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SHORT-TERM EVALUATION OF THE RETREATING CLIFFS OF TIBAU DO SUL BRAZIL

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Abstract

The objective of this article was to employ geotechnology tools, such as the Digital Image Processing (DIP) of the QUICKBIRD high-resolution satellite, spatial analysis in Geographic Information Systems (GIS) environments and the statistics modules of the Digital Shoreline Analysis System (DSAS), to identify the coastal sectors containing cliffs in Tibau do Sul, Rio Grande do Norte (RN) state, Brazil, and quantify the retreat rates between 2003 and 2013. The results showed that about 34% of the shoreline of Tibau do Sul, dominated by cliffs, has retreated significantly. The greatest cliff retreat occurred in subsectors N2, C3 and S2, with a decrease of 1.5, 1.71 and 1.9m, respectively. The constant value (LR²) was unchanged in all cases and greater than 0.75, suggesting a linear erosive process throughout the decade analyzed. Thus, the tools and methods used are essential subsidies for identifying coastal erosive processes and developing instruments for the control and environmental management of the coastal zone.

Keywords: Geotechnologies; Coastal Erosion; DSAS.

AVALIAÇÃO DE CURTO PRAZO DA RETRAÇÃO DAS FALÉSIAS DE TIBAU DO SUL-RN

Resumo

O objetivo desde artigo foi empregar as ferramentas de Geotecnologias, como o Processamento Digital de Imagens (PDI) do satélite de alta resolução espacial QUICKBIRD, a análise espacial em ambientes de Sistemas de Informações Geográficas (SIG) e os módulos estatísticos do *Digital Shoreline Analysis System* (DSAS) para identificar os setores litorâneos assinalados por falésias marinhas no município de Tibau do Sul/RN, e quantificar as taxas de retração entre os anos de 2003 a 2013. Os resultados demonstraram que cerca de 34% da linha de costa do Município de Tibau do Sul, dominado por falésias, têm sofrido recuos expressivos. As maiores magnitudes de retração da borda das falésias ocorreram nos subsetores N2, C3 e S2, com recuo de 1,5m, 1,71m e 1,9m, respectivamente. O valor da constante LR² esteve mantido em todos os casos e foi maior que 0,75 sugerindo o processo erosivo linear instalado por toda a década avaliada. Deste modo, as ferramentas e métodos empregados servem como subsídios imprescindíveis aos estudos de identificação de processos erosivos costeiros e à construção de instrumentos de controle e gestão ambiental da zona costeira.

Palavras-chave: Geotecnologias; Erosão Costeira; DSAS.

Resumen

EVALUACIÓN A CORTO PLAZO DE LA RETIRACCIÓN DE ACANTILADOS DE TIBAU DO SUL, RN

El objetivo de este artículo fue emplear herramientas de Geotecnología, como el Procesamiento Digital de Imágenes (PDI) del satélite QUICKBIRD de alta resolución, el análisis espacial en entornos de sistemas de información geográfica (GIS) y los módulos estadísticos del *Digital Shoreline Analysis System* (DSAS) para identificar los sectores costeros marcados por acantilados marinos en el municipio de Tibau do Sul / RN, y cuantificar las tasas de retracción entre los años 2003 a 2013. Los resultados mostraron que alrededor del 34% de la costa del municipio de Tibau do Sul, dominado por acantilados, ha sufrido importantes retrocesos. Las mayores magnitudes de retracción del borde del acantilado ocurrieron en los subsectores N2, C3 y S2, con una disminución de 1.5 m, 1.71 m y 1.9 m, respectivamente. El valor de la constante LR² se mantuvo en todos los casos y fue superior a 0,75, lo que sugiere el proceso erosivo linear instalado a lo largo de la década evaluada. De esta manera, las herramientas y métodos utilizados sirven como subsidios esenciales para los estudios para identificar procesos erosivos costeros y para la construcción de instrumentos de control y gestión ambiental en la zona costera.

Palabras-clave: Geotecnologías; Erosión Costera; DSAS.

1. INTRODUCTION

Human habitation in coastal zones has always been on the fringe of spatial planning and corresponds to the region where nearly 25% of the world population lives (SMALL and NICHOLLS, 2003). The areas contiguous to the shorelines at altitudes of at least 10m above sea level account for around 2% of the world's land area, but 10 and 13% of the total and urban population, respectively (MCGRANAHAN *et al*., 2007). It is important to underscore that a high population concentration increases the risk of a relative rise in average sea levels and other dangers caused by the driving forces of coasts, amplified by the risks of climate change (NICHOLLS, 2004).

According to some estimates, sea cliffs represent more than 80% of the world's shorelines (EMERY and KUHN, 1982). In Rio Grande do Norte (RN) state, cliffs correspond to around 25% of the shorelines, from the municipality of Baía Formosa to the south on the east coast, to Tibau at the northwesternmost point on the north coast of RN (VITAL *et al*., 2018). The significant erosive events in some stretches of these cliffs on the eastern coast, the most populous of the state, have been studied for the last two decades by Amaral (2001), Severo (2005; 2011), Santos Júnior *et al*. (2011); Souza Júnior (2013), Taquez (2017), Vital et al (2018) and Camara *et al*. (2019), among others.

The wide variety of shorelines worldwide suggests the multiple processes involved in the formation of sea cliffs (EMERY and KUHN, 1982). Martime cliff erosion occurs from the complex combination between sub-aerial and marine processes, weakening the geological and structural integrity of the cliffs, causing gradual erosion and episodic gravitational and material transport movements (TRENHAILE, 1987; SUNAMURA, 1992). These processes include wave abrasion, the action of rain and wind, temperature variations, biochemical and biophysical erosion that promote the action of water and the physical and chemical weathering of the lithotypes contained in the cliffs (SUNAMURA, 1992; MASSELINK *et al*., 2003; TRENHAILE, 2016; EARLIE *et al*., 2017).

The erosive action on the cliffs often threatens the public and private infrastructures erected there and impacts the socioeconomic sectors that exploit the coast (GRIGGS *et al*., 2004). The continuous increase of human habitation in coastal regions has exacerbated coastal erosion problems and other globally relevant issues, which explains the significant attention in scientific studies and coastal management, primarily due to permanent land loss (MENTASCHI *et al*., 2018), resulting from the rising sea levels caused by global warming (BIRD, 2008; DAVIDSON-ARNOTT, 2010).

The hazards and risks for human activities on coastal regions with sea cliffs, due to the geotechnical instability inherent to these features, are a relevant challenge to coastal management and monitoring (CAI *et al.*, 2009). Information is scarce on slope stability, historical spatial distribution of landslides and the magnitude of coastal erosion, which are important indications of the potential of future landslides that help the decisions of local managers (FALL, 2009; SAROGLOU and ALEXANDROU, 2016). Active cliff instability can be summarized as a single erosive cycle consisting of four stages, according to Moore *et al.* (2010): the detachment of particles or blocks of material, transport of this material through the cliff system, its deposition on the foreshore slope and its removal by wave and tidal action.

The use of geotechnology tools has made it possible to analyze the temporal evolution of the types of coastal relief and quantify cliff retreat and landslide volumes on the slopes in different space-time scales, thereby enhancing coastal monitoring and, with this qualitative-quantitative information, strengthening analyses of the risks and dangers associated with coastal erosion (AMARO *et al*., 2012; WILLIAMS *et al*., 2017). The time series of remote sensing images of the coast, for example, have made it possible to record the dynamics of changes in use and occupation, establish the degrees of natural and environmental vulnerability, and quantify the erosive processes (KIRK, 1975; AL-TAHIR and ALI, 2004; BOAK and TURNER, 2005; DAHDOUH-GUEDES *et al*., 2006; AMARO *et al*., 2012, BUSMAN *et al*., 2014; CAMARA *et al*., 2019).

