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Shoreline changes between 1954 and 2007 in the marine protected area of the Rosario Island Archipelago (Caribbean of Colombia)

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ABSTRACT

Aerial photography and satellite imagery analysis (1954–2007) have enabled the assessment of the changes in the net insular zones and the morphological adjustment processes of the Rosario Island Archipelago over last 50–55 years (Grande Island, Rosario Island, and Tesoro Island). Significant erosion was observed (>3% of the initial area) as a result of the morphodynamic imbalance of the insular system. The Grande, Rosario, and Tesoro Islands have lost 6.7%, 8.2%, and 48.7% of their territory, respectively. Data indicate an inverse relationship between the size of the island and the magnitude of the erosion. Erosive processes were detected along ~85% of coastline exposed directly to NNE–NE waves. The erosive activity on the archipelago has been constant for the last 50 years as consequence of continual wave action and rising sea levels. However, anthropogenic intervention has caused significant changes to the geomorphologic setting of the coast, which creates different morphologic outputs for the erosive processes.

1. Introduction

1.1. Background and scope

Coastal erosion has emerged in recent decades as one of the most pressing environmental problems for Caribbean coral islands and has become a direct threat to both their physical and biological sustainability as well as to tourism, which is the primary economic activity for most of these islands (PNUMA, 2009). The erosion of the Caribbean islands can be fundamentally attributed to natural factors, such as rising sea levels, temporary surges, and hurricanes, as well as to anthropogenic factors, such as sand mining, rapid coastal development, and poorly planned sea defenses (Burke et al., 2001; Cambers, 1998). The studies that have been conducted to evaluate the morphological response of coral island areas to global climate change can be classified into two large groups. The first group uses the formation of these islands during the Holocene as an analog of their response to future global changes to establish relationships between the growth of reef systems, sea level, and the configuration of the island systems (e.g., Dickinson, 1999; Kench et al., 2005; Martínez et al., 2010; Woodroffe and McLean, 1992). Other studies focused on analyzing the geomorphological characteristics of the islands to determine their resistance to external factors, which varies with properties such as the topography, configuration, and degree of sedimentary lithification (e.g., Woodroffe, 2008; Woodroffe and McLean, 1993; Yamano et al., 2007). However, these studies did not include detailed assessments of the current morphodynamics of the island areas or consider the magnitude and type of morphological changes expected in the short term (Webb and Kench, 2010). Coral island areas are dynamic systems capable of reorganizing their sedimentary reserves in response to changing limit variables, such as the wind, wave regime, sea level, and human intervention (Kench et al., 2009).

Despite both substantial evidence of the presence of morphological changes documented in the early 1990s and the vulnerability of Caribbean island areas, particularly marine protected areas,

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to changing sea levels, climate, and human intervention (Burke et al., 2001; Cambers, 1998), only a few studies quantifying these morphological changes on the same time scale as the natural variations and increasing human intervention currently exist (Kench and Harvey, 2003; Webb and Kench, 2010). This study presents data on changes in the coastline of the Rosario Island Archipelago (1954–2007), which was declared a National Park in 1977 for its biodiversity and ecological importance to Colombia, and seeks to examine whether this system shows morphodynamic imbalances as a result of factors such as the wave patterns, rising sea levels, or increasing human interventions by analyzing the net changes in the island areas and morphological adjustment processes over the last 50–55 years. Although the Archipelago consists of 27 islands, the analysis focused on the Grande, Rosario, and Tesoro Islands (Fig. 1), which were selected for their physical (size), geomorphology (the existence of sandy beaches), environment (the presence of vulnerable ecosystems and protected areas), and socio-economic (human settlements and tourism) characteristics.

1.2. Study area: Rosario Island Archipelago (Colombian Caribbean)

The formation of the Islas del Rosario Archipelago was linked to tectonic activity of the Sinú and San Jacinto fold belts and to Holocene fluctuations in sea level (Leble and Cuignon, 1987; Vernette, 1989). According to Cendales et al. (2002), during the Pleistocene, mud diapirism and plate tectonics elevated the continental shelf and extended the photic zone where the first coral structures formed. During this period, fluctuations in the sea level were significant and eroded these structures during regressions while forming various terrace levels during transgressions. As a result of this formation process and the actions of short-term coastal agents, three primary geomorphological units formed together within the archipelago: (1) fringing reefs, (2) marine terraces, and (3) emerged areas (islands) (Cendales et al., 2002). The fringing reefs are separated from the island coastline by narrow, shallow channels with bottoms covered by calcareous sands and gravel. Additionally, two terraces have been identified; the first is located at a depth of approximately 9–12 m and the second between 20 and 25 m. Both have served as the support and substrate for coral formations (Cendales et al., 2002). Most of the Archipelago is comprised of reef terraces (~60% of the coastal strip) formed during the last Quaternary marine transgression (Leble and Cuignon, 1987). This geological configuration has created extensive horizontal cliffs with heights ranging from 1.5 to 5.0 m that are primarily composed of gravels and calcareous stones cemented into a matrix of medium to coarse sands. Therefore, the substrate of these terraces is characterized by the high porosity, high permeability and weak cohesion of its constituent materials (Fig. 2). The total length of the beaches on both Rosario and Tesoro Islands (the protected areas) has been estimated at 0.19 km and 0.30 km, respectively (Castro et al., 2010). However, less extensive beaches have also been observed ($\leq$50 m in length) in disturbed areas, such as Grande Island (Fig. 2).

The Archipelago's marine dynamics are influenced significantly by how both the intensity and seasonality of the trade winds effects wave propagation in the shallow waters and rising sea levels. The significant wave height regime in the Archipelago varies between 0.1 and 2.5 m, while the peak period regime varies between 2.8 and 14.0 s. Most of the year (November–July), the archipelago wave system is dominated (72%) by the presence of swells from the north–northeast (NNE) (Fig. 3), which have average heights and periods of 0.71 ± 0.4 m, and 6.3 ± 1.7 s, respectively; between August and October, waves from the southwest (SW), west–southwest (WSW), and northwest (NW) are also frequent and account for 25% of occurring waves (Fig. 3) (Restrepo et al., 2012). This seasonal change in the wave direction coincides with a decrease in their significant height, with the lowest values occurring each year between August and October ($\leq$1.5 m), whereas the most energetic waves occurring from November to July have significant wave heights in excess of 2.0 m (Fig. 3) (Restrepo et al., 2012). The tide in the archipelago is mixed but is primarily diurnal and maintains a tidal range, which varies between 0.32 m and 0.17 m during spring and neap tides, respectively, and averages ~0.25 m (Molares, 2004). The data recorded by the GLOSS program *(Global Sea Level Observing System)* at the Cartagena station (1949–1992) show a progressive rise in the mean sea level with a rate of 3.8 mm y^{-1} between 1950 and 1970 and 5.6 mm y^{-1} between 1970 and 1990 (Fig. 3) (GLOSS, 2010); according to these data, the Rosario Island Archipelago may have had an approximately 19 cm rise in the relative sea level over a 40 year period.

