

**ANTHROPOGENIC IMPACTS ON THE MORPHOLOGICAL
EVOLUTION OF THE PACOTI ESTUARY, NORTHEAST BRAZIL**

***IMPACTOS ANTROPOGÊNICOS NA EVOLUÇÃO MORFOLÓGICA DO ESTUÁRIO
DO PACOTI, NORDESTE DO BRASIL***

***IMPACTS ANTHROPOGÈNES SUR L'ÉVOLUTION MORPHOLOGIQUE DE
L'ESTUAIRE PACOTI, NORD-EST DU BRÉSIL***

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ABSTRACT

The problem of anthropogenic occupation on the banks of estuaries and rivers has been a factor of concern and frequently addressed around the world. In the State of Ceará, this problem has been persistent, despite the reasonable environmental legislation dealing with this issue. Along the Pacoti River Estuary, this problem was addressed in this study and added to the analysis of the wind action in the evolution of this coastal environment. Thus, direct and indirect methods were applied, mainly based on field work and remote sensing based in the use of tools from a GIS platform. The results show persistent and continuous participation of aeolian activity, notably dunes migration, in the evolution process of this estuary. Additionally, human interference over 63 years, whether in the form of exploitation of natural resources and/or urban occupation on the banks of the estuary and in the possible area of expansion of this environment, has produced serious environmental damage and restricted the natural area of this important coastal ecosystem. This process of environmental degradation was largely accelerated from the occupation of the area to the east of the estuary by the Beach Park development, and to the west by the Alphaville Residential Condominium.

Keywords: Estuary. Dunes. Pacoti River. Anthropization.

RESUMO

O problema da ocupação antrópica nas margens de estuários e rios tem sido um fator de preocupação e frequentemente abordado em todo o mundo. No Estado do Ceará, esse problema tem sido persistente, apesar da razoável legislação ambiental que trata do assunto. Ao longo do estuário do rio Pacoti, este problema foi abordado neste estudo e somado à análise da ação do vento na evolução deste ambiente costeiro. Assim, foram aplicados métodos diretos e indiretos, baseados principalmente em trabalhos de campo e sensoriamento remoto baseado no uso de ferramentas de uma plataforma SIG. Os resultados mostram a participação persistente e contínua da atividade eólica, notadamente a migração das dunas, no processo de evolução deste estuário. Além disso, a interferência humana ao longo de 63 anos, seja na forma de exploração dos recursos naturais e/ou ocupação urbana nas margens do estuário e na possível área de expansão desse ambiente, tem produzido sérios danos ambientais e restringido a área deste importante ecossistema costeiro. Esse processo de degradação ambiental foi amplamente acelerado a partir da ocupação da área a leste do estuário pelo empreendimento Beach Park, e a oeste pelo Condomínio Residencial Alphaville.

Palavras-chave: Estuário. Dunas. Rio Pacoti. Antropização.

RESUMÉ

Le problème de l'occupation anthropique des berges des estuaires et des fleuves a été un facteur de préoccupation et fréquemment abordé dans le monde. Dans l'État de Ceará, ce problème persiste, malgré la législation environnementale raisonnable traitant de cette question. Le long de l'estuaire de la rivière Pacoti, ce problème a été abordé dans cette étude et ajouté à l'analyse de l'action du vent dans l'évolution de cet environnement côtier. Ainsi, des méthodes directes et indirectes ont été appliquées, principalement menées sur le travail de terrain et la télédétection basée sur l'utilisation d'outils issus d'une plateforme SIG. Les résultats montrent une participation persistante et continue de l'activité éolienne, notamment la migration des dunes, dans le processus d'évolution de cet estuaire. De plus, l'ingérence humaine pendant 63 ans, que ce soit sous forme d'exploitation des ressources naturelles et/ou d'occupation urbaine sur les rives de l'estuaire et dans l'éventuelle zone d'expansion de ce milieu, a produit de graves dommages environnementaux et restreint l'espace naturel de cet important écosystème côtier. Ce processus de dégradation de l'environnement a été largement accéléré depuis l'occupation de la zone à l'est de l'estuaire par le développement de Beach Park, et à l'ouest par l'Alphaville Residential Condominium.