In this respect, the aim of the present study was to use geotechnology tools to identify and quantify cliff retreat in coastal regions of the municipality of Tibau do Sul, Brazil between 2003 and 2013.

2. METHODOLOGY

The methodological development involved characterization of the study area with a view to evolutionary analysis between 2003 and 2013, using high spatial resolution digital imaging processing (DIP), identifying the shorelines in a geographic information system (GIS) environment and spatial analysis with Digital Shoreline Analysis System (DSAS) software to quantify the average cliff retreat rates (THIELER *et al*., 2009; PRUDÊNCIO *et al.*, 2019).

2.1. Study area characterization

The study area corresponds to approximately 16km of the shoreline in the municipality of Tibau do Sul, on the eastern coast of RN, around 60 km south of Natal, the state capital (Figure 1). The sea coast exhibits climate conditions classified as a tropical dry summer zone (*As*) according to the Köppen-Geiger system

(ALVARES *et al*., 2013), with regular rainfall between March and August.

The continuous low intensity winds (average of 4.4 m/s) blow from the SE and are classified as trade winds. There is a regime of semidiurnal mesotides, with average spring and neat tide amplitudes of around 2.2 and 1.1m, respectively. Waves are predominantly ESE during all the seasons of the year, with an increase in waves from the E in summer. Heights range from 0.5 to 2.8m, with a predominance of waves under 1.6m, peak periods between 4 and 20s, with those under 8s prevailing. This set of factors generates continuous coastal drift that transports sediments from south to north.

This coastal sector contains rich ecosystems characterized by species of the Atlantic Forest, Restinga and Cerrado.

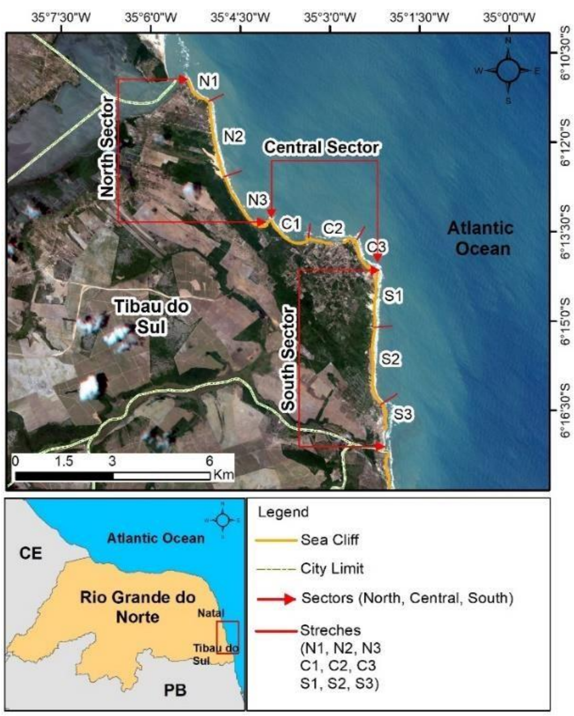

Figure 1 - Study area on the eastern coast of Rio Grande do Norte (RN) state, Brazil.

The eastern coast of RN is located in the geological context of the Natal Shelf, composed of the marginal sedimentary sub-basins of Canguaretama and Natal, located between the Alto de Mamanguape to the south and Alto de Touros to the north and its contiguous continental shelf, which is stratigraphically correlated with the Potiguar Basin (LANA and ROESNER, 1999; FEITOSA *et al*., 2002; BARBOSA *et al.*, 2007). The contact to the south is made with the Paraíba-Pernambuco Basin by the Mamanguape fault (BARBOSA *et al.*, 2007). Evidence from gravimetric and seismic maps and core samples from deep wells suggest that the crystalline basement of the Natal Shelf is shallower than that of the Paraíba-Pernambuco basin. The geodynamic evolution of these coastal basins from the Brazilian passive margin, formed in the separation between South America and Africa during the Mesozoic, and recent seismicity indicate that reactivations of Precambrian shear zones in the NNE-NE direction controlled rifting, sedimentary deposition and coastal morphology (FERREIRA et al., 1998; BEZERRA *et al.* 2001). In this tectonic context, the Natal Shelf features horst and graben structures running NE (40-60ºAz) and NW (300-320ºAz), limited by faults that affect the geological units of the basement, Cretacean units and the Barreiras Formation in the Miocene-Pliocene (BEZERRA *et al.*, 2001).

The sea cliffs of this study, delimited by the grabens of Guarairas to the north and the Cato River valley to the south (Figure 1), make up the edge of the horst, which forms the uplifted block including the flat-topped coastal tableland of the Barreiras Formation (BEZERRA *et al.*, 2001). The sedimentary lithotypes that predominate are conglomerates, sandstones and claystones, which expose continental depositional systems represented by intertwined alluvial and fluvial fan sediments, gradings for marine depositional systems. The tablelands are dissected by angular drainage patterns and covered by Quaternary units that include alluvial terraces and wind sediments (moving dunes and dunes fixed by vegetation, called grey dunes) and in the flat and low portions of the relief, by lake deposits from the Guaraíras Lagoon and mangroves, in addition to beach deposits and stretches of beachrocks parallel to the coast (BEZERRA *et al.*, 2001).

The intercalation between lithotypes from the Barreiras Formation predominant in the cliffs of the study area satisfies the variation in energy flows in the terrigenous depositional system, from the high-energy flows with levels of conglomerates and coarse sands (Figure 2A), including storms (Figure 2C), to the low energies with the deposition of fine sediments such as fine sands, siltstones and claystones (Figure 2B). In addition, old and recent gravitational deposits occur in different sectors of sea cliffs (Figure 2a), irrespective of the degree of anthropic pressure. These talus/colluvium deposits are limited to the base of escarpments, consisting of blocks of poorly selected rudaceous materials, characteristic of the mass movement of material from the Barreiras Formation cliffs (GOBBI and LADEIRA, 2011).

Wind deposits that cover coastal tablelands constitute the moving and grey dunes currently used for intensive agriculture. They consist of whitish quartz sands without plant cover in the more recent deposits and reddish ones in their older counterparts, due to the presence of clays and iron oxides (NOGUEIRA, 1975). In both types of wind deposits, sand particle size is well sorted and largely with average diameters.

Beachrocks are distributed parallel to the shoreline, varying from 10cm to 3.0m thick, dozens of meters wide and between meters or kilometers long, with slight dips towards the ocean. Beachrocks are composed primarily of sandstone lithofacies with a quartz matrix exhibiting low-angle grooved tubular-planar cross beddings, conglomeratic and bioturbated sandstones and massive sandstones, with carbonate cementation, deposited in an upper shoreface zone, but currently found in an intertidal zone (VIEIRA and DE ROS, 2006). Erosional features are found on beachrock outcrops, with dissolution in basins and kettles, pyramids separated by cracks and fractures suggesting tilting from gravitational landslides related to erosion and variation in relative sea level, since they receive the direct impact of the wave breaking pattern (BEZERRA *et al.,* 2001).

Beach deposists are extensive, narrow belts sloping slightly to moderately towards the ocean, facing the escarpments of the cliffs, consisting of quartz sands, heavy minerals, rock fragments and bioclasts (NOGUEIRA *et al*., 1990). In the rectilinear portions of the beaches, particle size varies from medium to coarse, whereas in the curvilinear parts it ranges from medium to fine. The exception is Simbaúma beach, which receives sediments from the Catu River carried by the coastal drift. Stretches of sandy beach are absent at the bases of headlands, where marine abrasion terraces occur.

With respect to geomorphological aspects, the following relief features are prevalent: coastal tableland with sharply sloping cliff edges, commonly with talus/colluvium deposits at the base; zeta-form bays with sandy beaches and headlands with marine abrasion terraces, evident at low tide; moving and grey dunes; the Catu River fluvial plain; the Guaraíras Estuary-Lagoon System; and the subcoastal plains with no cliffs.