The Rosario Island Archipelago houses marine (coral reefs, seagrass) and coastal (mangroves, tropical dry forest) ecosystems with high biodiversity and biological productivity. These ecosystems form a natural corridor, which is essential for migration of species of ecological importance (PNNCRSB, 2006). Hence, a marine protected area of 420 km^2 was delimitated in the Archipelago as National Natural Park in 1977. This natural park comprises the 82% of coral species in Colombian's Caribbean Sea. The islands of Rosario and Tesoro were also included as protected areas as both are important for nesting of turtles and birds (Castro et al., 2010). Several institutions are involved in the Archipelago management. The Unidad Administrativa Especial de Parques Nacionales Naturales (Management Unity of National Natural Parks – UAESPNN) is responsible of surveillance, monitoring, and conservation of protected areas; CARDIQUE (Regional Environmental Agency) holds the environmental authority in the emerged areas that are not part of the natural park, but are located in the archipelago; the Colombian Institute of Rural Development (INCODER), holding legal authority, manages the properties located in the islands; the Maritime General Directorate (DIMAR – Direccion General Maritima) controls the public goods in the intertidal flats, maritime traffic and navigation pathways; and finally, the local government authority (Municipality of Cartagena) promotes tourism in the archipelago (PNNCRSB, 2006).

The development of tourism in the archipelago consolidated in the mid 1970s when the first evidence of environmental deterioration began to appear (Werding and Sánchez, 1979). Since then, an increase in coral diseases, a loss of biodiversity, and a decline in seagrass beds, mangroves, and coral have all been reported (Cendales et al., 2002; Restrepo et al., 2006; Werding and Sánchez, 1979). The archipelago is currently one of the most popular tourist destinations in the Colombian Caribbean. The number of visitors grew by 30% over the last five years from 220,485 tourists in 2005 to 286,962 tourists in 2009 (Castro et al., 2010). Eighty percent of the island territory is dedicated to tourism, and thus the majority of the island population (close to 720 people) is dedicated to this activity (85%). Grande Island has 150 properties, which includes hotels and cottages, that house an average floating population of 3000 visitors each month, primarily during the months of greatest tourist activity (Castro et al., 2010). This tourism boom has led toa growing demand for sand, aggregates, and mangrove wood for both construction and the modification of various topographic profiles as well as increased activity in the reef areas (fishing, diving, and snorkeling). Even though both Rosario and Tesoro Islands have been classified as protected zones since 1977, which prohibits all human disturbances except for artisanal fishing without gear, scientific research, and environmental monitoring, these islands have been affected by the periodic removal of sand to create artificial beaches in other areas of the Archipelago (PNNCRSB, 2006).

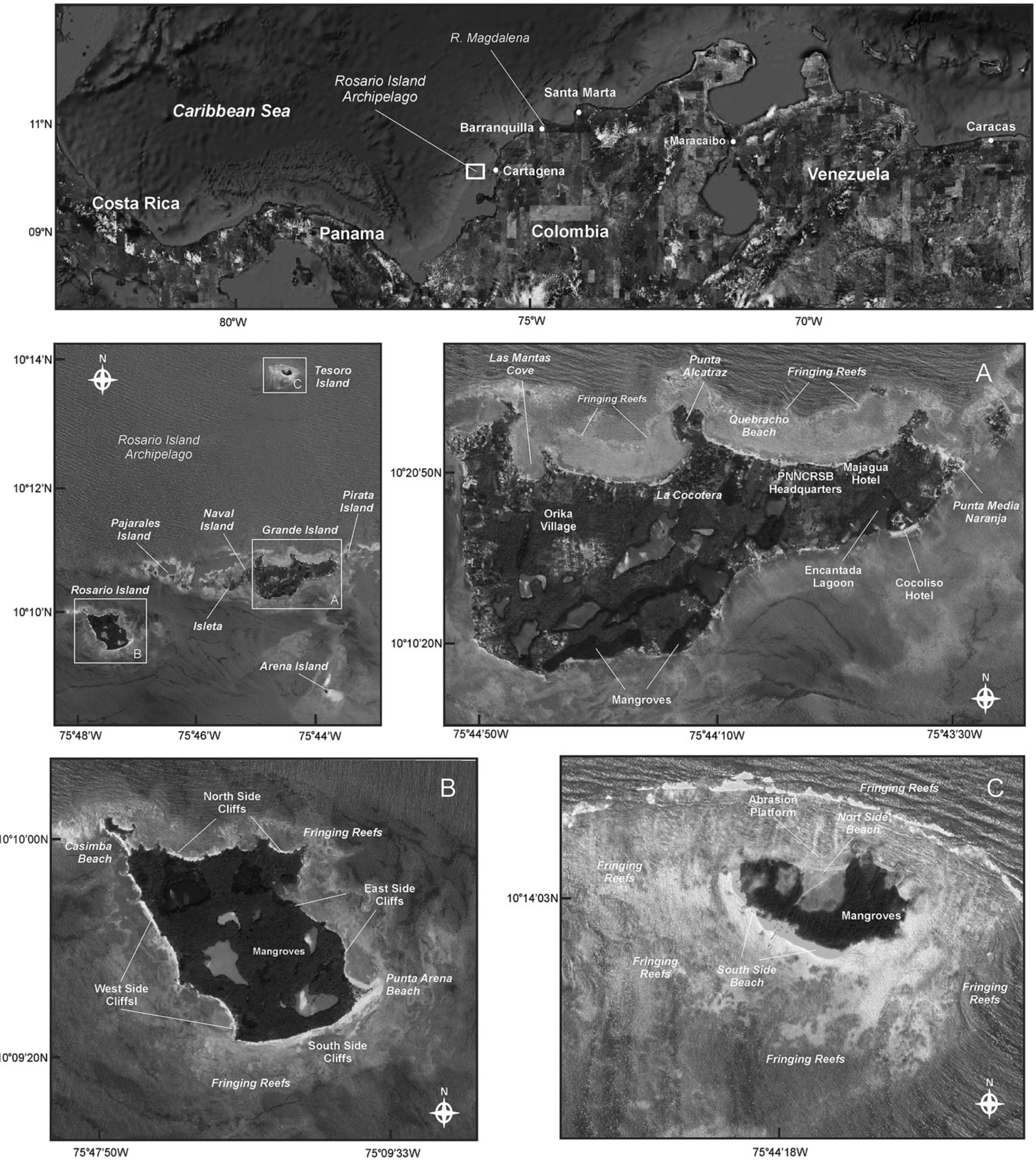

Fig. 1. Macro and general locations of the Rosario Island Archipelago (Colombian Caribbean): (A) Grande Island, (B) Rosario Island, and (C) Tesoro Island.