Mots clés : Estuaire. Dunas. Rivière Pacoti. Anthropisation

INTRODUCTION

Estuaries are part of mixed coastal environments, which diverse geological, oceanographic, and sedimentological characteristics make them unique systems (Davis, 1985). Because they are semi-confined and undergo strong interaction between marine and river processes (Pritchard, 1967), they correspond to a transitional environment (Dalrymple et al., 1992). The interaction between freshwaters with marine waters develops an environment where tides promote the circulation of nutrients and food, in addition to the removal of waste from the metabolism of organisms (e.g. Van Es & Laane, 1982; Fisher & Likens 1973; Kemp, et al., 1997).

Additionally, on tropical coasts, the sediments deposited in this environment are colonized by several animal species and by characteristic vegetation in arboreal and shrubby areas (e.g. Soavinski & Maretti, 2018). This vegetation is subject to intermittent immersion, forming mangroves, which are characterized as one of the most productive and fertile environments in the world, as shown by Lacerda (2002, Soares et al., 2021). In this process, most of the nutrients remain in the estuary and another part is carried to the sea, creating favorable conditions for it to function as a "nursery" for several species (e.g. Nguyen et al., 2016; Josiah and Frantz, 1992).

Although mangrove vegetation is capable of assimilating a large number of contaminants, this capacity has limits, which requires a certain control over what and the number of pollutants and contaminants released into this environment. Thus, mangroves are considered vital areas on our planet and require maximum protection from environmental disturbances. Therefore, according to Kandasamy (2012), mangroves act to protect the coast against UV-B solar radiation, "greenhouse" effects, storms, floods, sea-level rise, wave action, and coastal erosion. They also act as traps for sediment and sinks for nutrients, and their root systems keep the substrate firm, thus contributing to the lasting stability of the coast.

On the northeastern coast, these environments generally evolve under the interaction of effective wind activity and have been suffering from the increase in anthropogenic activities. The area of this study involves the sustainable use conservation unit (Environmental Protection Area-EPA) of the Pacoti River, which was created by DECREE No. 25,778, on February 15, 2000. This EPA covers an area of 2,914.93 hectares located between the Municipalities of Fortaleza, Eusébio, and Aquiraz (Fig. 1). This area, over many years, has been experiencing a constant process of occupation and degradation. Thus, this work aimed to qualitatively and quantitatively evaluate the process of occupation of the Pacoti River Estuary, as well as to address its evolution. For this, direct and indirect methods of measurement and analysis were used.

STUDY AREA

The study area, corresponding to the stretch of the Environmental Protection Area (EPA) of the Pacoti River Estuary (Fig. 1), is under the general domain of semi-arid tropical climate, in the sense of Köppen (1936). In the coastal region, it has characteristics of a sub-humid tropical climate with a rainy season between January and May and a dry season between June and December. Rainfall rates in the coastal region reach around 1,400 mm/year, associated with an average temperature of 27°C with a low amplitude of variation (IPECE, 2018).

Most of the time, the dynamics of the northeast coast are controlled by sea waves, but it is also strongly influenced by dispersive waves or swell (Morais, 1980, Maia, 1998, Carvalho, 2003).

