes and human disturbances of each particular coastal sector. Natural processes are mainly associated with meteo-oceanographic conditions (waves, tides, winds), sea level variations, local tectonics (uplift/subsidence), sediment supply and geological inheritance (Van and Binh, 2008; Posada and Pineda, 2008; Short, 2010).

Analysis of shoreline morphodynamics is a really useful proxy of coastal erosion or accretion processes (Absalonsen and Dean, 2011). Over a multiannual or longer term scale, a shoreline can present a stable, transgressive or regressive trend. In association with these shoreline behavior, the coastal sedimentary environment can present a stable surface, erosion or accretion processes, last one including progradation, agradation or retrogradation patterns (Curray, 1964).

The objective of this study is to analyze the beach accretion processes on the eastern margin of the Tayrona National Natural Park (Tayrona-NNP; Colombian Caribbean) and the factors controlling it. The relevance of this study is evidenced by the generalized beach erosion trend in the world, relate to global sea level rise. Furthermore, the results of this study can contribute to improve the management of tourism activities in the park.

STUDY AREA

This study focuses on 6 beaches located on the eastern margin of the Tayrona-NNP and named Piscina, Arenilla, Arrecifes, La Gumarra, Príncipe San Felipe and Cañaveral beaches (Fig. 1). They are pocket beaches limited by small rocky headlands. Length of the beaches ranges between 157.5 and 1035.9 m, with a NW-SE...
shoreline orientation. Piscina and Arenilla beaches present a coral reef barrier. Sediment size mainly corresponds to medium and coarse sand, including both siliciclastic and carbonate grains. The beaches present low urbanization, but they suffer intense tourist pressure.

The Tayrona-NNP is located within the mountainous system of the Sierra Nevada de Santa Marta, a geological complex massif that shows an isostatic equilibrium (Tschanzet al., 1974).

The region has a semi-arid tropical climate, with two main climatic periods, dry season (summer) and wet season (winter). It presents average temperatures of 28°C, varying from 29°C (dry season) to 23°C (rainy season) (Acosta and Díaz, 1990, Posada et al., 2008). The rainfall regime is correlated with the displacements of the so-called intertropical convergence zone, of bimodal character with a period of rain (May and October) (PMPNN-Tayrona, 2006).

The Caribbean is directly influenced by trade winds, with a predominantly northwest-southwest direction and blowing with greater intensity from December to April (PMPNN-Tayrona, 2006). The region can be affected by extreme events, the most frequent being tropical storms, hurricanes, tropical cyclones and cold fronts. The hurricane season covers from June to November, with September and October being the busiest months (Ortiz, 2006). The region can be affected by strong winds, heavy rains and storm surges on the coast (Posada and Pineda, 2008).

Cold fronts, also called atmospheric fronts, are formed by the collision of a mass of cold air and a mass of hot air, producing torrential rains, which in turn cause floods and landslides. Analysis of historical data from a buoy (located at 11°N and 75°W) between 1996 and 2012 of a buoy reveals an average of six cold fronts occur annually with a maximum of up to 20 cold fronts in 2010 (Ortiz et al., 2013). The high number of cold fronts in 2010 coincides with a transient ENSO warm phase (El Niño event) between May 2009 and March 2010, and later an ENSO cold phase (La Niña event) between April 2010 and April 2011.

Ocean waves in the study area mainly approach from the ENE (37.5%), NE (21.2%), and E (29%); rest of directions do not reach 1% (Tejada, 2001). Normal wave heights are in the order of 1 m, but they can reach up to 3 m during stormy periods. The net longshore drift along the Caribbean coast has a southwest direction, probably with minor inversions to the northeast at times (Correa, et al., 2005). The astronomical tides correspond to a mixed microtidal regime, generally with lower amplitude than 0.5 m (Molares et al., 2001; Posada and Pineda, 2008).

METHODS

The use of satellite images, aerial photographs, DGPS measurements and drone images, in conjunction with Geographic Information System (GIS), have progressively improved the resolution and versatility of shoreline extraction and mapping, and describing medium-term coastal morphodynamics (Maiti and Bhattacharya, 2009; Aedla et al., 2015; Alcantara-Carrió et al., 2019; Fontán et al., 2019).

In this study, the shoreline morphodynamics of the beaches was analyzed over a 16-years period (2002 - 2018). Orthorectified satellite images, combined with topographies from both drone images and RTK-DGPS measurements, were used to draw the successive shorelines. All satellite images, drone images and DGPS data were processed using the WGS84 - Zone 18N coordinate system. For this work, it was considered the shoreline definition suggested by Crowell et al. (1991), i.e. the position of the land-sea interface in sandy coastal areas, marked by the limit reached during the high tide of syzygy. According to these authors, this limit corresponds to a sharp tonality change for the sand of the beach.