2. Materials and methods

A comparative historical analysis of aerial and satellite images was conducted to measure any changes in the coastlines of Rosario, Tesoro, and Grande Islands (Fig. 1). Although the analyzed period was the same for all three islands (1954–2007), the comparison intervals were defined in terms of the coverage and availability of aerial photographs (Table 1). Tesoro and Rosario Islands are largely untouched by humans (protected marine and terrestrial areas), while Grande Island has the largest population and most tourism in the Archipelago (Castro et al., 2010). This difference allows for a comparison of the magnitude and dynamics of erosion processes between protected island zones and areas disturbed by humans.

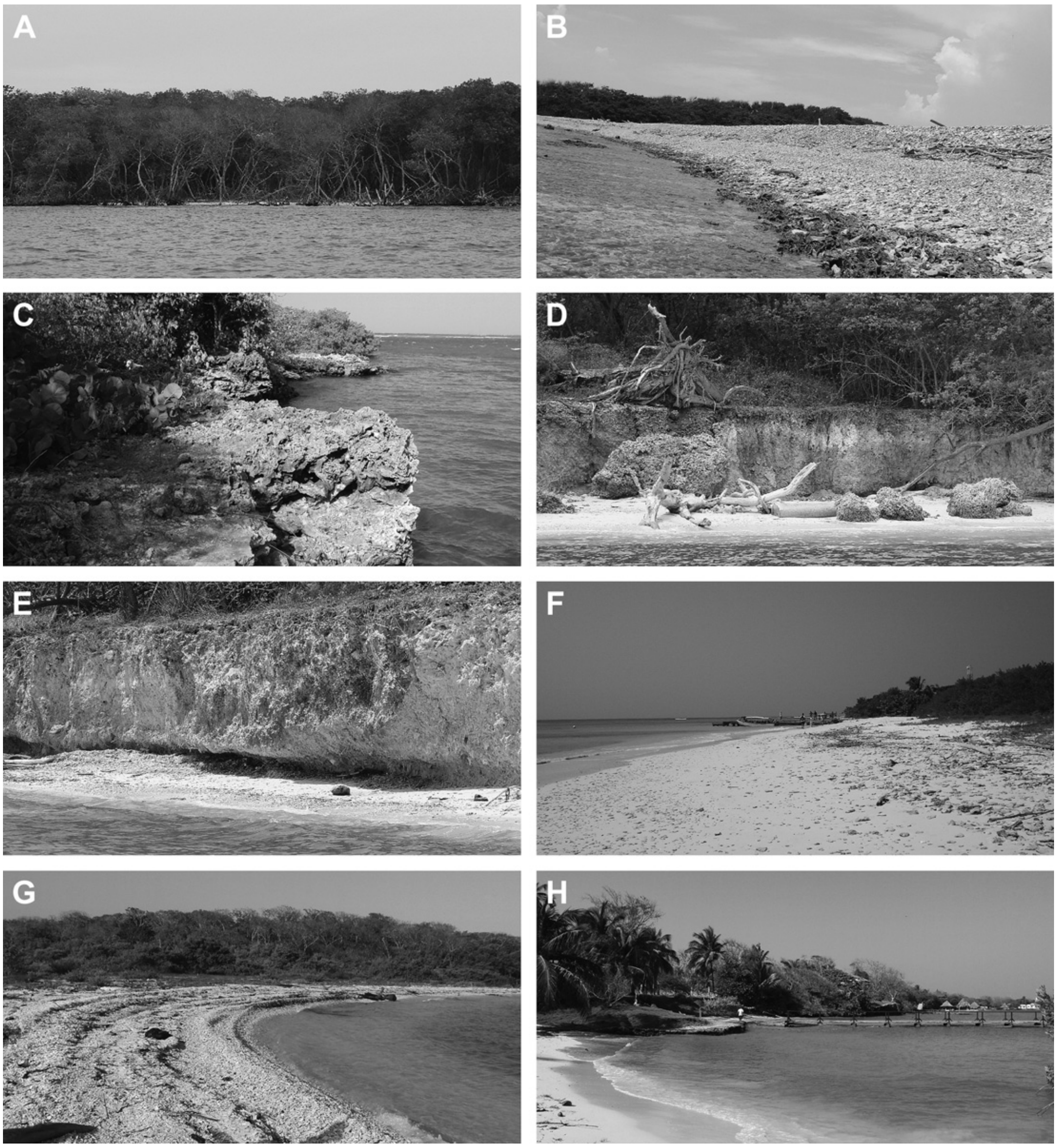

Fig. 2. Major coastal systems of the Rosario Island Archipelago: (A) mangrove areas, (B) both abrasion platforms and, gravel beaches (C) emerged terraces, (D, E) both cliffs and pocket beaches, (F, G) beaches in protected emerged zones, and (H) both beaches and emerged areas affected by humans.

All aerial photographs had a scale of ≤1:18,000 and were scanned at a minimum resolution of 900 dpi. The software programs *ArcGis 9.3* and *ESRI (Environmental Systems Research Institute)* were used for the image rectification and georeferencing with georeferenced satellite images (IKONOS) used as a source of ground control points and the WGS 84 coordinate system used as the reference. Each image was verified by comparing the georeferenced satellite images to historical images rectified from reliable ground control points (e.g., Graham and Koh, 2003; Thieler and Danforth, 1994). This process was repeated until the error between the satellite and aerial imagery was a result of their spatial resolution rather than systematic errors caused by the position of the control points (Moore, 2000). These errors were primarily caused by the spatial resolution of the satellite image (IKONOS: ~4 m); therefore, changes in the position of the shoreline of approximately ±3% were not considered significant and reflected a morphodynamically stable system (e.g., Webb and Kench, 2010).