The coastal tablelands are exhumed (Figure 3A) by the constant action of the trade winds, leaching processes and anthropogenic actions that commonly promote the loss of plant cover (SCUDELARI and FREIRE, 2005). Active cliffs represent the scarped edge of the coastal tablelands, with unevenness of up to 20m, submitted to the direct action of hydrodynamic forcing (Figure 3B). When cliffs are retreated, they are covered by moving and grey dunes (Figure 3C).

The marked morphology of the coastal plain on the eastern coast consists of the parabolic or zeta-form bays caused by the differential erosion of lithotypes from the Barreiras Formation, in a structural framework of alternating grabens and horsts, under the erosive action of hydrodynamic forcing and driven by the refraction and diffraction climate patterns of the dominant ESE waves (AMARAL, 2001). The marine abrasion terraces occur in the portions above the current beach face, at the base of the active cliff, suggesting a higher relative sea level, likely related to the last interglacial episode.

Sandy beaches, usually protected by elongated stretches of beachrocks, are intermediary (WRIGHT and SHORT, 1983; CALLIARI *et al.,* 2003), with medium to coarse sand,and low to moderate beach face slope (Figura 3c), marked by features such as beach cusps and rip currents due to mesotidal action and wave climate.

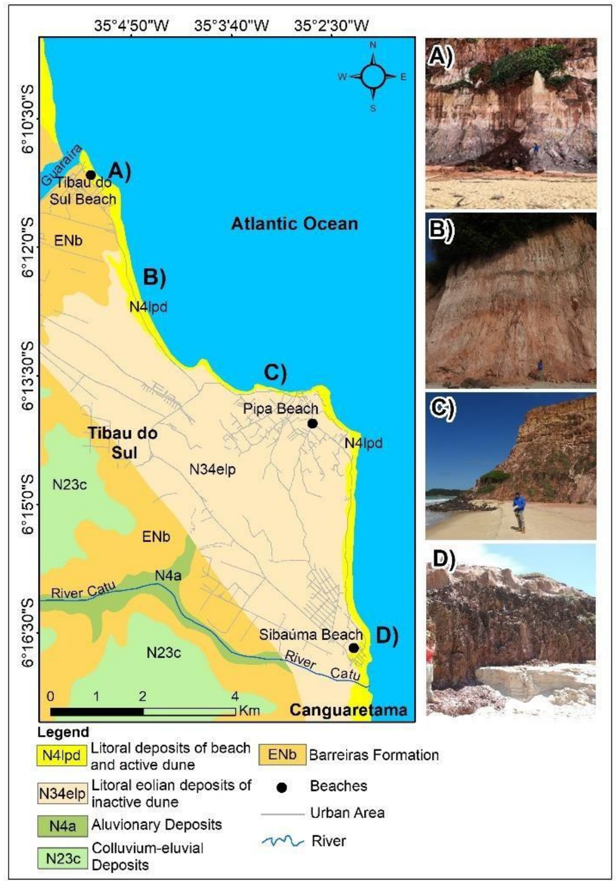

Figure 2 – Simplified map of the study area geology: (A) From the base to the top: intercalation of clayey sandstones with conglomeratic levels and massive sandstone; talus deposits; (B) Conglomeratic sandstone at the base, sandy argillite and massive argillite at the top; (C) Conglomeratic sandstone at the base, grading to clayey sandstone at the top, with conglomeratic levels; (D) From the base to the top: conglomeratic sandstone, clayey sandstone and sandy sandstone at the top, covered with soil.

The dunes are small (embryonary), with incipient vegetation covering the post-beach zone, marine terraces and the foot of the cliffs (Figure 3d). Parabolic dunes and large blowouts cover the tops of coastal tablelands interconnected with the beach, undergoing a thrust faulting process in the cliffs (Figure 3c), with large shrubby-arboreal vegetation that harbors Atlantic Forest, Caatinga and Cerrado species (AMARAL, 2001; PIERRI, 2008).

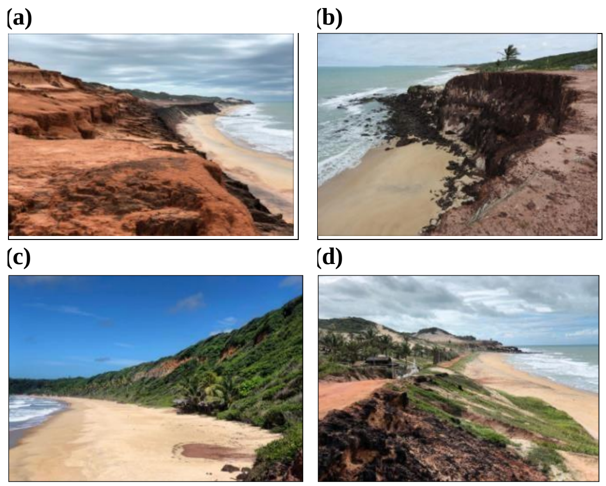

Figure 3 – Geomorphological features on the eastern coast of RN: (a) Exhumed coastal tableland bare of vegetation, with an abrupt edge on the active cliff; (b) Active cliff with a scarped edge and ample unevenness, with the base of the headland covered by talus deposits and submitted to direct wave action, and a sandy beach with moderate slope; (c) Retreated cliff with escarpment covered by vegetation; (d) Embryonary and frontal dune formation, with incipient vegetation, thrust faulting in the cliffs.

2.2. Multitemporal Image Analysis

Multitemporal analysis of high spatial resolution QUICKBIRD satellite images involved three stages (Figure 4, 5 and 6): the first consisted of image selection and pre-processing; the second involved the application of DIP techniques to identify and extract the shorelines, outlined by the edges of the escarpments of the cliffs; and the third was based on analysis of shoreline evolution using the DSAS, Linear Regression Rate (LRR), End Point Rate (EPR) and Net Shoreline Movement (NSM) statistics modules. The LRR establishes the variation rate of the set of shorelines based on simple linear regression, whereas NSM assesses mobility over a given time period by measuring the distance between the oldest and most recent shoreline, and EPR provides the average rate of shoreline variation over a given time interval.

In the first stage, the multispectral QUICKBIRD satellite images from 2003, 2008 and 2013 in the visible to near-infrared range were selected, with nominal spatial resolution of 2.5 m, for periods with low cloud cover and similar tidal patterns (Figure 4, Table 1). The geometric correction of images was based on the polynomial quadratic equation and orthorectification, including ground control points (GCP) obtained in geodesic surveys.

Table 1 presents the mathematical models and accumulated errors used in georeferencing. The Universal Transverse Mercator (UTM), Zone, 25-South and SIRGAS 2000 datum coordinate systems were used. The importance of this stage is to amplify contrast enhancement between the surface features, reducing the distortions and imperfections in the multispectral images (AGRAWAL; SARUP, 2011).

Table 1 - Characteristics of the multispectral optical characteristics of the QUICKBIRD satellite and the references adopted in the analytical procedures .

Satellite	**QUICKBIRD**		
Imaging Data	08/12/2003	05/05/2008	03/12/2013
Spatial Resolution (m)	2.5	2.5	2.5
Geometric Correction	Quadratic polynomial	Quadratic polynomial	Quadratic polynomial
Accumulated error (m)#	**0.577**/4.584	**0.679**/3.489	**0.679**/3.489

#Accumulated error (m): value after georeferencing/original value

For atmospheric correction, the dark object subtraction (DOS) empirical method was used, with a view to reducing the effect of atmospheric scattering and enhancing the brightness quality at different points of the image (CHAVEZ JR., 1988; 1996), providing greater contrast in the visual identification of the scarped edges of the cliffs.