Shoreline migration was analyzed in ArcGIS 10.5 by the Digital Shoreline Analysis System - DSAS 5.0 (Thieler et al., 2009), over transects perpendicular to the coast, located at intervals of 10 m from a landward reference baseline. Three methods were applied to characterize shoreline migration: the Net Shoreline Movement (NSM), which is the distance (m) between the oldest and the youngest shorelines; the Shoreline Change Envelope (SCE), which is the largest distance (m) between the coastlines, regardless of dates; and the End Point Rate (EPR), which is the migration rate (m yr$^{-1}$) calculated by dividing the distance between the most recent and the oldest shoreline by the time elapsed (Thieler et al., 2009). For each method, statistics parameters were determined with a confidence interval of 95%.

The basin area of the rivers flowing into the study area was determined using topographic data Shuttle Radar Topography Mission (SRTM). Processing was performed on ArcGis 10.5.

RESULTS

The studied beaches presented an intense shoreline migration, with both shoreline retreat and advance. The highest beach accretion was measured at Arrecifes Beach, with a maximum NSM value of 214.02 m in transect 229. This same transect also presented the greatest envelope (SCE) and the highest shoreline migration rate (EPR) seaward, reaching 13.69 m yr$^{-1}$. In contrast, the highest beach erosion occurred at the central sector of
Cañaveral Beach, where transect 21 present a NSM of -5.70 m and shoreline retreat rate (EPR) of -0.36 m·yr⁻¹.

Nevertheless, both beaches presented positive values for both the average NSM and the EPR, similarly to Arenilla, La Gumarra and Principe San Felipe beaches. On the other hand, Piscina Beach presented shoreline retreat, reaching an average NSM of -3.32 m and average EPR of -0.21 m·yr⁻¹ (Fig. 2 and Table 1).

Table 1. Statistic summary of shoreline migration for the 6 analyzed beaches after the NSM, EPR and SCE methods.

| Beach            | Transects | Arenilla | Arrecifes | La Gumarra | Piscina | Cañaveral |
|------------------|-----------|----------|-----------|------------|---------|-----------|
| Total number of transects | 26        | 14       | 96        | 14         | 15      | 13        |
| Minimum shoreline distance (m) | 14.02     | 8.46     | 21.06     | 17.09      | 18.43   | 17.98     |
| Maximum shoreline distance (m) | 48.72     | 43.68    | 43.68     | 43.68      | 43.68   | 43.68     |
| Shoreline length (m) | 397.3     | 165.5    | 157.5     | 157.5      | 144.6   | 275.4     |
| NSM (m·yr⁻¹) | -0.32     | -0.42    | -1.01     | -0.34      | -0.36   | -0.36     |
| EPR (m·yr⁻¹) | -0.21     | 0.22     | 0.41      | -0.17      | 0.18    | 0.18      |
| SCE (m·yr⁻¹) | 0.09      | 0.28     | 0.39      | 0.23       | 0.25    | 0.25      |

Table 1. Statistic summary of shoreline migration for the 6 analyzed beaches after the NSM, EPR and SCE methods.

The magnitude of the envelope is greater for beaches showing shoreline advance (Arenilla, Arrecifes, La Gumarra and Principe San Felipe beaches) than for Cañaveral Beach (with both shoreline retreat and shoreline advance) and Piscina Beach (with shoreline retreat). It indicates that magnitude of accretion in the first four beaches is more significant that erosion in the other two.

In summary, for the past 16 years, most of the beaches at the western margin of Tayrona-NNP have shown an accretion trend, with the exception of Piscina Beach, that have presented erosion.

The analysis of the hydrographic basins area, for the main rivers flowing to the study area, showed that the Piedras hydrographic basin has the greater drainage area (160.44 km²). The other rivers present within the Tayrona-NNP have medium to small hydrographic basins, with areas of 5.70 km² for Cañaveral River; 0.33 km² for River 3; 1.14 km² for Santa Rosa River; 9.22 km² for River 2; and 0.20 km² for River 1 (see Fig. 1 for location of the rivers and their hydrographic basins).

**DISCUSSION**

Natural processes and human activities continuously modify the shoreline, the precise detection of changes on the shoreline provide information of coastal dynamics and therefore is very important for planning measures. The main historical shoreline changes along the Colombian Caribbean coast reflect both erosive and accretional events, the latter in very localized zones (Correa et al., 2005). Erosion of the Colombian Caribbean coast seems to have accelerated from the 70s and 80s with the growth of coastal cities (Navarrete-Ramírez, 2014). Approximately 50% of this area (of great importance for the country) is undergoing erosive processes that result in the retreat of the shorelines. The factors that influence erosion are sedimentary imbalances, extreme waves, sea level rise and destruction of natural ecosystems (Rangel-Buitrago et al., 2016).