The processed images were superimposed to determine the historical changes in the shoreline of each island and identify areas of erosion and accretion. The coastline was defined as the land–sea connection, which was expressed as the instantaneous sea level at the moment the aerial photograph was taken. Finally, any changes in the area of the islands were calculated and compared to establish the variability over time in terms of their size, configuration, and morphology.

3. Results and discussion

3.1. Historical changes in the coastline: evolution and morphological adjustments

Between 1954 and 2007, Grande, Rosario, and Tesoro Islands experienced a total reduction of 28.3 ha, which represents 8.6% of the total area analyzed (Table 2). All of these islands experienced significant erosion (>3% of initial area) as a result of morphodynamic imbalances in the island system. Grande, Rosario, and Tesoro Islands lost 6.7%, 8.2%, and 48.7% of their territory, respectively (Fig. 4 and Table 2), with an inverse relationship between their size

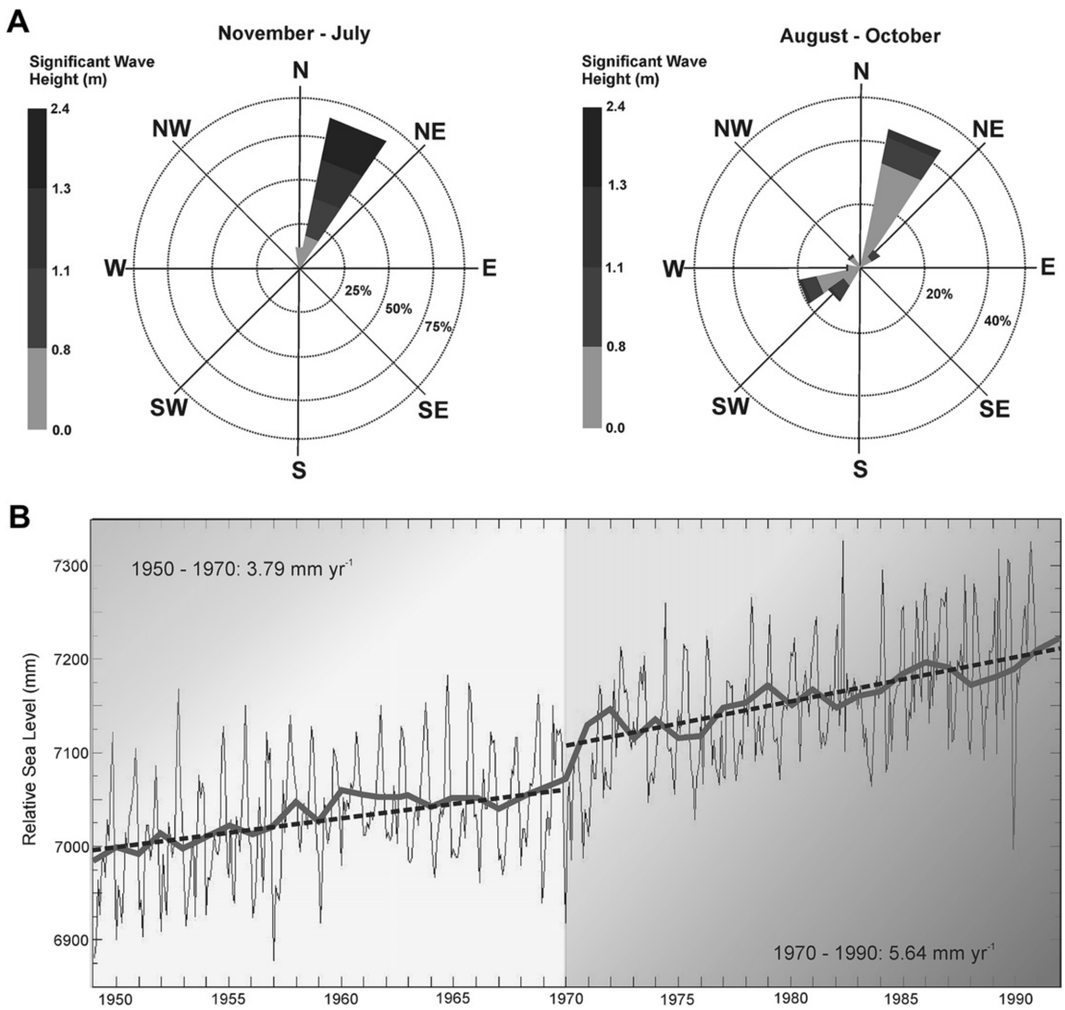

Fig. 3. (A) Indicator of direction and significant wave height for the periods from November to July and August to October; (B) relative sea level time series for the Cartagena station (thin line: monthly values, thick line: annual values; dotted line: historical trend) (adapted from Restrepo et al., 2012).

(ha) and the magnitude of erosion (%). Rapid erosion was also observed in small islands in the Central and South Pacific, as a result of short-lived storm and interannual sea level changes. These small islands showed to be less prone to achieve morphological adjustment, and thus underwent greater net sediment loss (Solomon and Forbes, 1999; Webb and Kench, 2010). Our data indicate that the islands of the Archipelago experienced various morphological adjustments between 1954 and 2007. The magnitude and type of the observed changes differed for each of the islands throughout the period of analysis (Fig. 4 and Table 3). On Grande Island, a balance between the erosional and sedimentary processes was observed between 1954 and 1976 (Table 3), which was a period dominated by the redistribution of sediment from erosive areas to accretion zones that resulted in no net loss of the sedimentary material in the system (Fig. 4). However, since 1976 a significant increase in erosion has led to an imbalance in the coastal dynamics, especially for the northern cliffs and southwestern coastal mangrove areas of the island (Fig. 4). The magnitude of erosion on Rosario Island was greater between 1954 and 1963 than between 1963 and 2007 (Table 3). Initially (1954–1963), erosive processes were found throughout the entirety of the island except for the northern cliffs, where there was a significant accretion area. The amount of erosion decreased significantly from 1963 to 2007 in the southern and eastern portions of the island, while noticeable erosion and accretion processes occurred in the north and west, respectively (Fig. 4). Tesoro Island experienced the most dramatic erosion, and the area of this island decreased from 11.1 ha to 5.5 ha between 1954 and 2007, a reduction of approximately 50% of its

Table 1
Location, principal morphological characteristics and time period of available information for the island areas included in the morphodynamic analysis.

