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Temporal Analysis of Coastal Erosion and Environmental Degradation at Suape Beach

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Abstract

Coastal erosion is a global phenomenon that affects almost all countries that have coastlines. In Brazil, these processes have intensified due to anthropic activities such as disorderly urbanization and unsustainable tourism. In Pernambuco, Suape beach has been suffering from chronic erosion. So, this study evaluated the coastal erosional processes and their correlations with some land use and occupation classes at Suape beach. For this, orthophotocharts from the years 1974, 1988, 1997, 2010 and 2020 were collected. After vectorization and georeferencing these materials, thematic maps of land use and occupation were created, which composed a historical series of 46 years (1974 – 2020). Then, a multitemporal analysis of the evolution of each land use and occupation class (land cover) was carried out. The land covers analyzed were: urbanized area, natural vegetation, exposed soil, emerged beach sand and body of water. The results showed that the urbanization of the area expanded from 0.30 hectares to 9.92 hectares, a percentage increase of 3206.67%. The natural vegetation lost 26.52% of its space, mainly for urbanization and exposed soil. In relation to the emerged beach sand the area gain was 118.84%. Thus, it was verified a rapid and continuous environmental degradation in the region. Coastal erosion was evidenced by the presence of its geoindicators and environmental degradation was observed from the study of thematic maps. Correlations were found *between erosion and the increase or reduction in the area of the classes of land use and occupation.*

Keywords: coastal erosion; environmental degradation; geoindicators; thematic maps; multitemporal analysis.

INTRODUCTION

Coastal zones are, naturally, dynamic and diverse because they are areas where soil, water and atmosphere interact with each other (AHMAD, 2019). Most of countries with coastlines suffer from coastal erosion (SOUZA; FURRIER, 2015). Currently, 25% of the planet's beaches suffer from this phenomenon at rates above 0.5 meters per year. Projections for 2050 indicate that by then 15% of the planet's sandy beaches could face severe coastal erosion (VOUSDOUKAS *et al*., 2020).

In Brazil, 85% of the country's inhabitants live in urban areas mainly in coastal areas. This high population density has caused ecological imbalances in coastal ecosystems. In Pernambuco state, although only 4% of the territory corresponds to coastal areas, 56% of the population resides in the coast (CABRAL; DA SILVA; GIRAO, 2014).

The coastal region has several relevant functions to the preservation of the environment. The main function is to protect the continent from the erosive effects of the shock waves against beaches, cliffs and rocky shores. In addition, the coast is home to dozens of ecosystems typical of this region, such as beaches, mangroves, dunes, estuaries, deltas and coral reefs. These environments are currently at risk (BRASIL, 2018). Both natural processes and anthropogenic activities have increasingly reduced the space of these ecosystems by reducing the width of the coastline (SOUZA; LUNA, 2010).

Some authors define coastal erosion, considering just natural factors, as the movement of ocean waters that act on the coastal edges, shaping the relief in a destructive way (CASTRO et al., 2003); excessive sediment outflow from the ocean-continent system (ABREU; ABREU NETO, 2013) and deficiency in the sedimentary balance in a segment of the coastline (BULHÕES, 2020). On the other hand, British Geological Survey (2012) considers coastal erosion “the removal of sediment from the coast through the action of waves, ocean currents and human activities".

The consequences of coastal erosion have environmental, social and economic effects, however, the impacts are only perceived due to the human presence in the coastal zone (GOIS, 2011). Monitoring the evolution of marine erosion is essential for the assessment of possible impacts caused by coastal dynamics (MARANHÃO et al., 2012). These erosional processes can be identified through geoindicators and their evolutionary trend monitored through multitemporal analysis (MARTINS et al., 2016).