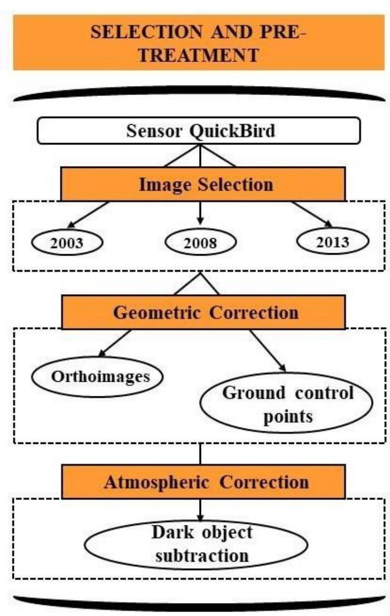

Figure 4 – Flowchart of the first stage: selection and procedures involved in the pre-processing of high-resolution multispectral images from the QUICKBIRD satellite.

DIP treatments were used in the second stage (Figure 5) to enhance the contacts between Barreiras Formation lithologies, dominant in the cliffs, types of vegetation and moving dune fields, facilitating the delimitation of cliff edges. The contrast enhancements used were linear and nonlinear histogram enlargements of the pixel to pixel contrast of color compositions in the reg-green-blue (RGB) additive model in true and false colors.

Multitemporal analysis involved mapping changes in the cliffline with a basic focus on identifying, analyzing and interpreting clifflines, following the methods described by Fletcher *et al*. (1997), Batista *et al*. (2009) and Amaro *et al*. (2012). The upper edge of the rocky escarpments of the Barreira Formation was established as a reference to detect the cliffline line in the satellite images, in contrast with wind, beach and abrasion terrace sediments. This interpretation of satellite images was done on site, in addition to a description of the erosional characteristics in the different cliff sectors.

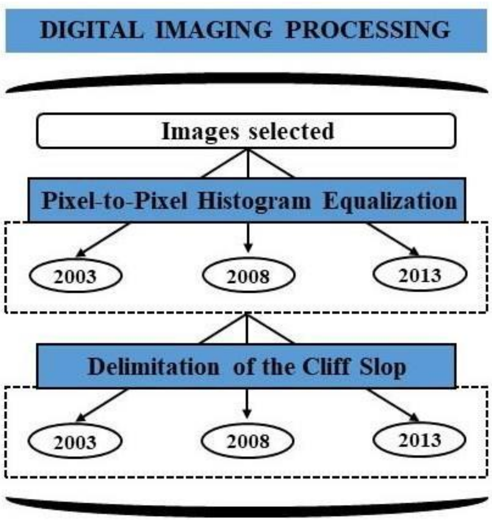

Figure 5 – Flowchart of the second stage: main DIP treatments to enhance and delimit the cliff edges.

In the third stage, the retreat rates were quantified using the geographic information system (GIS) based on the DSAS (Figure 6) statistics module, an extension of ArcGIS software (THIELER *et al*., 2009). DSAS was executed in five phases (HIMMELSTOSS *et al*., 2018): (1) detecting clifflines on multitemporal images; (2) establishing the baseline that follows the overall trend of the shoreline; (3) demarcating transects orthogonal to the baseline, placed 10m apart; (4) calculating the distances between the baseline and clifflines of each transect; (5) calculating the variation in clifflines. Thus, the attributes of the differences between the clifflines of each of the images was calculated based on 1,153 transects, separated into three sectors: North, Central and South. The results of the variation in maximum, average and minimum cliff retreat rates were grouped for the sectors (North, Central and South) on the coast of Tibau do Sul.

Quantification of the retreat rate over time and the other calculations of the variation in the clifflines in DSAS involved the three statistical methods (LRR, NSM and EPR) expressed in meters/year and meters (m), as shown in Figure 6.

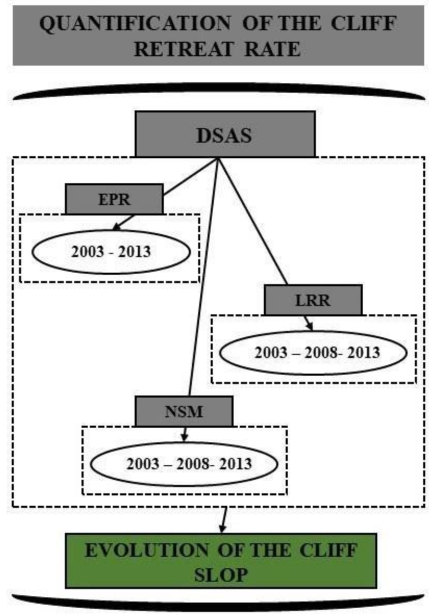

Figure 6 – Flowchart of the third stage: DSAS statistics module used to quantify the cliffline retreat rates.

3. RESULTS AND DISCUSSIONS

In general, the average retreat rate for the coast of Tibau do Sul between 2003 and 2013 was -0.442 m/year, demonstrating that 37% of the shorelines containing cliffs were subject to erosion. Compared with a number of recent studies with similar methodological approaches and short-term analyses, the retreat rate is also high on the southern and central coast of California, with -0.044 m/year (YOUNG, 2018), and parts of the French coast, with a retreat between -0.060m/year and -0.390 m/year (LOPEZ-SAEZ *et al*., 2018).

The high retreat rates directly demarcate the differential erosion of active cliff edges (Table 2). However, for some of the sectors assessed, the increase in erosion rates is due to the intense runoff caused by splash erosion, especially in the exhumed sea cliffs.

Table 2 - Average and maximum retreat rates in m/year and the total amount between 2003 and 2013 on the cliffs along the coast of Tibau do Sul.

Sectors	*North Sector*	*Central Sector*	*South Sector*
Average rate (m/year)	-0.22	-0.14	-0.12
Maximum rate (m/year)	-1.64	-2.15	-2.14
Maximum retraction (m)	16.23	21.31	21.09
Extension (km)	4.08	3.04	4.41
Retreat (%)	58	30	21

3.1. North Sector

More significant changes occurred in the sea cliffs of the North sector (Figure 7). Around 58% of the 4.1km of cliffs retreated, with an average rate of -0.22 m/year, in the decade assessed. It was divided into three subsectors (N1, N2, N3), in line with the general direction of the shoreline, where the highest retreat rate occurred in 82% of subsector N2 (Figure 7A-N2), and the central part of the North sector, with a maximum rate of approximately -1.64 m/year.

Figure 7B shows the transects with the highest retreat rates, highlighting transect T212, which exhibited a maximum retreat of 16.23m in the decade. This stretch of cliffs is characterized by a beach with a moderate slope and incision escarpment and gravitational movement of material intensified by surface runoff (Figure 7C). Previous geotechnical studies showed the strong instability on the slope of this stretch, intense splash erosion and landslides (soil and rocks) from the upper part, suggesting low cliff resistance due to less cementation of the surface layer (SEVERO, 2005). Studies by Braga (2005) and Camara (2018) showed the intense and pervasive splash erosion in this sector with high exhumation, causing the formation of gullies at the top and on the scarped face of the cliff.

Although this sector is sparsely occupied by business ventures and urban areas, the access road to the main points of interest was built very near the cliff edge (Figure 7B) and the removal of vegetation to erect any infrastructure intensifies erosive processes.

3.2. Central Sector

The central sector covers around 3.04 km of cliff edges, 30% of which had retreated, and the rest remained stable between 2003 and 2013. The results for this sector (Figure 8) revealed an average retreat rate of -0.14 m/year, less than that of the North sector, especially because this sector exhibits the highest population density and tourist occupation in the municipality of Tibau do Sul, at Pipa beach, which has several stretches with coastal protection undertakings against erosive processes.

Subsector C3 saw the highest cliff retreat percentage (51%) (Figura 8A-C3), with a maximum rate of -2.15 m/year.

A high retreat rate between-0.45 and 1.00 m/year also occurred in subsector C1.