Island	Location		Morphological characteristics			Information	
	Latitude	Longitude	Length (km)	Width (km)	Area (ha)	Aerial photography	Satellite image
Grande	10°10′40N	75°44′10W	2.47	1.25	200.2	1954, 1976	2007
Rosario	10°09′40N	75°47′23W	0.97	1.12	95.2	1954, 1963	2007
Tesoro	10°14′03N	75°44′18W	0.23	0.14	5.7	1954, 1987	2007

Note: Length = the length of the major axis of the island parallel to the coast; Width = the average width; Area = calculated from the 2007 satellite image.

Table 2
Summary of changes in the areas of the islands between 1954 and 2007.

Island	Initial area 1954 (ha)	Final area 2007 (ha)	Lost area (ha)	Lost area (%)
Grande	214.6	200.2	14.4	6.7
Rosario	103.7	95.2	8.5	8.2
Tesoro	11.1	5.7	5.4	48.7

initial size (Table 2). Erosive processes were severe across the entirety of the island except for the eastern side, which consisted of emerged terraces that remained stable. The northern and western fore-reef terraces were transformed into a broad abrasion platform (Fig. 4), which currently affects the dissipation and wave diffraction processes. Since 1987, the magnitude and rate of erosion has decreased dramatically because a significant deposition of sediment onto the southern beach of the island made accretion the dominant process between 1987 and 2007 (Table 3).

The net changes in the island areas generally mask the variability of their surface morphological configurations, which reflect the positional adjustments of the island systems (Webb and Kench, 2010). The analysis of these surface morphological changes indicates that the entire coastline experienced various positional adjustments as a result of both morphodynamic processes and human intervention throughout the period analyzed (Figs. 4 and 5). Erosion processes were detected for ~85% of the coastline exposed to direct NNE–NE wave action, which receives the largest proportion of the marine energy received by the island system. In most cases, displacements of more than 10 m occurred, and sectors such as Quebracho (0.96 m y^{-1}), La Cocotera (1.12 m y^{-1}) and Media Naranja (1.41 m y^{-1}) on Grande Island as well as North Beach on Tesoro Island (1.04 m y^{-1}) experienced significant retreat rates between 1954 and 2007 (Figs. 4 and 5). In contrast, coastlines exposed to the less energetic waves from the WSW–SW experienced marginal retreats of less than 5 m except for in the western and southern cliff areas of Rosario Island, which had retreat rates of approximately 0.68 and 1.81 m y^{-1}, respectively (Fig. 4). Although coastline regression was the dominant process between 1954 and 2007, the processes of contraction–displacement, contraction–expansion, and coastline elongation were also identified. For example, between 1954 and 2007 the nodal point of Casimba Beach moved approximately 27 m, while the maximum width of the beach reduced drastically from 51 m to 24 m (−0.51 m y^{-1}); if this trend were maintained, the sandy beach could disappear in the

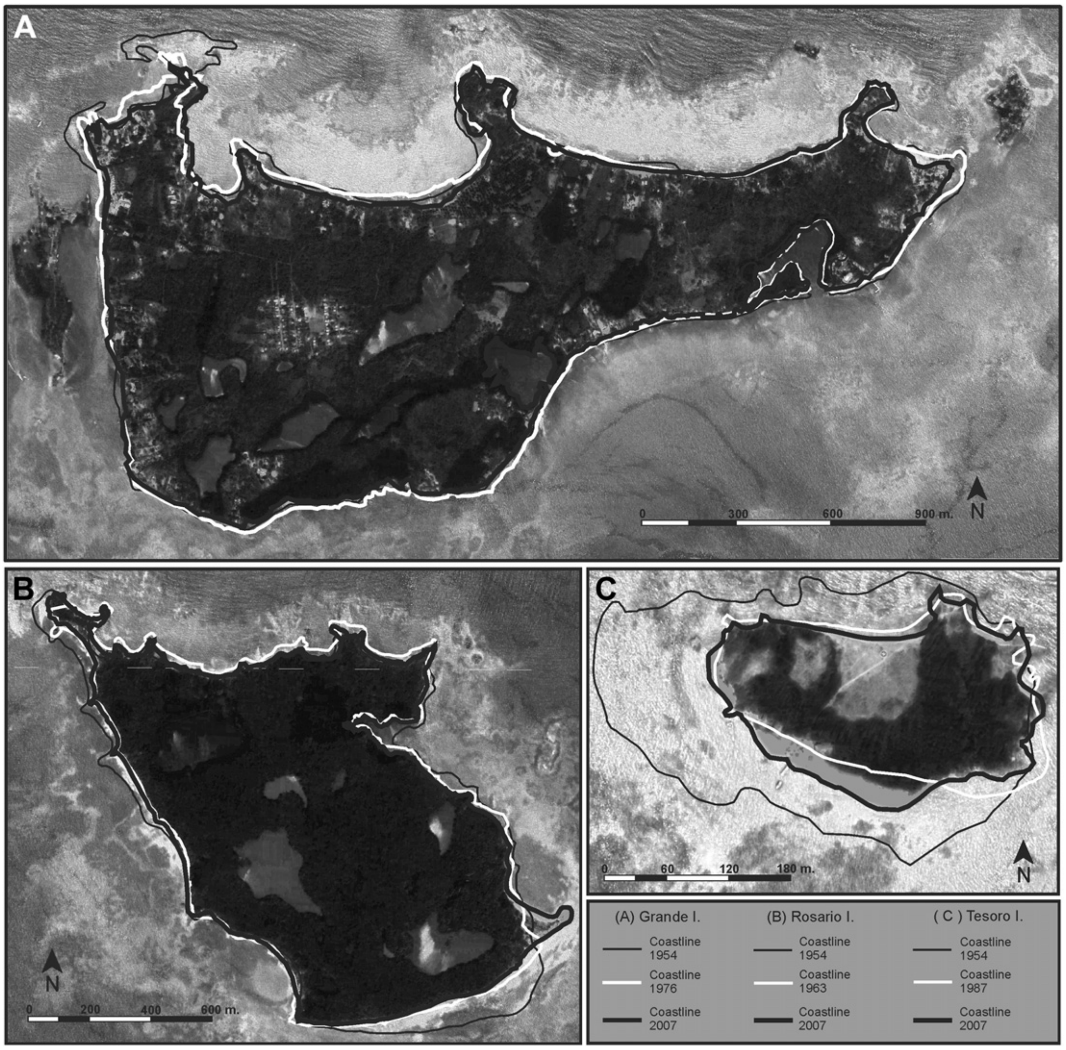

Fig. 4. Historic shoreline changes (1954–2007) on (A) Grande Island (1954–1976–2007), (B) Rosario Island (1954–1963–2007) and (C) Tesoro Island (1954–1987–2007).