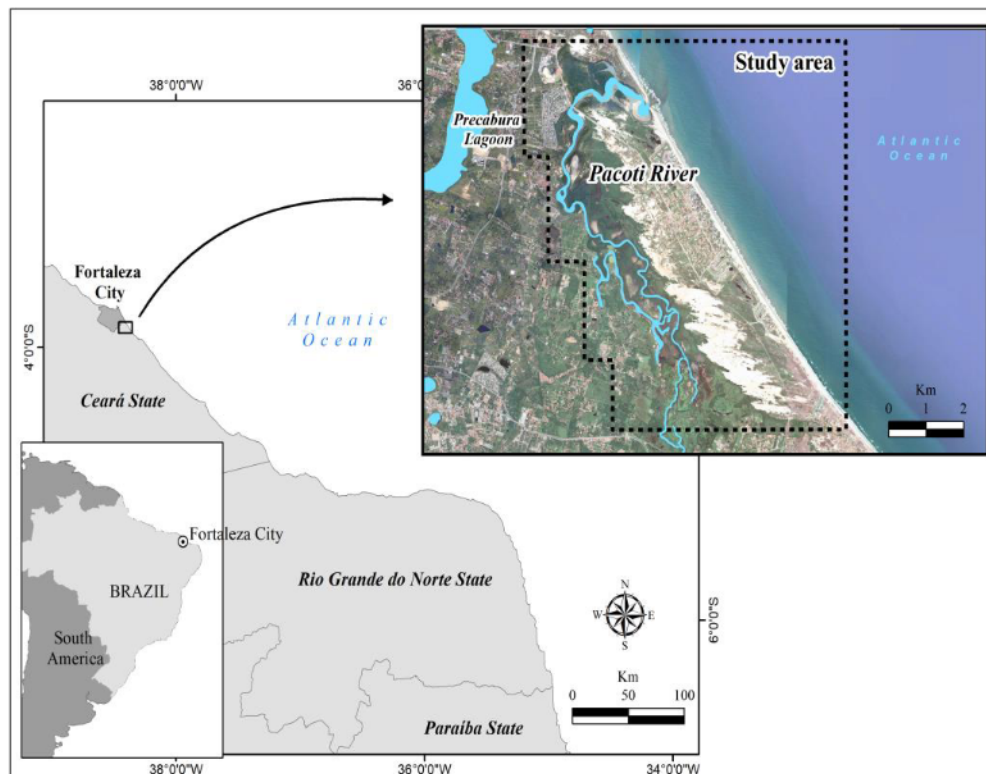
The wind regime varies seasonally and is inversely proportional to the rainfall pattern (Carvalho, 2003; Claudino-Sales, 1993; Claudino-Sales, Wang, and Carvalho, 2018), with low-velocity values in the first semester and maximum values in the second semester. of the year. Wind directions are predominantly in the E and ESE quadrants, under the primary influence of the southeast trade winds (Chung, 1982; Carvalho, 2003; Utida et al., 2019). The wind is characterized as unidirectional easterly winds, with RDP/DP values close to 1 and average drift potential of about 692 v.u. (Tsoar et al., 2009).

The tidal regime is characterized by a semidiurnal and meso-tidel system, subject to a tidal variation of 2 to 3 m, with astronomical tides reaching a maximum value of 3 m and a minimum of 0.2 m (Eduardo et al., 2021).

Under the influence of southeast trade winds, higher energy marine states can occur between September and November, when the withdrawal of the intertropical convergence zone (ITCZ) from the area allows the development of very intense winds. Meanwhile, the arrival of swell events is most often identified between January and March (Fisch, 2008), as low-pressure cyclonic systems are frequent over the North Atlantic Ocean, and the region becomes one of the main zones of cyclogenesis (Fisch, 2008; Mendes and Mendes, 2004; Trigo, Davies, and Bigg, 1999). The swell is generated by the formation of these cyclogenesis zones, mainly between latitudes 35° N and 65° N, and reaches the Brazilian northeast coast, with an average response time of 3 days (Farias, 2012). The incidence of swell waves up to 2.8 m of significant height (Hs), peak periods (T) from 11 to 20 seconds, and peak direction from NW to NE (Dp), are associated with a maximum spring tide, reaching resulting heights (Hr) up to 5 m characterize local storm surge events (Fisch, 2008).

Figure 1 - Location Map of the studied area.

Fonte: the authors



METHODOLOGY

Mapping

The identification and mapping of the geological/geomorphological features was performed through remote sensing and fieldwork. The remote sensing applied was based on historic aerial photograph of 1958, 1976 and 1980. Additionally, to carry out this study, a survey of the Landsat/Copernicus satellite images available from 2004 to 2021 was also carried out. These images and aerial photographs were processed and georeferenced on the SIRGAS2000/UTM ZONE 24S datum in a GIS environment. Various working scales were used according to the need to expand the visualization of contacts between morphologies and sedimentological units, resulting in a presentation scale of 1:25,000.

Morphodynamic and Environmental Analysis

The geomorphology study and its interaction with the wind dynamics were carried out in two stages: (1) remote sensing, evaluating the conditions of wind incidence according to the shape and positioning of the coastline, and dune crest positioning over time, and also the analyses of human occupation history; (2) fieldwork, when the local geomorphology, surface structures, and human occupations were evaluated. The active aeolian morphologies and the terrain surface and their relationship with the current dynamics were also evaluated.

The measurements and attitudes of cross-strata were done using a Brunton compass and Stereonet Mobile for iOS v. 3.0 © (Allimendinger, 2006) for iPhone. The measurement of the

tidal curve in the Pacoti estuary was performed using a TWR-2050 pressure sensor for 13 hours. Corrections were based on the historical tidal curve for Porto de Mucuripe in Fortaleza-CE.