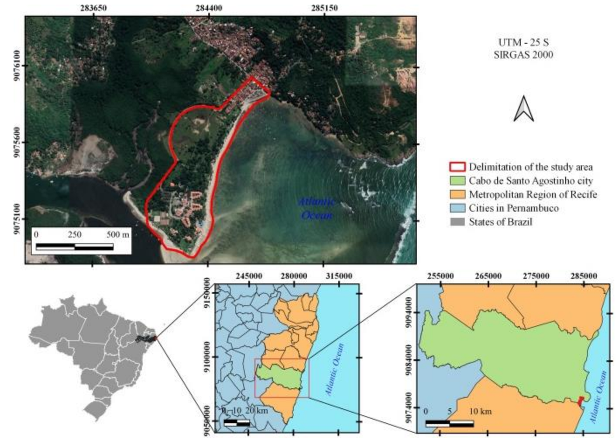
Over the last decade, at Suape beach, located in Cabo de Santo Agostinho city, it was possible to observe chronic erosion. The coastline has been advancing more and more towards the mainland (HOLANDA et al., 2020). It is believed that the increase in environmental degradation, the construction of the Port of Suape and real estate speculation are the main causes of the worsening of this process (NASCIMENTO; COELHO FILHO; DE CASTRO, 2016).

Given this issue, it is relevant to investigate the process of coastal erosion at Suape beach (PE) and its consequences on land covers, in order to provide data to urban planning institutions. The acquisition of medium and long-term data is important for a reliable analysis of the evolution of the erosional process.

AREA CHARACTERIZATION

The study area is Suape beach (Figure 1), located in Cabo de Santo Agostinho, on the southern coast of Pernambuco, about 40 kilometers from the capital Recife. The beach is limited to the north by the coordinate 8º21'18"S - 34º57'15"W and to the south by the coordinate 8º21'53"S - 34º57'36"W. The beach is approximately 1.3 kilometers long and is part of the Suape Bay. The region extends from the mouth of the Massangana River (south) to paradise beach (north) (FABIN, 2018).

Figure 1 – Study Area Location Map.



Source: Author

The Suape Bay is an estuary partially isolated from the open sea by the sandstone reef line of approximately 800 meters in length (BARCELLOS et al., 2019). These beachrocks are located at a distance of approximately 1.5 kilometers from the beach strip and offer protection by the significant influence on wave dissipation (SOUZA; FURRIER, 2015).

The local economy is related to tourism activities, nautical leisure and subsistence fishing. The main source of income for people living around the beach is fishing (MUNIZ, 2014). According to Köppen-Geiger climate classification, Suape beach has an As' climate, hot and humid tropical climate, characterized by autumn/winter rains and with average rainfall in the order of 2000mm.y-1 (BARCELLOS et. al, 2019). The relative humidity of the air is approximately 80%. Wind speeds remain between 2 and 4 m/s (LAFAYETTE, 2006).

The average annual temperature is 25°C (77°F) (BARCELLOS et. al, 2019) and annual temperature range around 5°C (41°F) (SOARES JUNIOR, 2014) (GOMES JUNIOR, 2015). Between January and April, it is observed the highest annual temperatures, which can reach 35°C (95°F), as well as the lowest rainfall rates (DANTAS, 2019).

The coastal vegetation is represented by "*restinga*" fields, "*restinga*" forest, Atlantic forest, "*cerrado*" and mangrove swamps (GOIS, 2018).

The city of Cabo de Santo Agostinho is located in the physiographic zone of Atlantic Forest and has a vegetation cover corresponding to the Atlantic tropical evergreen forest. This tropical forest has been deforested due to sugarcane cultivation (LAFAYETTE, 2006). In Suape, there was a compact coastal tropical forest that was profoundly modified and destroyed (NASCIMENTO; COELHO FILHO; DE CASTRO, 2016). More than 60% of the area has been deforested (MUNIZ, 2014), with some preserved areas of Atlantic forest, mangrove and salt marshes still remaining in the region, bathed by the Tatuoca and Massangana rivers with the Atlantic Forest biome (IBGE, 2019).

Until the construction of the Suape Port Industrial Complex in 1978, four rivers (Massangana, Tatuoca, Ipojuca and Merepe) flowed into Suape Bay. After the construction of the Port, two rivers (Ipojuca and Merepe) had their courses diverted and only the Massangana and Tatuoca rivers continued to flow into the Bay, thus reducing the amount of sediment that entered the Suape Bay. The analysis of sand samples taken from the bottom of the bay showed the presence of heavy metals (BARCELLOS et. al, 2019).

MATERIALS AND METHODS

In order to observe the progress of coastal erosion over time, it is necessary to have a historical series covering a few decades. For this, it was collected available cartographic materials that show the study area. Table 1 presents the collected materials.

Table1 – Materials collected to carry out the temporal analysis.