Table 3
Magnitude of both the erosion and accretion processes for Grande, Rosario, and Tesoro Islands between 1954 and 2007.

Island	Period											
	1954–1963, 1976, 1987[a]				1963, 1976, 1987[a]–2007				1954–2007			
	Erosion		Accretion		Erosion		Accretion		Erosion		Accretion	
	Mag. (ha)	Rate (ha y^{-1})	Mag. (ha)	Rate (ha y^{-1})	Mag. (ha)	Rate (ha y^{-1})	Mag. (ha)	Rate (ha y^{-1})	Mag. (ha)	Rate (ha y^{-1})	Mag. (ha)	Rate (ha y^{-1})
Grande	8.35	0.38	8.37	0.38	13.37	0.43	3.27	0.10	15.23	0.28	3.49	0.07
Rosario	9.54	1.06	4.07	0.45	5.03	0.11	2.01	0.05	11.04	0.20	2.55	0.05
Tesoro	5.75	0.17	0.16	<0.01	0.55	0.03	0.74	0.04	5.46	0.10	0.05	<0.01

Mag.: Magnitude.
[a] 1963 = Rosario Island, 1976 = Grande Island, 1987 = Tesoro Island.

medium term and leave an islet (stacks) in the far north (Fig. 5D). South Beach on Tesoro Island retreated at a rate of 1.41 m y^{-1} between 1954 and 1987; however, the period from 1987 to 2007 was characterized by both the deposition of thick, granular sediments (sands and gravels) and the progressive expansion of the shoreline (1.28 m y^{-1}), which ultimately recovered approximately half of its original width (Fig. 5F). One of the most significant changes occurred in Punta Arenas (Fig. 4) where a ~135 m gravel spit formed over 44 years (~3.06 m y^{-1}) and created an elongated endpoint in the southeast of Rosario Island (Fig. 5C).

3.2. *Contribution of morphodynamic agents: sea level changes and wave regime*

This study presents an analysis of the morphological changes in three islands over a 54 year period. Instrumental records from this time indicate the relative sea level increased at least 19 cm (Fig. 3: 1950–1970 = 3.8 mm y^{-1}, 1970–1990 = 5.6 mm y−1). The interactions of both this rise in sea level and the wave variability with either coral or fringing reefs have been identified as the primary controlling mechanism of the morphodynamic stability of the coral island environments (Dickinson, 1999; Sheppard et al., 2005; Dawson and Smithers, 2010; Webb and Kench, 2010). The increase in the mean sea level and reduction in the extent of the fringing reefs lead to an increase in the average depth of shallow waters, which increases the penetration of waves through the reef and the energy acting on the coast. In this context, the predicted morphological response is the erosion of the coastline experiencing the greatest wave energy under these conditions. Both the elevation and width of the fringing reefs are important influences on the geomorphological activity, as they determine the frequency that wave energy can propagate through the reefs and the relative degree of dissipation that may occur across the bottom (Sheppard et al., 2005). The erosion process experienced by Grande Island has intensified over the past 30 years during which time the rate of the rising relative sea level has increase (Fig. 3) and the extent of the fringing reefs (Cendales et al., 2002; PNNCRSB, 2006), which currently reach a length of ~1.9 km along the northern sector, has reduced. It was estimated that the incident wave height on Grande Island could be reduced by up to 40% because of the dissipation effect stemming from the wave-breaking and bottom

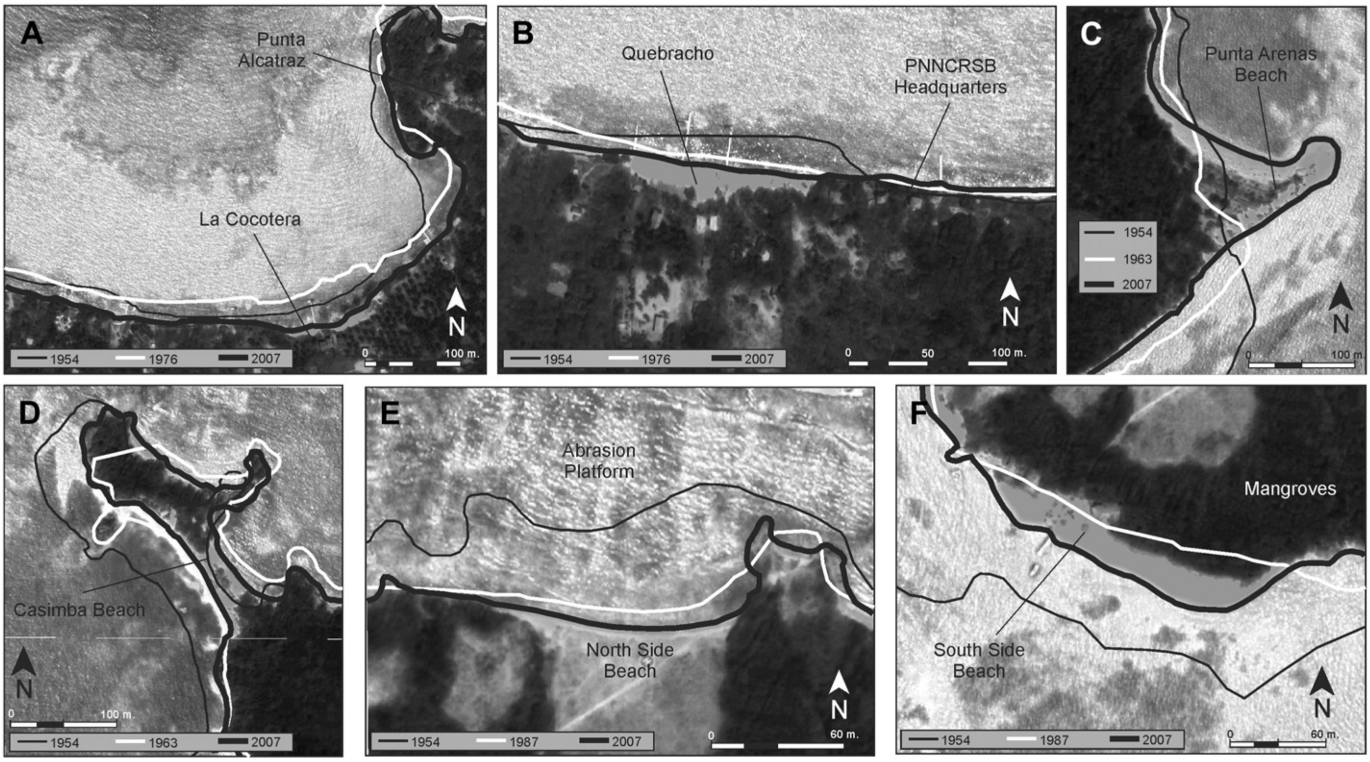

Fig. 5. Historical shoreline changes (1954–2007) at specific points within the Rosario Island Archipelago: (A) The Cocotera (Grande Island), (B) Quebracho (Grande Island), (C) Punta Arenas (Rosario Island), (D) Casimba Beach (Rosario Island), (E) North Beach (Tesoro Island), and (F) South Beach (Tesoro Island).