Geometric Correction (georeferencing) of Satellite Images and Aerial Photographs

In many image processing applications and aerial photographs, it is necessary to compare multiple images of the same scene, acquired by different sensors, or images from the same sensor, but from different times. These images and photographs may have relative translation, rotation and scale, and other geometric transformations between them (Silva & Dutra, 2005).

In the present work, the geometric correction (image registration) was the technique used to solve this question of the aforementioned transformations. Silva & Dutra (2005) comment that the registration of images establishes the correspondence between two images and determines the geometric transformation that aligns one with the other. And through the image registration it is possible to perform multi-temporal analysis, the combination of images from different sensors, the combination of spatial and spectral resolution, the elaboration of mosaics and the integration of an image to the existing database in an Information System. Geographical (GIS).

In order to perform the geometric correction of the images, the authors suggest obtaining control points in satellite images, which is done from features identified both in the base image and in the adjustment image.

In this context, the present work used this technique of geometric correction for the georeferencing of aerial photographs and satellite images. The features used for georeferencing were: lines (roads) and points (intersections of lines and points that highlight high relief).

The choice of control points was made in the base images of the QUICKBIRD satellite, with a spatial resolution of 0.61 meters, extracted from the Google Earth Pro program. For that, easy identification points were chosen in the images so that the geometric correction could be carried out. The process was carried out in the QGIS program version 2.4 “Chugiak” (Sherman et al., 2007), using the horizontal DATUM Sirgas 2000 and UTM zone 24 South projection.

Application of DSAS (Digital Shoreline Analysis System) and adaptation to study the evolution of dunes

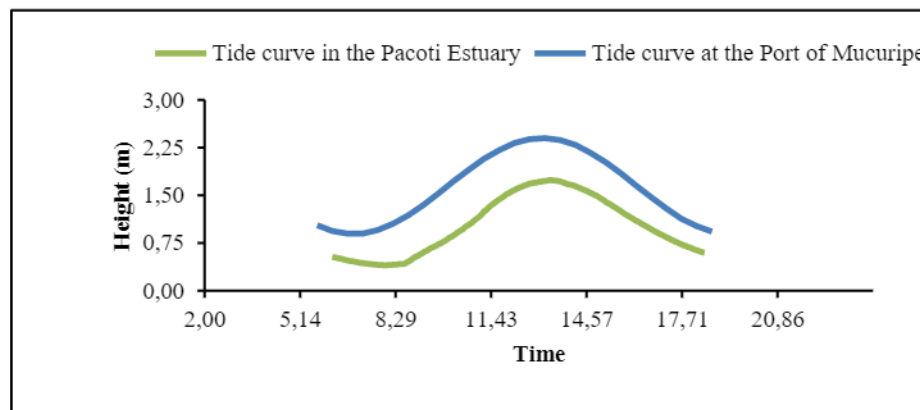
The integration of georeferenced data, from satellite images and aerial photographs, using QGIS software version 2.4, provided the calculation of dune advance rates from the dune frontal baseline trace between the years 1958 and 2021.

The forward rates of the dune front base were obtained using the Digital Shoreline Analysis System (DSAS) tool version 4.4 (Thieler et al., 2009) which is a free software application that works within the Environmental Systems Research Institute (ESRI) Geographic Information System (GIS) software for ArcGis. It calculates rate of change statistics for a time series of shoreline vector data, so it has been adapted to the dune front baseline. The DSAS input data is generated within a geodatabase, which also serves as a storage location for the software resource class generating transects and tables related to the statistical results.

RESULTS

The Pacoti River Estuary presents characteristics of a tide-dominated estuary, with the advance of the flood tide faster than the retreat of the ebb tide (Fig. 2). In this estuary, the channels are narrow, presenting favorable conditions for the seawater trapping in embayments and abandoned meanders during the high tide, and returning to the main channel in the ebb tide.

Figure 2 - Tide curve of Pacoti River Estuary showing advance of the flood tide faster than the retreat of the ebb tide.