COLLECTED MATERIALS	YEAR	SCALE	AMOUNT	SOURCE
ORTHOPHOTOLETTERS	1974	1:2,000	2	CONDEPE/FIDEM
	1988	1:10,000	2	
AERIAL PHOTOGRAPH	1997	1:6,000	4	CONDEPE/FIDEM
GOOGLE EARTH PRO IMAGE	2010	1:25,000	1	GOOGLE EARTH PRO V. 7.3.3 (64-bit)
	2020	1:25,000	1	

Source: Author

The orthophotoletters were the first materials collected for the formation of the historical series. Orthophotoletters are cartographic products generated from corrected aerial photographic images, and were obtained from the State Agency for Research and Planning of Pernambuco (CONDEPE / FIDEM).

The agency had orthophotoletters of the study region from the years 1974 and 1988. CONDEPE/FIDEM also made available four aerial photographs from the year 1997. For completing the historical series, images from the years 2010 and 2020 were used. They were obtained through the software Google Earth Pro 7.3.3.7786 (64-bit), which is based on the WGS 84 Geodetic Reference System.

The materials that make up the historical series (images, orthophotoletters and aerial photographs) were georeferenced and vectorized with the help of the software QGIS 3.10.9, based on the Geocentric Reference System of the Americas (SIRGAS 2000) and on the UTM Projection (Universal Transverse Mercator), in the time zone 25S. Vectorization was performed by stereophotogrammetric rendering from visual analysis.

In order to perform the georeferencing of orthophotoletter from the year 1974, it was used the “Georeferencer” function of the “Raster” menu in QGIS 3.10.9. In the software, the matrix file was added, in .jpeg format, and the control points were indicated from the coordinates presented in the image itself. The configuration of the transformation parameters was type 1 polynomial and the sampling method was closest neighbor. The orthophotoletters from 1988 and 1997 were already acquired in. tiff format; therefore, they were already georeferenced.

From this process, 5 (five) vectorized maps come out. Each map refers to a year of the historical series. In each map, 5 (five) classes of land use and occupation (land cover) were highlighted. The classes of land cover analyzed were: Urbanized Area, Natural Vegetation, Exposed Soil, Emerged Beach Sand, and Body of Water (Table 2).

Table 2 – Classes of land use and occupationin the study area.

LAND COVER	DESCRIPTION
URBANIZED AREA	Impermeable surface through human action (buildings and/or paved areas).
NATURAL VEGETATION AREA	Area with large and/or small vegetation cover (trees, undergrowth).
EXPOSED SOIL AREA	Area without vegetation (erosive processes and/or burning).
EMERGED BEACH SAND AREA	Area covered and discovered periodically by the waters. Strip of sand, gravel, pebbles or boulders, up to the limit where the natural vegetation begins, or, in its absence, where another ecosystem begins.
BODY OF WATER AREA	Area with significant surface water accumulations.

Source: Author

In order to highlight the classes of land use and occupation in the thematic maps, it was created some layers in the software QGIS 3.10.9. Each layer is equivalent to a land use and occupation class. The shape file of the layers is a polygon. Each polygon represents one type of land cover.

After the creation of all thematic maps, the temporal analysis of land use and occupation was carried out. This comparative analysis enabled the identification of the variation of each layers of land use and occupation over the years. The layers of each land cover were compared to each other in order to verify whether there was an increase or decrease in area.

The comparison of layers was made in relation to their areas. In the software QGIS 3.10.9, the attribute table of a given layer offers the field calculator option and through that table was possible to quantify the areas of each layer of land cover. The percentage of contribution of each layer in relation to the total area of the studied region was determined according to Equation 1.

$$A_c(\%) = \frac{A_c}{A_t} \times 100$$ Equation (1)

Where:

Ac (%): Percentage of contribution ofarea of a specific land cover class;

Ac: Area of a specific land coverclass (ha);

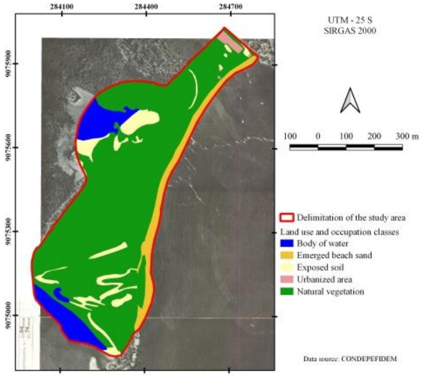
At: Total area of the study region (ha).