friction provided by these reefs (Restrepo et al., 2012). In the present case, the rising sea level and disappearance of fringing reefs has intensified the erosion of Grande Island (Fig. 4). However, this morphological response to the rising sea level does not necessarily imply a net reduction in the island area but usually involves morphodynamic adjustments (Kench et al., 2005; Webb and Kench, 2010). Although there was a marked increase in the rate of the rising sea level after 1970 (Fig. 3), there is no evidence of a significant reduction in the areas of Tesoro and Rosario after this date (Table 3); however, there have been notable contraction–displacement, contraction–expansion, and elongation processes for the coastline (Fig. 5). Unlike Grande Island, the fringing reefs of both Rosario and Tesoro islands cover a ~360° perimeter around the islands, have a lower disappearance rate (PNNCRSB, 2006), and reduce the incident wave height by up to 70% (Restrepo et al., 2012).

It has been observed that the seasonal variation of waves causes morphological changes in coastlines (Solomon and Forbes, 1999; Dawson and Smithers, 2010; Webb and Kench, 2010). For most of the year, waves from the NNE and NE impact extensive cliff areas on both Grande and Rosario Islands, gradually undermine their base and reducing both their support capacity and shear strength until they collapse because of gravity. This effect leads to the successive

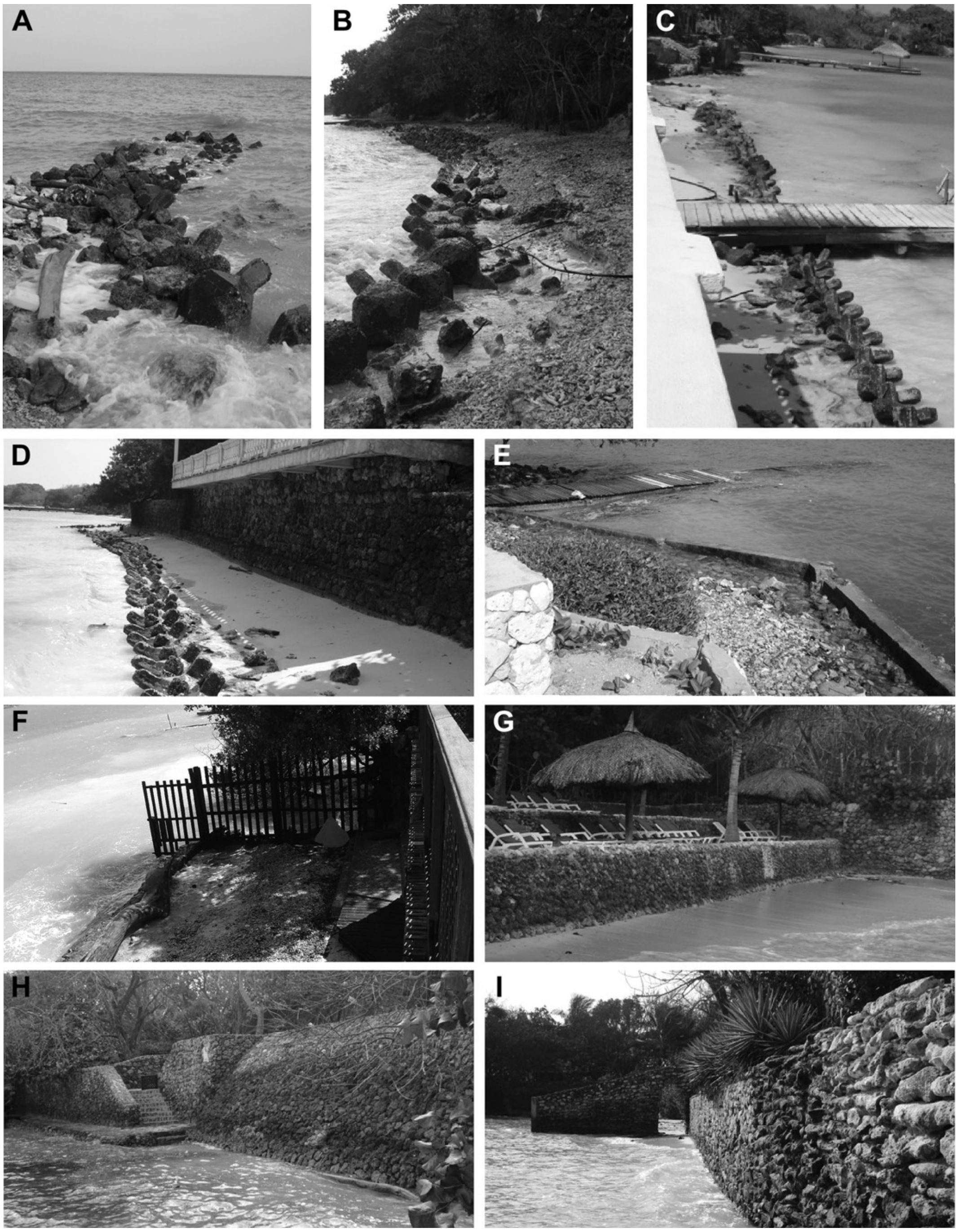

Fig. 6. Human structures and effects on the coast of Grande Island: (A) seawalls, (B) breakwaters (hexapods), (C) breakwaters (fill and dock), (D) breakwaters (retaining wall), (E, F) filled in intertidal zones, (G) both a retaining wall and artificially generated beach, and (H, I) retaining walls in the cliff areas.