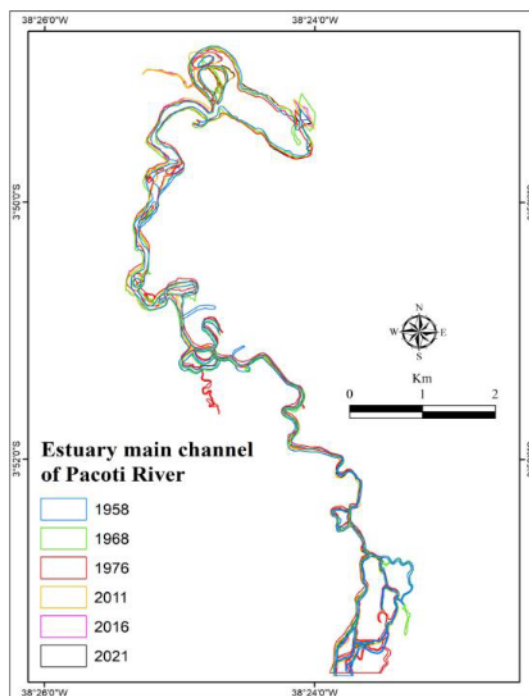


Source: the authors

The mouth of the estuary has exhibited internal sand deposition characteristics of flood tidal delta type, with an eastern river mouth spit developed with the aid of wind activity, and the western spit has been for a long time reinforced with the introduction of concrete structures to prevent erosion. The Beachrocks outcrops, positioned parallel to the coastline in front of the river mouth, difficult the direct access of marine water to the estuary basin. The estuary is completely bordered and conditioned to the east by the advance of a wide field of crescentic transgressive dunes with a sequence of chevron-shaped front of about 15 km (Figure 3), involving barchanoid and parabolic dunes. Over time, the heterogeneous migration of these dunes has penetrated westward and in some places pushed the main channel of the estuary, consequently causing its displacement towards the west. In this context, the channel develops meanders that moved from the center of the main channel towards the west, in addition to developing other meanders towards the east in the rainy season when the wind transport decreases concomitantly with the increase in water volume of the river (Fig. 4).

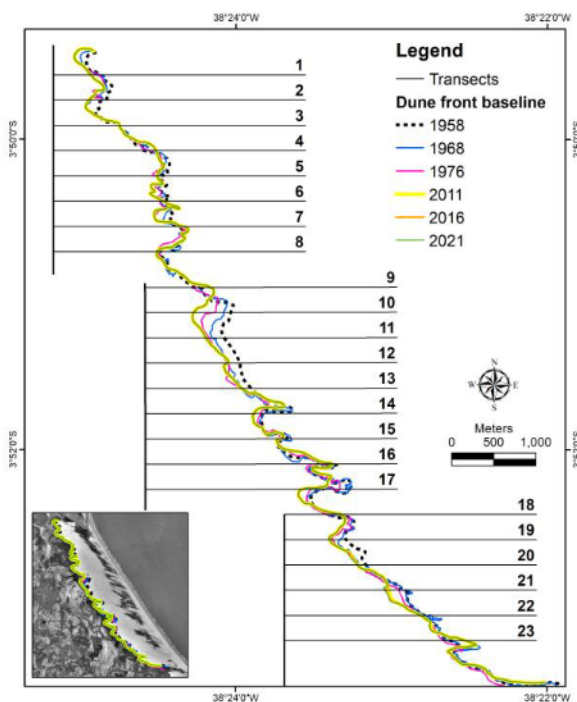
The analysis of the migration of the dune front for about 63 years, based on the 23 transects generated by the DSAS that cross the frontal baselines of the dune field between the years 1958 and 2021 (Fig. 5) shows that the greatest displacement was recorded between the years 1958-1968, 1968-1976 and 1976-2011. As for the intervals between the years of 2011-2016 and 2016-2021, little general movement was noted in the dune field, only some spits or isolated points, where there was no growth of vegetation or urban occupation. Between 1958 and 1968 the average dune migration rate was 7.1 m/year, decreasing to 4.2 m/year between 1968 and 1976; 2.9 m/year between 1976 and 2011, and significantly between 2011 and 2016 and 2016 and 2021, when rates of 0.3 and 0.1 m/year were recorded (Figure 4).

Figure 3 - Dune front movement towards and over the Pacoty River Estuary area between 1958 and 2021. The transects used to calculate this movement are shown.