Figure 8B indicates the position of transect T47, which exhibited a maximum retreat of 21.31m between 2003 and 2013. Both subsector C1 and C3 have no occupation or coastal protection undertakings, with relatively preserved vegetation on the top of the sea cliff.

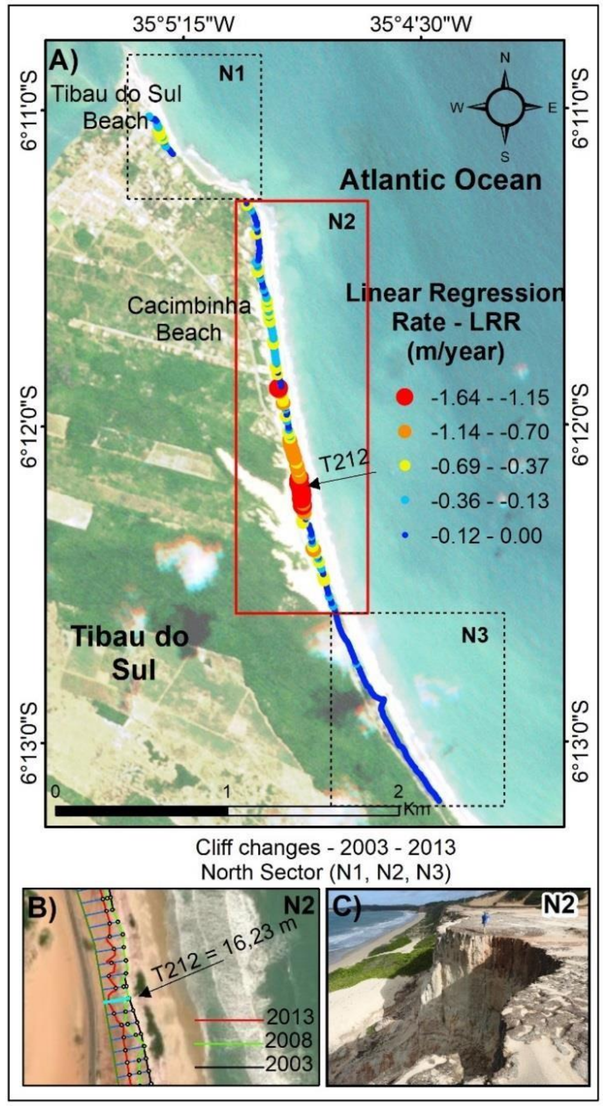

Figure 7 – Changes in the cliff retreat rate in the North sector: (A) Map representing the linear regression rate (m/year) between 2003 and 2013 identifying the most critical subsector (N2); (B) Transect T21, with maximum retreat and near the access road; (C) panoramic view of transect T212.

In subsector C3, the beach exhibits a low slope gradient, and the presence of talus deposits at the foot of the cliff suggests that even with plant cover, it is subject to mass movements. This indicates a strong erosive process, recorded in the maximum retreat value of transect T47 (Figure 8C). Splash erosion is equally intense and the slope of the cliff is steep in this subsector. Braga (2005) and Câmara (2018) observed conspicuous rockfalls and topplings in the escarpments of this sector.

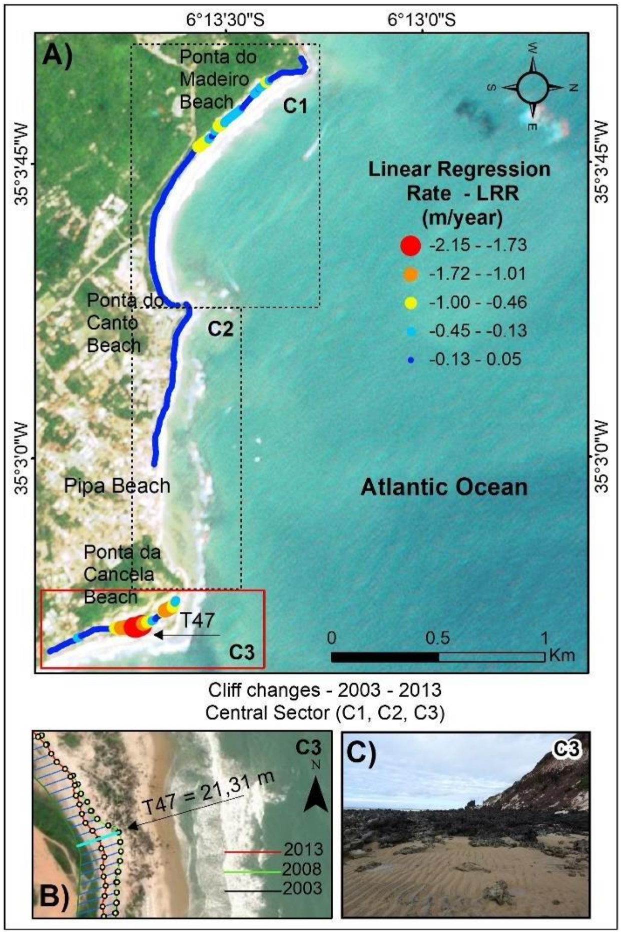

Figure 8 - Changes in the cliff retreat rate in the Central sector: (A) Map representing the linear regression rate (m/year) between 2003 and 2013, identifying the most critical subsector (C3); (B) Transect T47 with maximum retreat; (C) Paroramic view of transect T47.

3.3. South Sector

The South sector extends for 4.41 km, 21% of which underwent cliff retreat, with an average of -0.12 m/year. This sector also obtained high retreat rates, especially in two main stretches, one in subsector S1 and the other in S3 (Figure 7).

Subsector S1 is distinguished by its extensive flat and exhumed top called "Chapadão de Pipa", with a high tourist presence throughout the year. Subsector S3, in the area around the mouth of the Cátu River, exhibits occupational concentration and tourist activities. The results show that subsector S3 (Figure 9A-S3) was the most affected by retreat, with 47% submitted to the cliff retreat process, compared to the 30 and 23% of subsectors S1 and S2, respectively.

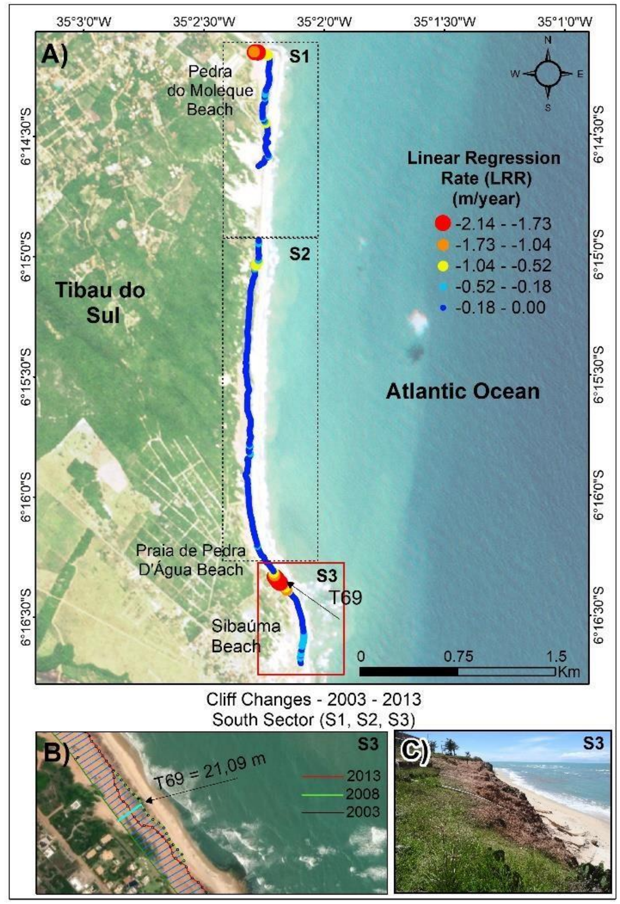

Figure 9 - Changes in the cliff retreat rate in the South sector: (A) Map representing the linear regression rate (m/year) between 2003 and 2013 identifying the most critical subsector (S3); (B) Transect T69); (C) Panoramic view of transect T69.