RESULTS

Quantitative and qualitative analysis: temporal analysis of the study area

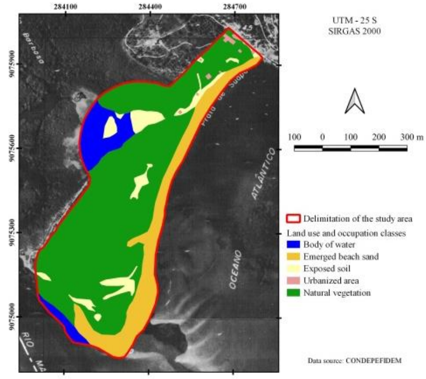
The construction of thematic maps enabled the analysis of the evolution of eachclass of land use and occupation. Figures 2 to 6 show the thematic maps made during the research. It is possible to see the highlighted areas of exposed soil (light yellow), body of water (blue), emerged beach sand (dark yellow), urbanized area (pink) andnatural vegetation (green).

Figure 2 – Thematic map of land use and occupation from 1974.



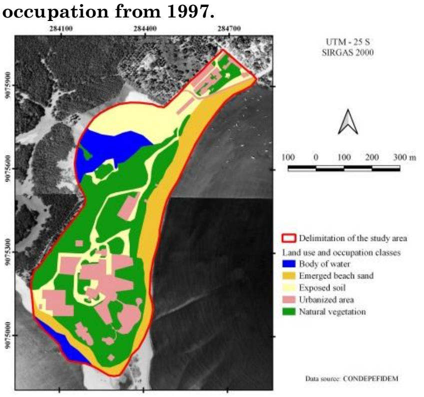
Source: Author

Figure 3 – Thematic map of land use and occupation from1988.



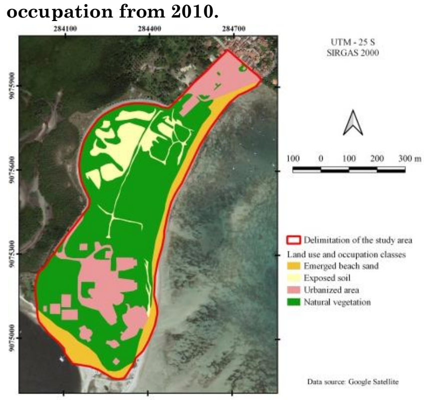
Source: Author

Figure 4 – Thematic map of land use and occupation from 1997.



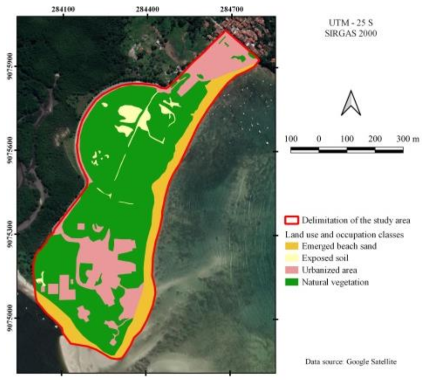
Source: Author

Figure 5 – Thematic map of land use and occupation from 2010.



Source: Author

Figure 6 – Thematic map of land use and occupation from 2020.



Source: Author

Table 3 shows the area (in hectare) and percentage of occupancy (%) of each class of land use and occupation. Table 4 demonstrates the evolution of each land cover compared to the previous evaluated year. Through the analysis of tables 3 and 4 and thematic maps, it is possible to observe that the level of urbanization increased in all years. Between 1974 and 1988, the urbanized area increased by 16.67%. Between 1988 and 1997 there was a population explosionwhere the urbanized area increased by 1114,29%. In the period from 1997 to 2010, the growth was lower, 52%, and between 2010 and 2020 it was 53.56%.

Table 3 – Area and percentage of occupancyof eachtype of land use and occupation.