regression of the cliff faces, which creates pocket beaches and gradually changes the coastline. The differences in erosion rates can be explained based on wave transformation processes in shallow waters (Restrepo et al., 2012) and the textural characteristics of the Archipelago cliff faces. For example, the cliffs on the western and southern sectors of Rosario Island demonstrated significant erosion rates (Fig. 4) even though they were impacted by waves with lower intensities and frequencies because these waves impact substrates with increased susceptibility to erosion as indicated by the present erosional landforms (stacks and islets). The transformation processes of waves in shallow waters generate the coastal currents responsible for sediment exchange on each of the analyzed islands. The action of these currents is further reinforced by the presence of narrow channels between the fringing reefs and the coastline (Restrepo et al., 2012). On Grande Island, there are east–west longitudinal currents that favor the deposition of sediments in western spits comprised of harder rock and the limited formation of pocket beaches. However, on Rosario and Tesoro Islands, the prevailing currents are north–south, which allows for the longitudinal redistribution and accommodation of sediments and promotes the morphological adjustments experienced by these systems (Fig. 5). For example, the diffraction process induced by the emerged terraces located in the extreme eastern and western zones of Tesoro Island, which generates intense longitudinal currents (Restrepo et al., 2012), contributed to the expansion–consolidation process experienced by the beaches located in the southern portion of the island (Fig. 5F).

3.3. Impact of human intervention and administrative aspects

Grande Island has experienced the greatest human intervention with the continual presence of both settlers and tourists, whereas both Rosario and Tesoro Islands are largely untouched areas where human intervention is restricted (PNNCRSB, 2006). Since 1976, the erosion rate has increased significantly on Grande Island (13.6%) to almost four times that estimated for accretion (Table 3). This imbalance has occurred over a period of time during which the coastline and coastal process dynamics have been significantly altered by human action. The construction and tourism booms that began in the 1970s throughout the Rosario Island Archipelago increased the demand for both beach sands and aggregates, the removal of coastal dunes, and the construction of coastal infrastructure. The absence of berms, escarpments, and dunes indicates that there are no sediment reserves that allow morphodynamic stability conditions to be achieved seasonally; therefore, a net loss of sediment occurs as a result of various transport processes and littoral drift. Various structures on the waterfront, such as breakwaters, seawalls, and fills on intertidal flats (Fig. 6) are poorly planned and have altered the magnitude and direction of nearshore currents as well as the dynamics of the littoral drift, which disrupts both the zonal sediment exchange and the morphodynamic balance observed from 1954 to 1976 when the accretion and erosion rates were virtually identical (Table 3). In contrast, on Rosario and Tesoro Islands, where neither human intervention nor infrastructure is allowed, erosion rates have declined by approximately 85% over the last few decades (Table 3).

The high amount of different institutions with interrelated functions in the same region (UAESPNN, CARDIQUE, INCODER, DIMAR, Municipality of Cartagena) has originated a lack of definition regarding legal authority over the natural park and its buffer zones (PNNCRSB, 2006). The weak coordination of inter-institutional efforts and the incipient interaction with settlers have allowed the proliferation of coastal manmade structures and the rapid growth of tourism. Even though coastal structures have been forbidden since 1996, there are more than 100 structures among breakwaters, seawalls, and fills, in only ~4.6 km in the northern side of Isla Grande (Fig. 6). These poorly planned and illegally built structures have altered littoral morphodynamics and disrupted the morphological adjustment processes. The growth of tourism has led to an increased demand for sand for artificial beaches, and thus to coral reef degradation as a result of water pollution and environmental stress (caused by excess snorkeling activities and maritime traffic). The coral reef coverage has an important role in the morphodynamical balance of small islands (Solomon and Forbes, 1999; Kench et al., 2005; Webb and Kench, 2010). In recent years the UAESPNN has carried out programs to prevent and mitigate coastal erosion (including the protection and regeneration of coral reefs), but the corresponding application have been hampered for its limited sphere of competence and technical capacity (PNNCRSB, 2006). Future management strategies to deal with erosion in Rosario Island Archipelago should focus in: (i) strengthening governance in the area with the coordinate support of all authorities, (ii) reducing the stress against protected ecosystems, (iii) promoting ecotourism with the active involvement of local communities, and (iv) implementing sustainable soft structures to mitigate erosion processes in critical zones, especially in areas of ecological importance.

4. Conclusions

The Rosario Island Archipelago has been consistently eroded over the past 50 years as a result of constant wave action and the progressive increase in sea level. Although the both geological origin and influence of the primary morphodynamic agents is similar on Grande, Rosario, and Tesoro Islands, the degree of human intervention experienced over the past 50 years on each island is different, which has significantly changed the geomorphological configuration of their coasts and, in turn, led to varying erosion dynamics. The morphodynamic equilibrium that characterized Grande Island between 1954 and 1976 was altered by the erosive processes that emerged from 1976 to 2007, which coincides with the period of greatest human pressure on the archipelago as characterized by the extraction of both sand and mangrove wood, the removal of both sand dunes and escarpments, and the construction of extensive coastal infrastructure. In contrast, because of their protected status, erosion on both Tesoro and Rosario Islands was more closely related to the combination of rising relative sea levels, persistent NNE–NE wave action, and ocean current circulation system dynamics. However, on these islands, the magnitude of the erosive processes declined over the last 30 years, and they experienced morphological adjustments rather than net area reductions. Although the magnitude of erosion has been greater on Grande Island, Tesoro, and Rosario Islands have been affected the most in terms of lost area, which indicates an inverse relationship between the island size and erosion magnitude. Moderate to high wave energy conditions are persistent throughout most of the year in the archipelago, which allows for direct impact on the coastal cliffs and generation of circulation systems favoring sedimentary transport to the channels that border the islands. The rise in the relative sea level has created conditions favorable to the exposing increased areas to the effects of waves and currents.

Historical analysis of air photos and satellite imagery, in addition to geological interpretation can provide a strong basis for assessment of erosion hazard. However, much of the coastal zone management strategies begin with inter-institutional and policy issues, and science as a secondary component. The high amount of different institutions with interrelated functions in the Rosario Islands has originated a lack of definition regarding legal authority over the natural park and its buffer zones. Lack of institutional coordination has created duplicity and inadequate assignment of functions, thereby preventing the management of marine coastal areas. In consequence, future management strategies should include strengthen governance in the area with the coordinate support of all authorities, reducing the stress against protected ecosystems (protection of fringing reefs), promoting sustainable ecotourism with the active involvement of local communities, and implementing sustainable soft structures, as effective means to diminish the magnitude of erosive processes in critical zones of the Archipelago, especially in areas of ecological importance.

Ethical statement

This kind of research does not require any ethical statement.

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