In subsector S3 (Figure 9B), transect T69 indicated the highest cliff retreat (21.09 m) in the decade. The cliffs in this sector are dark brownish-red, demonstrating high ferruginous cementation in relation to the other stretches of cliffs. This may indicate the greater resistance to erosive processes in this sector (BRAGA, 2005; CAMARA, 2018). These authors also reported the formation of ravines on the tops of the cliffs and points of subsurface water upwelling, with flow directed towards the slope below, indicating splash erosion. Another driving force of erosion in these areas are the drainage structures erected haphazardly by the community on the cliff edges.

Thus, the stretches with the highest cliff retreat in each sector identified are represented by transects T212, T47 and T69, indicated in Figures 7, 8 and 9, respectively. For each of the stretches, the linear regression model and R^2 value (LR^2) were above 0.75 (Figure 10), showing the erosive trend between 2003 and 2013, or the liquid retreat movement of the cliff edge. These results reveal the strong erosive trend in all the sectors, suggesting temporal progression, demonstrating the erosive process in response to the pressure that these areas are submitted to, due to the nature of rock instability, greater impact from splash erosion and/or anthropic pressure.

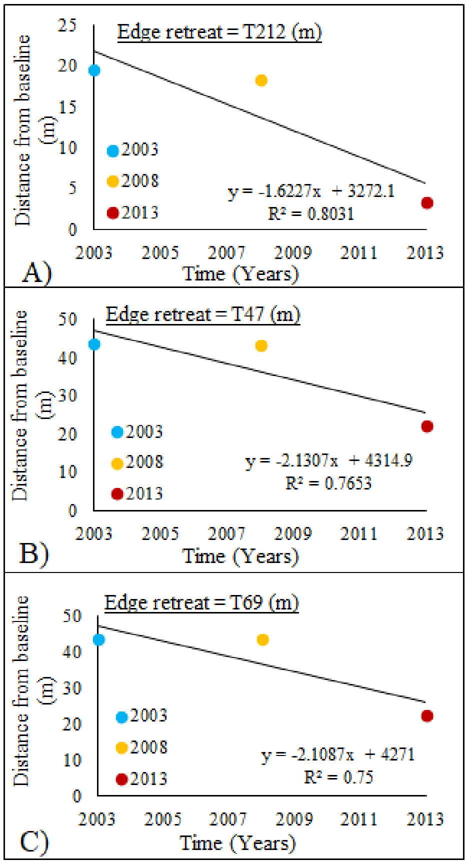

Figure 10 - Linear regression model with the R^2 value (LR^2) for cliffline retreat between 2003 and 2013 in the main erosive transects of each sector: (A) North sector (N02), transect T212;(B) Central sector (C3), Transect T47; C) South sector (S3, Transect T69.

Thus, it was demonstrated that erosion rates, in correlation to that of deposition and sediment transport, may vary significantly from one stretch of coast to another, depending on a number of factors, including hydrodynamic regime, climate, rainfall and the geological features of the cliffs (MOORE and DAVIS, 2015). However, natural processes are also sensitive to anthropic interference, such as retaining structures and coastal erosion defenses, which intentionally or inadvertently alter the hydrodynamic regime and local sediment transport, especially upstream from the transport direction. In any sector there are several inter-related variables that contribute to cliff instability and erosion, such as geological discontinuities, rock and soil resistance, morphology, subsurface water behavior, drainage patterns, surface runoff, plant cover and anthropogenic interference (LEE and CLARK 2002; MOORE and DAVIS, 2015).

4. FINAL CONSIDERATIONS

The present article identified and quantified cliff retreat processes, based on the analysis of high-resolution QUICKBIRD satellite images of coastal sectors of Tibau do Sul, Brazil.

The results corroborate previous geotechnical investigations (BRAGA, 2005; SEVERO, 2011; CAMARA, 2018), and the average retreat rates (m/year) obtained in the different sectors are in line with studies conducted in other areas of the world, confirming that cliff retreat, its quantification and the location of cliffs with the highest retreat rates can be accurately mapped with geotechnologies, based on high-resolution multitemporal satellite images, statistical analyses in a GIS environment, in addition to scientific support with information such as geotechnical maps, geological data, and aerial photographs, among others.

The methodological procedures developed can be applied in other sectors containing cliffs on the RN coast, for which there is little regional qualitative-quantitative information. Thus, mapping with high-resolution multitemporal images of cliff retreat is a relevant indicator of mass movement.

The analysis period of this investigation was between 2003 and 2013, showing that 37% of cliff edges underwent erosion, corresponding to an average retreat rate of -0.44 m/year. Sector analysis showed that the Central sector experienced the highest retreats, with a maximum of 23.31 m and average rate of -2.15 m/year.

With respect to the processes involved, corroborating earlier studies and identified on site in the present investigation, the magnitude of the erosive process is related to the fragile cementation process of the rocks in the upper and surface strata of the cliffs, intense splash erosion, the constancy of hydrodynamic forcings and inadvertent anthropic alterations, in the search for weathering protection, given the economic activities established to explore the scenic beauty of the coastal cliffs that attracts tourists and local inhabitants alike.

5. REFERENCES

AGRAWAL, G.; SARUP, J. Comparision of QUAC and FLAASH Atmospheric Correction Modules on EO-1 Hyperion Data of Sanchi. *International Journal of Advanced Engineering Sciences and Technologies*, Raipur, v. 4, n.1, p. 178-186, 2011.

ALHEIROS, M. M.; LIMA FILHO, M. F. A Formação Barreiras. Revisão geológica da Faixa Sedimentar Costeira de Pernambuco, Paraíba e Rio Grande do Norte. *Série Estudos Geológicos*, Recife, v. 10, n. 0, p: 77-88, 1991.

AL-TAHIR, R.; ALI, A. Assessing land cover changes in the coastal zone using aerial photography. *Surveying and Land Information Science*, Oxford, v. 64, n. 2, p. 107-112, 2004.

ALVARES, C.A.; STAPE, J.L.; SENTELHAS, C.; GONÇALVES, J.L.M.; SPAROVEK, G. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, Stuttgart, v. 22, n. 6, p. 711-728, 2013.

AMARAL, R. F. *Contribuição ao estudo da evolução morfodinâmica do litoral oriental sul do Rio Grande do*

Norte, entre a Ponta de Búzios e Baía Formosa. Tese de doutorado, Programa de Pós Graduação em Geociências da Universidade Federal do Rio Grande do Sul, 1999. 252p.

AMARO, V. E.; SANTOS, M. S. T.; SOUTO, M. V. S. *Geotecnologias aplicadas ao monitoramento costeiro: Sensoriamento Remoto e Geodésia de Precisão*. 1 ed. Natal: 2012. 118p.

BARBOSA, J. A., NEUMANN, V. H, LIMA FILHO, M., SOUZA, E.M., MORAES, M. A. Estratigrafia da faixa costeira Recife-Natal (Bacia da Paraíba e Plataforma de Natal), NE Brasil. *Série Estudos Geológicos*, v. 17, n. 2, p. 1-30, 2007.

FEITOSA, E.C.; FEITOSA, F.A.C.; LIRA, H.M.P. Relações estratigráficas e estruturais entre a Bacia Potiguar e a Bacia Costeira PE/PB – uma hipótese de trabalho. In: XII CONGESSO BRASILEIRO DE ÁGUAS SUBTERRÂNEAS, 12, 2002, Santa Catarina, Anais. Santa Catarina: ABAS, 2002. p. 1-12.