LAND COVER	AREA (hactare)					AREA (%)				
	1974	1988	1997	2010	2020	1974	1988	1997	2010	2020
Urbanized Area	0,30	0,35	4,25	6,46	9,92	0,79	0,92	11,16	16,96	26,04
Natural Vegetation	28,47	25,17	15,11	22,79	20,92	74,74	66,08	39,67	59,83	54,92
Exposed Soil	2,97	2,49	7,84	3,83	1,21	7,8	6,54	20,58	10,06	3,18
Emerged Beach Sand	2,76	6,83	7,05	5,01	6,04	7,25	17,93	18,51	13,15	15,86
Body of water	3,59	3,25	3,84	0	0	9,43	8,53	10,08	0	0
Total	38,09	38,09	38,09	38,09	38,09	100	100	100	100	100

Source: Author

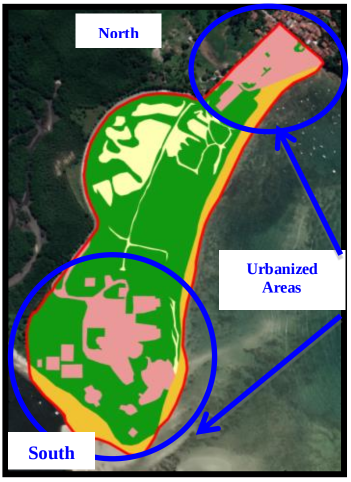
Table 4 – Rate of change of each type of land use and occupation.

LAND COVER	AREA (hactare)					RATE OF CHANGE (%)				
	1974	1988	1997	2010	2020	1974 - 1988	1988 - 1997	1997 - 2010	2010 - 2020	1974 - 2020
Urbanized Area	0,30	0,35	4,25	6,46	9,92	16,67%	1114,29%	52,00%	53,56%	3206,67%
Natural Vegetation	28,47	25,17	15,11	22,79	20,92	11,59%	39,97%	50,83%	8,21%	26,52%
Exposed Soil	2,97	2,49	7,84	3,83	1,21	16,16%	214,86%	51,15%	68,41%	59,26%
Emerged Beach Sand	2,76	6,83	7,05	5,01	6,04	147,46%	3,22%	28,94%	20,56%	118,84%
Body of Water	3,59	3,25	3,84	0	0	9,47%	18,15%	100,00%	0,00%	100,00%

Source: Author

In the 46 years covered by the historical series, the urbanization of the area expanded from 0.30 hectares to 9.92 hectares, a percentage increase of 3206.67%. Urbanization has expanded from the extremes to the center of the beach (Figure 7). Due to the fast and disorderly occupation process, it can be deduced that this area did not experience territorial planning and ordering.

Figure 7 – Urbanized area in the extremes north and southof Suape beach.



Source: Author

Where there is a higher percentage of urbanized area (north and south parts of the beach) there is a higher incidence of coastal defense structures. Venancio et al. (2020) claim that urbanization puts pressure on the coastal area preventing the beach from progressing towards the mainland. To prevent the sea from advancing on human constructions, people try to protect their property through coastal protection structures.

In relation to exposed soil, in the 46 years of the historical series, there was a 59.26% reduction in the exposed soil area. Between 1974 and 1988, this land cover had an area regression of 16.16%. However, between 1988 and 1997, there was an increase of 214.86%. Through the analysis of thematic maps, it is possible to realize that exposed soil expanded taking place mainly from vegetation.

From 1997 onwards, the area of exposed soil declined considerably, but not because of the restitution of vegetation, but due to the growth of the urbanized area. From 1997 to 2010 there was a reduction of 51.15% and from 2010 to 2020 there was a decrease of 68.41% mainly due to the advance of urbanization.

The removal of vegetation generates environmental problems such as water resource degradation and soil disturbances (RODRIGUES et al., 2019). The natural vegetation that covers the soil protects it from erosion and sediment carriage. The main form of soil degradation in Brazil is the erosion that comes from the impact of raindrops and runoff on exposed soil (LUIZA; ARAÚJO, 2017).

In relation to the land cover natural vegetation, practically in all yearsthere was a reduction in vegetation cover compared to the previous year. During the historical series, vegetation lost 26.52% of its space, mainly for urbanization and exposed soil. Between 1974 and 1988, there was a decrease of 11.59% in its area and from 1988 to 1997 there was a reduction of 39.97%.