Erosion rates in the Colombian Caribbean are very varied. (e.g. INGEOMINAS, 1998; Correa, 1992; Rangel-Buitrago and Posada 2005; Correa and Vernetta, 2004). The highest shoreline retreat rates have been recorded for the departments of Cordoba and Atlántico, with -56.6 and -29.5 m·yr⁻¹ respectively. Other sectors maintain rates between -1.7 (urban areas of Cartagena) and -4 m·yr⁻¹ (Riohacha beaches). In the Magdalena Department, where this study is located, maximum rates of -15 m·yr⁻¹ have been observed (sector Ciénaga- Tasajera) (INGEOMINAS ECOPETROL ICP, INVEMAR, 2008).
In contrast with this generalized erosive trend, accretion was observed for the beaches of the Tayrona-NNP. Thus, for the period 1958-2004, despite erosive processes were identified in the adjacent beaches, reaching average values of -3.23 m yr⁻¹, the beaches of the Tayrona-NNP showed relative stability and even accretion, with a maximum value of 0.97 m yr⁻¹ (Rangel-Buitrago, 2008).

The present study shows that this accretion trend resulted more expressive for the period 2002-2018, with a maximum rate of 13.69 m yr⁻¹ for Arrecifes Beach. On the other hand, the beaches of Cañaveral and Piscina presented erosion. A technical report presented by INVEMAR (2016) also identified a greater regression on the beaches of Cañaverale and Piscina, where an escarpment formed by a small terrace recoiled considerably.

Analysis of the factors that trigger these processes, such as the identification of sediment sources, their redistribution or transportation, as well as losses due to extreme events and anthropic pressures is essential to understanding these sedimentary trends of the beaches.

The sediment input can be evaluated by the size of the drainage basin of the rivers that reach the beaches. The largest drainage basin in the study area is for the Piedras River, which supply sediments to the eastern margin of Cañaveral Beach.

Redistribution of sediments is mainly due to coastal currents induced by waves. In the study area, these coastal currents predominate towards the west (Morales, 2001), promoting significant sedimentary input from the Piedras River mouth to the whole Cañaverale Beach, as well as for the other analyzed beaches. The geomorphology of the beaches of the Tayrona-NNP is presented as embayments with rock headlands at its ends, being that the accommodation space for each of the beaches varies with bathymetry. Then, the filling of the beaches follows a trend from East to West, after the predominant littoral drift direction. Arenilla Beach presents accretion trend and accretion could begin shortly in Piscinas Beach.

Cañaveral Beach has stability, erosion and accretion associated with meteorological events. As a result, the sediment bypass to Principe San Felipe and La Guamarra beaches provides variable rates of erosion and accretion, with a general accretion trend. The beaches of Arrecifes and Arenilla have the highest rates of accretion, without erosive periods. This indicates that the sedimentary input is continuous, both by the littoral drift and by the drainage basin.

Piscina Beach, the western most beach, is the only one that presents an erosion trend and the presence of an escarpment. It also presents a more dissipative beach profile when compared to the other beaches analyzed. It evidences the arrival of swellwaves that erode the backshore and impact on the cliff back.

Since 1980, the strongest wave events affecting the coast of the Magdalena Department, where the beaches of Tayrona-NNP are located, occurred during the passing of Hurricanes Joan (1988) and Lenny (1999), with significant wave heights reaching or exceeding 6 m. Between 2000 and 2009 five other extreme events with significant wave height (up to 5.4 m) reached this coastal stretch (Rangel-Buitrago, 2008). In 2016 the passing of Hurricane Matthew caused heavy precipitation and strong wave heights, with waves that contributed to erosion in most of the beaches, except for Arrecifes and Arenilla beaches, which maintained their accretion trend.

On the other hand, the biennium 2010/2011 was marked by a strong La Niña event, in which November and December 2010 recorded a much higher rainfall than average one (IDEAM, 2018). It resulted in a large sedimentary input.

Human activities in the area can produce disturbances in the sedimentary processes, for instance in the sedimentary input through the drainage basin. The human occupation of the Tayrona-NNP is very low, although it has presented in the last 30 years increase of beach tourist activities. Nevertheless, local activities such as the use of horses (about 200-250 animals) for access to the park may be generating sediment remobilization.

The development of tourism activities on the Colombian beaches constitutes an important component in the economy and culture of the country’s population. To increase the productivity of this sector, in the last decades the promotion of beach recreational uses for domestic and foreign tourists has been encouraged. However, the high demand for tourism and its poor management and control have caused many of the beaches to undergo a process of deterioration, thus considering tourism as an environmental tensor (INVEMAR, 2016). It would be advisable a more detailed analysis of the horses routes, their location and impact for the management plan of the park.

CONCLUSIONS

This study shows that during a period of 16 years (2002-2018), beach accretion is dominant on the eastern sector of the Tayrona-NNP. These accretion trend are the result of different factors such as: i) an effective sediment supply from the Piedras River, flowing in the eastern margin of the study area; ii) an effective littoral drift towards the west by the coastal currents, with sediment bypassing across the small headlands limiting the beaches, iii) an increase of sediment inputs during La Niña events; iv) a low impact of human activities, despite the effect of horse routes for tourism need to be better analyzed. In summary, the maintenance of natural inputs of sediments and the resilience of the beaches to the low impact of extreme events (i.e. hurricanes), combined with a low human pressure permit a good sedimentary budget for the beaches. On the other hand, Piscinas Beach is the most cut off from fluvial sediment input, and despite it has a coral reef barrier, its dissipative profile indicate that it is the most exposed to wave impact.

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