FERREIRA, J.M.; OLIVEIRA, R.T.; TAKEYA, M.K.; ASSSUMPÇÃO, M. Superposition of local and regional stresses in northeast Brazil: evidence from focal mechanisms around the Potiguar marginal basin. *Geophysical Journal International*, Oxford, v. 134, p. 341–355, 1998.

LANA, M. C. C.; ROESNER, E. H. Palinologia do Cretáceo Superior marinho subaflorante na região de Natal, RN. *Anais* da Academia Brasileira de Ciências, Rio de Janeiro, v. 7, n. 1, p. 149-50, 1999.

BARRETO, A. M. F.; SUGUIO, K.; BEZERRA, F. H. R.; TATUMI, S. H.; YEE, M.; GIANNINI, P. C. F. Geologia e geomorfologia do quaternário costeiro do estado do Rio Grande do Norte. *Geologia USP Série Científica*. São Paulo, v. 4, n. 2, p. 1-12, 2004.

BEZERRA, F. H. R.; AMARO, V. E.; VITAFINZI, C.; SAADI, A. Pliocene-Quaternary fault control of sedimentation and coastal plain morphology in NE Brazil. *Journal of South American Earth Sciences*. v. 14, p. 61-75, 2001.

BATISTA, E. M.; SOUZA FILHO, P. W.; SILVEIRA, O. F. M. Avaliação de áreas deposicionais e erosivas em cabos lamosos da zona costeira amazônica através da análise multitemporal de imagens de sensores remotos. *Revista Brasileira de Geofísica*, São Paulo, v. 27, n. 1, p. 83-96, 2009.

BIRD, E.C.F. *Coastal geomorphology: an introduction*. 2 ed. Melbourne: John Wiley & Sons, 2008. 436p.

BOAK, E.H.; TURNER, I.L. Shoreline definition and detection: a review. *Journal of Coastal Research*, Florida, v. 21, n. 4, p. 688-703, 2005

BRAGA, K. G. *Uso de Checklist para Identificação da Erosão Costeira em Tibau do Sul/RN. Natal, 2005*. Dissertação de mestrado apresentado ao Programa de Pós Graduação em Engenharia Civil da Universidade Federal do Rio Grande do Norte, 2005. 96p.

BRANNER, J. C. The stone reefs of Brazil, their geological and geographical relations. *Bulletin of the Museum of Comparative Zoology*, Massachusetts, v. 44, n. 7. P. 1-196, 1904.

BUSMAN, D. V.; AMARO, V. E.; PRUDÊNCIO, M. C. Comparison of prognostic models in different scenarios of shoreline position on Ponta Negra beach in Northeast Brazil. *International Journal of Environmental and Ecological Engineering*, New Castle, v. 8, n. 3, p. 170-174, 2014.

CAI, F.; SU, X.; LIU, J.; LI, B.; LEI, G. Coastal erosion in China under the condition of global climate change and measures for its prevention. *Progress in Natural Science*, Amsterdam, v. 19, n. 4, p. 2009.

CALLIARI, L.R.; MUEHE, D.; HOEFEL, F.G.; TOLDO JR., E. Morfodinâmica praial: uma breve revisão. *Revista Brasileira de Oceanografia*, São Paulo, v. 5l, p. 63-78. 2003.

CAMARA, M.R. *Análise de recuo de falésias no litoral do Estado do Rio Grande do Norte*. Dissertação de mestrado apresentado ao Programa de Pós Graduação em Engenharia Civil da Universidade Federal do Rio Grande do Norte, 2018. 148p.

CAMARA, M.; SCUDELARI, A.; AMARO, V.; MATOS, M.; RABELO, T. Geotecnologias como Subsídio para Gestão de Ambientes Costeiros: Análise do Recuo em Falésias/Arribas no Estado do Rio Grande do Norte, Brasil, e Suas Implicações Socioambientais. *Revista de Geografia e Ordenamento do Território*, Porto, v. 16, n. 4, p. 53-79, 2019.

CHAVEZ JR., P.S. An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data. *Remote Sensing of Environment*, Amsterdãm, v. 24, p. 459-479, 1988.

CHAVEZ JR, P.S. Image-based atmospheric correction - revisited and improved. *Photogrammetric Engineering and Remote Sensing*, Maryland, v. 62, n. 9, p.1025-1036, 1996.

DAHDOUH-GUEDES, F.; VERHEYDEN, A., KAIRO, J.G., JAYATISSA, L.P. AND KOEDAM, N. Capacity building in tropical coastal recourse monitoring in developingcountries: A re-appreciation of the oldest remote sensing method. *International Journal of Sustainable Development and World Ecology*, Oxford, v. 13, n. 1, p. 62-76, 2006.

DAVIDSON-ARNOTT, R. *Introduction to coastal processes and geomorphology*. 1 ed. Cambridge: Cambridge University, 2010. 410p.

EMERY, K.O.; KUHN, G.G. Sea cliffs: their processes, profiles, and classifications. *Geological Society of American Bulletin*, Colorado, v. 93, n. 7, p. 644-654, 1982.

EARLIE, C.; MASSELINK, G.; RUSSEL, P. The role of beach morphology on coastal cliff erosion under extreme waves. *Earth Surface Processes and Landforms*, London, v. 43, n. 6, p. 1213-1228, 2017.

FALL, M. A GIS-based mapping of historical coastal cliff recession. *Bulletin of Engineering Geology and the Environment*, Germany, v. 68, p. 473-482, 2009

FLETCHER, C. H.; MULLANE, R. A.; RICHMOND, B. M. Beach loss along armored shorelines on Oahu, Hawaiian Islands. *Journal of Coastal Research*, Florida, v. 13, n. 1, p. 209-215, 1997.

GRIGGS, G.B.; PATSCH, K.B. Cliff erosion and bluff retreat along the California coast. *Sea Technology*, Arlington, v.45, n. 9, p. 36-40, 2004.

GOBBI, E. S.; LADEIRA, F. S. B. Proposta para Mapeamento de Riscos Associados à Movimento de Massa e Inundação: o caso de Ubatuba, SP. *Geociências*, São Paulo, v. 30, n. 3, p. 445-456, 2011.

HIMMELSTOSS, E.A.; HENRERSON, R.E.; KRATZMANN, M.G.; FARRIS, A.S. Digital shoreline analysis system (DSAS) version 5.0 user guide. *U.S. Geological Survey Open-File Report 2018–1179*. Virginia, 2018.

KIRK, R.M. Coastal changes at Kaikoura, 1942- 1974, determined from air photographs. N.Z. *Journal of Geology and Geophysics*, New Zealand, v. 18, p. 787-801, 1975.

LADEIRA, F.S.B.; SANTOS, M. O uso de paleossolos e perfis de alteração para a identificação e análise de superfícies geomórficas regionais: o caso da Serra de Itaqueri (SP). *Revista Brasileira de Geomorfologia*, Brasília, v. 6, n. 2, p. 2005.

LEE, E.M.; CLARK, A.R**.** *Investiogation and managent of soft rock cliffs*. 1 ed. London: Thomas Telford: 2002.

LOPEZ- SAEZ, J.; CORONA, C.; MOREL, P.; ROVÉRA, G.; DEWEZ, T. J. B.; STOFFEL, M.; BERGER, F. Quantification of cliff retreat in coastal Quaternary sediments using anatomical changes in exposed tree roots. *Earth Surface Processes and Landforms*, London, v. 43, n. 15, p. 2983-2997, 2018.

MABESOONE, J. M.; ALHEIROS, M. M. Origem da bacia sedimentar costeira Pernambuco-Paraíba. *Revista Brasileira de Geociências*, São Paulo, v. 18, n. 4, p. 476-482, 1988.

MABESOONE, J. M.; ALHEIROS, M. M. Evolution of the Pernambuco-Paraíba Rio Grande do Norte Basin and the problem of the South Atlantic conection. *Geologie en Mijnbouw*, Switzerland, v. 71, p. 351-362, 1993.