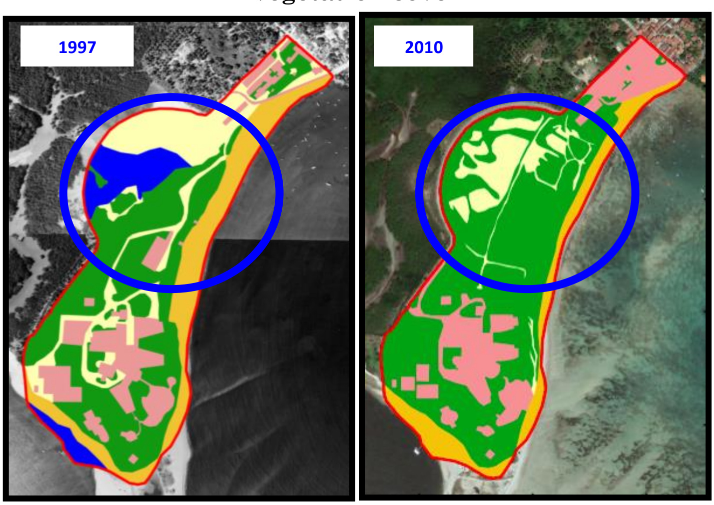
Between 1997 and 2010 there was an atypical increase of 50.83%. The probable reason was the disappearance of the body of water. The area that used to be water went filled with vegetation and exposed soil. Between 2010 and 2020, the area of natural vegetation dropped again, reducing by 8.21%, mainly due to the advance of urbanization. According to Barbosa et al. (2011), disorderly urbanization increases significantly environmental damage.

It is also possible that coastal erosion plays a role in the constant removal of vegetation. As the sea advances, the emerged beach (coastline) also advances in relation to the continent, thus destroying the native vegetation cover. Maranhão et al. (2012) verified in their research that the advance of the coastline along the historical series destroyed the post-beach vegetation. Finally, the more vegetation is removed from coastal areas, the faster the erosional process becomes (CABRAL; DA SILVA; GIRAO, 2014).

In relation to the body of water, from 1974 to 1988, the area had a small reduction of 9.47% and between 1988 and 1997, the area increased by 18.15%. It is noticed that, between 1974 and 1997, there were no great variations in the bodies of water area.

However, between 1997 and 2010, after the population explosion (1988 to 1997), the entire body of water disappeared (Figure 8), no longer appearing until the last year analyzed in this research. Therefore, the area variation between 2010 and 2020 was 0% and the reduction between 1974 and 2020 was 100%. Figure 8 shows that the area where used to be water became exposed soil and vegetation.

Figure 8 – Replacement of the body of water with exposed soil and vegetation cover



Source: Author

One of the reasons for the end of the bodies of water can bedisorderly occupation that harmed waterresource areas by reducing infiltration rates (due to waterproofing and deforestation), which reduces the recharge of aquifers, harming the availability of water (MIRANDA; DECESARO, 2018).

In relation to the emerged beach, with the exception of the years between 1997 and 2010, in all others there was an increase in area. Between 1974 and 1988, there was an increase of 147.46%. Analyzing the thematic maps, it is observed that this increase in area occurred mainly at the mouth of the Massangana River, not on the beach as a whole. Holanda et al. (2020) also found that the sea was advancing over most part of Suape beach, but in the vicinity of the mouth of the Massangana River there was a punctual but significant increase in sand.

Between 1988 and 1997, the beach was stable with a small gain of 3.22% in area. In the years between 1997 and 2010, right after the population explosion, the surface of the emerged beach dropped 28.94%. Between 2010 and 2020, the area grew again (20.56%). During the entire historical series (1974 to 2020), the area gain was 118.84%. Despite this, Fabin (2018) showed that the Suape bay has been facing a negative sedimentary balance, which means that the eroded volume of sediments is greater than the deposited volume.

Holanda et al. (2020) used the fixed-point delimitation method along the coastline to assess coastal erosion. The authors concluded that the Suape beach has been facing chronic erosion and the shorelinehas advanced towards the continent. The coastline (stretch of sand) is being strangled at points where there are human constructions as the fixed structures prevented the sea from progressing.