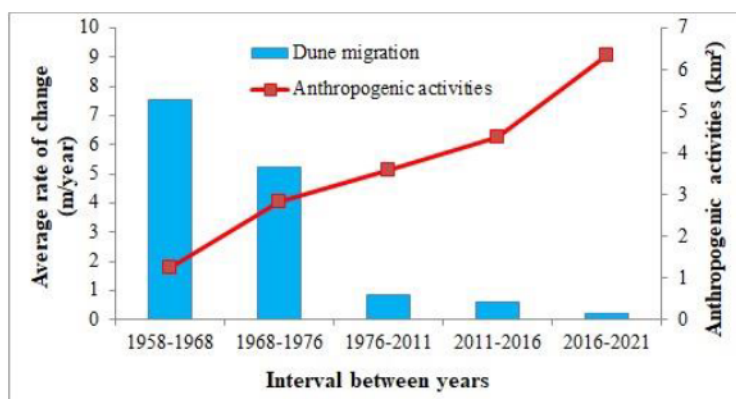
Source: the authors

Figure 4 - Evolution of the main channel of the Pacoti River Estuary under the influence of dune front migration.



Source: the authors

Figure 5 - The variation of the average rate of advance from the baseline of the leeward face of the dune field towards the estuary of the Pacoti River between 1958 and 2021 and its relationship with the anthropization of the area.



Source: the authors

In 1958, the area of what would become the EPA of the Pacoti River Estuary and its surroundings was characterized by a pretty small amount of anthropized area, consisting of only small farms, rudimentary houses and salt pans mining. The variation of anthropogenic occupation (Fig. 6), considering the salt pans mining, ranged since 1958, from just over 145.2 hectares, corresponding to what seems to have been the beginning of the exploitation of salt pans mining. Grew to about 237.0 hectares in the year 1968, and to 420.0 hectares in the year 1976. From then on, this activity decreased drastically to 14.8 hectares in the year 2011, followed by the complete abandonment of the exploitation of salt pans mining in this area (Table 1). On the other hand, as the salt pans were abandoned, many of these areas were recolonized by mangroves. However, shrimp farms were installed in part of the stretches previously occupied by salt pans mining. The variation in the dimensions of the mangrove area fit negatively with the these salt pans implantation and later with the replacement of this activity by shrimp farms and also by urban expansion (Table 1).

The process of human occupations by rudimentary houses and farms of about 407.03 hectares in the 1958, evolving to second houses and finely the formation of a small city in the 2021, computing about 1041.27 hectares, can be followed as anthropogenic activities in Table 1. This occupation process reached a larger area since the Alphaville condominium was implemented in the year 2002, on the west bank of the estuary, and the Beach Park project, to the east, in the year 1989 (Figure 6). Since then, mainly the eastern portion has suffered an intense process of anthropization.

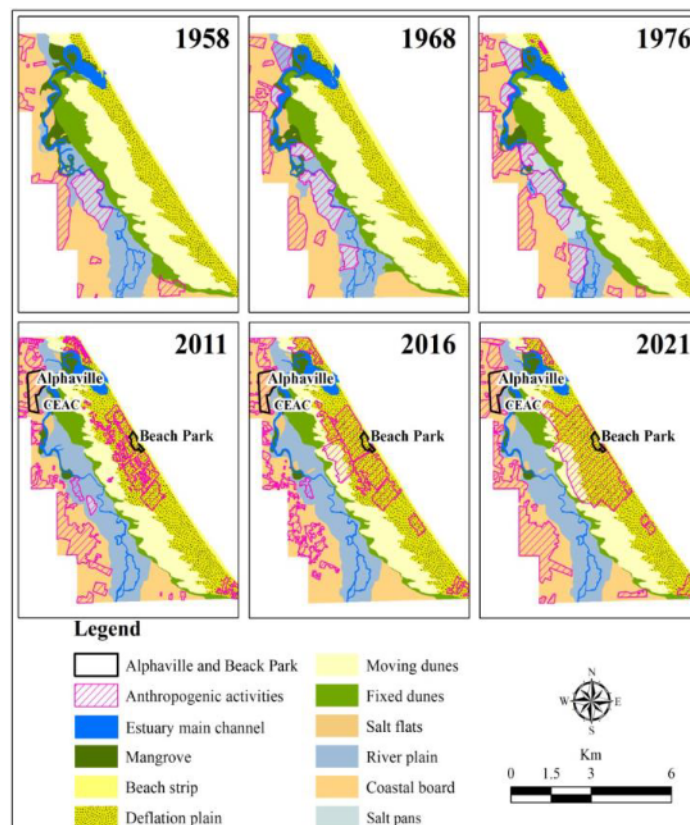
Table 1 - Measured areas of natural morphological units and anthropogenic occupations.