MASSELINK, G.; HUGHES, M.G.; KNIGHT, J. *Introduction to coastal processes and geomorphology*. 2 ed. New York: Taylor & Francis Group, 2003. 419p.

MCGRANAHAN, G.; BALK, D.; ANDERSON, B. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment & Urbanization*, Thousand Oaks, v. 19, n. 1, p. 17–37. 2007.

MENTASCHI, L.; VOUSDOUKAS, M. I.; PEKEL, J. F.; VOUKOUVALAS, E.; FEYEN, L. Global long-term observations of coastal erosion and accretion. *Scientific Reports*. Bethesda, v. 8, n. 1, p. 1-11, 2018.

MOORE, R.; ROGERS, J.; WOODGET, A. Climate change impact on cliff instability and erosion. *Floods and Water Management Act.* p. 1-12. 2010.

MOORE, R.; DAVIS, G. Cliff instability and erosion management in England and Wales. *Journal of Coastal Conservation*, Netherlands, v. 19, p. 771-784, 2015.

NOGUEIRA, A. M. B.; LIMA, M. S.; SALIM, J.; SÁ, J. M.; MANSO, V. A.V. Estudo das areias de dunas da faixa litorânea de Natal – Rio Grande do Norte. In: *Simpósio de Geologia do Nordeste*. Fortaleza: SBG-Núcleo Nordeste, 1975. p. 39.

NOGUEIRA, A. M. B.; COSTA NETO, L. X.; LIMA, M. S.; SILVEIRA, M. I. M.; FERNANDES, C. A. N. Evolução geo-ambiental da faixa costeira entre Ponta do Calcanhar e Ponta do Marcos-RN. In: CONGRESSO BRASILEIRO DE GEOLOGIA, 1990, Natal, *Anais*, Natal: CBG, 1990. p. 784-795.

NICHOLLS, R.J. Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socioeconomic scenarios. *Global Environmental Change*, Amsterdãm, v. 14, n. 1, p. 69–86, 2004.

PIERRI, G. C. S. *Análise de risco a erosão costeira na região de Tibau do Sul/RN, através de mapeamento geoambiental e análises morfodissemica*. Dissertação de mestrado apresentado ao Programa de Pós Graduação em Geodinâmica e Geofísica da Universidade Federal do Rio Grande do Norte, 2008. 140p.

PRUDÊNCIO, M.C.; AMARO, V.E.; SCUDELARI, A.C. Análise da Evolução Costeira entre os Anos de 1984 e 2014 de Trecho do Litoral Oriental do Rio Grande do Norte, Nordeste do Brasil. *Anuário do Instituto de Geociências***,** Rio de Janeiro, v. 42, n. 4, p. 189-205, 2019.

SAROGLOU C.; ALEXANDROU D. Coastal cliff instability, a case study from the UK. *Bulletin of the Geological Society of Greece*, v. 50, n. 2, p. 949-958, 2016.

SANTOS JÚNIOR, O.F.; SCUDELARI, A.C.; COSTA, Y.D.; COSTA, C.M. Sea Cliff retreat mechanisms in Northeastern Brazil. *Journal of Coastal Research*, Florida, v. 64. n. SI, p. 820-824, 2011.

SCUDELARI, A. C.; FREIRE, L. C. S. Determinação dos Impactos Ambientais na Construção de um Sistema Hoteleiro nas Falésias em Tibau Do Sul-RN. *Brazilian*

Journal of Aquatic Science and Technology, Camburiú, v. 9, n. 1, p. 39-43, 2005.

SEVERO, R.N.F. *Análise da estabilidade das falésias entre Tibau do Sul e Pipa – RN*. Dissertação de mestrado apresentado ao Programa de Pós Graduação em Engenharia Civil da Universidade Federal do Rio Grande do Norte, 2005. 139p.

SEVERO, R.N.F. *Caracterização geotécnica da falésia da Ponta do Pirambu em Tibau do Sul – RN considerando a influência do comportamento dos solos nos estados indeformados e cimentado artificialmente*. Tese de doutorado apresentado ao Programa de Pós Graduação em Engenharia Civil da Universidade Federal de Pernambuco, 2011. 280p.

SMALL, C.; NICHOLLS, R. J. A global analysis of human settlement in coastal zones. *Journal of Coastal Research*, Florida, v. 19, n. 3, p. 584-599, 2003.

SILVEIRA, J. D. *Morfologia do litoral*. In: AZEVEDO, A. 1 ed. São Paulo: Companhia Editora Nacional, 1964. 336p.

SUGUIO, K.; MARTIN, L.; BITTENCOURT, A. C. S. P.; DOMINGUEZ, J. M. L.; FLEXOR, J. M.; AZEVEDO, A. E. G. Flutuações do nível relativo do mar durante o Quaternário superior ao longo do litoral brasileiro e suas implicações na sedimentação costeira. *Revista Brasileira de Geociências*, São Paulo, v. 15, n. 4, p. 273-286, 1985.

SOUZA JÚNIOR, C.S. *Análise da Estabilidade de Falésias/arribas na Zona Costeira de Baía Formosa/RN*. Dissertação de mestrado apresentado ao Programa de Pós Graduação em Engenharia Civil da Universidade Federal do Rio Grande do Norte, 2013. 141p.

SUNAMURA, T. *Geomorphology of rocky coasts*. 1 ed. New York, John Wiley and Sons, 1992. 302p.

TAQUEZ, D.E.D. *Susceptibilidade à ocorrência de movimentos de massa e avaliação da estabilidade de falésias sob condição não saturada: estudo de caso no centro de lançamentos da barreira do inferno – Brasil*. Dissertação de mestrado apresentado ao Programa de Pós Graduação em Engenharia Civil da Universidade Federal do Rio Grande do Norte, 2017. 216p.

THIELER, E. R.; HIMMELSTOSS, E. A.; ZICHICHI, J. L.; ERGUL, A. "DSAS 4.0 Instruções de Instalação e Guia do Usuário ", em Digital Shoreline Analysis System (DSAS) versão 4.0 - uma extensão do ArcGIS para Calculando a mudança da linha costeira. *U.S. Geological Survey Open-File Report*. 2008-1278. 2009

TRENHAILE, A.S. *The geomorphology of rocky coasts*. 1 ed. Oxford: Clarendon Press, 1987. 384p.

TRENHAILE, A.S. Rocky coasts – their role as depositional environments. *Earth Science Reviews*, Amisterdam, v. 159, p. 1-13, 2016.

VIEIRA M.M.; DE ROS L.F. Cementation patterns and genetic implications of Holocene beachrocks from northeastern Brazil. *Sedimentary Geology*, Amsterdam, v. 192, n. 3, p. 207-230, 2006.

VITAL, H.; SILVEIRA, I.M.; LIMA, Z.M.C.; TABOSA, W.F.; SILVA, A.G.A.; SOUZA, F.E.S.; CHAVES, M.S.; GOMES, M.P. *Rio Grande do Norte*. In: MUEHE, D. 2 ed. Brasília: Ministério do Meio Ambiente, 2018. 761p.

WILLIAMS, A.; RANGEL-BUITRAGO, N. G.; PRANZINI, E.; ANFUSO, G.09 The management of coastal erosion. *Ocean & Coastal Management*, Amsterdam, v. 156, p. 114-129, 2017.

WRIGHT, L. D.; SHORT, A. D. 1983. *Morphodynamics of beaches and surf zones in Australia*. In: Komar P. D. ed. Handbook of coastal processes and erosion. Boca Raton, CRC Press, p. 35-64.

YOUNG, A. Decadal-scale coastal cliff retreat in southern and central California. *Geomorphology*, Amisterdam, v. 300, p. 164-175, 2018.

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