The area of the emerged beach has increased over the course of the historical series. This growth may leave the false impression that the shoreline is getting fatter (rather than thinner, what would be expected on a beach facing coastal erosion). However, the emerged beach land cover cannot be analyzed in isolation. The diagnosis of an erosional process is made taking into account a combination of factors. The growth observed in the emerged beach area was punctual, essentially near the mouth of the Massangana River, not along the entire length of the beach. In addition to this aspect, other reasons can be pointed out as possible causes for the rise of the emerged beach sand area even in regions facing coastal erosion:

1) As the sea advances towards the mainland, the beach sand may also advance. If the post-beach is occupied by fixed constructions, in fact the emerged beach sand has no way to progress and its area

will tend to reduce. However, at Suape beach, there is still a large part of the post-beach filled with natural vegetation. So, the emerged beach sand (coastline) can move forward and the vegetation land cover is the one thathas its area reduced. In fact, this research found that the green area continuously decreased throughout the historical series.

2) As the sea moves towards the continent, local population, who work in the beach huts, tend to remove part of the natural vegetation to maintain a stretch of sand (emerged beach sand) where chairs and umbrellas can be placed.

3) The methodology does not allow taking into account the tide level at the time the images was captured. In some images, the tide could be lower than the previous year, giving the impression that there was an increase in the beach sand area.

Qualitative analysis of geoindicators of coastal erosional processes

The use of indicators (evidences and indices) of coastal erosional processes is an alternative for carrying out erosion risk assessments in coastal areas (MARTINS et al., 2016). Souza and Suguio (1996), Martins et al. (2016) and Menezes (2016) determined geoindicators of erosional processes, some of them were found in the study area. Figures 9 to 12 show some of the geoindicators found on Suape beach.

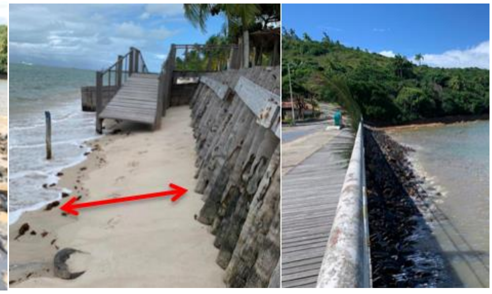
Figure 9 – Trees on the beach face with exposed roots.

Source: Author

Figure 10 – Erosion marks at the walls.

Source: Author

Figure 11 – Vey narrow or non-existent backshore zone.



Source: Author

Figure 12 – Presence of coastal protection structures

Source: Author (2021)

CONCLUSIONS

The existence of erosional process in the region was evidenced by the presence of geoindicators and environmental degradation was verified through the study of thematic maps over the 46 years of the historical series.

The multitemporal analysis of land use and occupation showed that the level of urbanization increased in all studied years, with a total growth of 3206.67% (1974 – 2020). These data represent the lack of territorial planning and ordering in the region. It was observed that where there is a higher level of urbanization, there is a greater incidence of coastal protection structures.

In the historical series, exposed soil had a reduction of 59.26%. Between 1988 and 1997, an atypical growth of 214.86% was verified. From 1988 to 1997, this land cover class took space mainly from the natural vegetation.

The area of natural vegetation reduced by 26.52% (1974 – 2020). Thematic maps showed that urbanized area and exposed soil were the main classes that suppressed vegetation land cover.

Between 1997 and 2010, the body of water was extinct in the region and its area replaced by exposed soil and vegetation. Disorderly urbanization may beone of the causes of the end of this land use and occupation class.

The emerged beach sand class showed growth in almost every year, totaling an increase in area of 118.84%. The distribution of this increase in area was not uniform, occurring essentially close to the mouth of the Massangana River.

From these results, it can be understood that the erosional process continues to act on the shore and causes problems not only on the beach itself but also on other land use and occupation covers and on the structures built by humansnear the shore.

The multitemporal analysis was very important for the evaluation of correlations between the classes of land covers. For example, it was found that there is a higher incidence of coastal protection structures where there is a lower incidence of natural vegetation and a higher incidence of urbanized area.

It could be understood that it is not possible to reach a precise diagnosis of presence of coastal erosional processesby evaluating only one class of land cover in isolation. Even with an increase in emerged beach sand area, this does not mean that there is no sea advance. Other factors such as geoindicators and variation in other land cover showed that there is erosion in the region.

Two probable reasons why the land cover emerged beach sand did not decrease are: the proximity to the mouth of the Massangana River and the advance of the sand stretch (coastline) over the vegetation as erosion progressed. It is likely that, if there was no river mouth in the region and there were more static structures in the post-beach that would make it impossible for the sea to advance, the emerged beach sand area would reduce along the historical series.

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