Ha	1958	1968	1976	2011	2016	2021
Anthropogenic activities	407.03	550.12	690.31	767.28	845.78	1041.27
Salt pan mining	145.22	236.93	419.94	14.77	-	-
Salt flats	58.95	46.52	60.63	34.55	38.70	36.47
Mangrove	179.32	154.3	115.14	85.56	83.13	88.78
River plain	965.07	874.63	781.37	924.70	927.66	932.07

Ha	1958	1968	1976	2011	2016	2021
Moving dunes	938.15	1000.01	978.35	602.59	595.08	600.24
Fixed dunes	448.56	349.66	383.60	259.66	259.06	258.43
Estuary main channel	172.38	195.46	183.46	164.18	160.59	156.21
Deflation plain	665.21	636.13	651.24	1074.84	1104.82	1103.94
Coastal boards	1052.06	1113.73	1083.10	1148.18	1158.52	1157.20
Beach strip	104.48	183.87	101.16	83.59	84.16	59.53

Source: the authors

Figure 6 - The sequence of human occupations from rudimentary houses and farms till the formation of a small city called Porto das Dunas.



Source: the authors

DISCUSSIONS

The dune front migration in the prolonged period of drought has been promoting a wide heterogeneous advance of the dune crests over the river bed. The crescentic dune fields, such as barchan, barchanoid, and parabolic dunes shapes migrate during about six months of drought and stay stuck or with much less movement during the six months of the wet season. Consequently, it causes a displacement of the main channel to the west as dune crests push it, and it may even experience temporarily blockade the course of the river and formed a lake during this process over the years. The migration of the parabolic dune front (Fig. 3) may

decrease the sand volume to the windward side, or east of this dune, while pushing the river bed to the west. This process, in the following rainy season, with an increase in the volume of the river, can facilitate the resumption of its original channel, abandoning the previous one (Fig. 4) positioned further west. This process was repeated over time, developing a kind of meandering system. The average rate of advance of the frontal baseline of the Pacoti River Estuary dune field between 1958 and 2021 fell according to the growth of the urban area in the windward area of the dune field.

Human occupation along the east and west banks of this estuary has resulted in a large degradation effect on the environment, since the introduction of salt pans, evolving to the implementation of shrimp farms. The establishment of salt pans mining began on the outskirts of the Ceará River, with several small units, such as the Vila Velha and Margarida salt pans in Fortaleza, dating back to 1925 and 1945 respectively.

However, the highlight of salt production took place in the 1960s, in the estuary of the Cocó River in Fortaleza, known as Salina Diogo. Additionally, the decline of this salt activity in the region occurred in the late 1970s, triggered by financial difficulties due to the process of expanding the use of machinery to obtain salt in Rio Grande do Norte, which made the activities give way to the industrial pressures, as well as due to the most suitable environmental characteristics for salt production in this region (Do Carmo, 2020). This information fits with the data from the Pacoti River Estuary, showing that this activity in this estuary began before 1958 and expanded until around 1970. From that date it declined, being abandoned in some stretches, resulting in the consequent small and localized recovery of mangrove cover, and in other stretches replaced by the implementation of a shrimp farm.

The expansion of urban occupation on these estuarine environments has represented a wide environmental impact and began in the 1990's and gradually advanced until the 2000's years, when the E.P.A. of the Pacoti River Estuary was created. From then on, the speed of urban occupation and other anthropogenic activities slowed down in part of the Pacoti River Estuary. However, with the wide scope of summer activity, implementation of second houses, and even permanent housing in the Porto das Dunas region, this process has been expanded and has put pressure on environmental legislation and control bodies. The apex of this process seems to have occurred with the implementation of the Beach Park in Porto das Dunas locality in the year 1989, and the Alphaville Condominium in the year 2002, where estuarine area under this domain was occupied both side, respectively on the east and west banks (Fig. 6).

CONCLUSIONS

The evolution of the Pacoti River Estuary has been largely controlled by the aeolian activity, managed by dune migration. Additionally, urban occupation, mainly after the implementation of the Beach Park project and the Alphaville Residential Condominium, seems to have played a determinant role in the process of evolution and degradation of this environment. This process has limited the areas of seasonal variation of the estuary and impacted its short, medium, and long-term behavior, in addition to producing many direct and indirect environmental impacts.

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