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Authors: Godoy, Mario Duarte Pinto, and de Lacerda, Luiz Drude

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River-Island Morphological Response to Basin Land-Use Change within the Jaguaribe River Estuary, NE Brazil

Mario Duarte Pinto Godoy* **and Luiz Drude de Lacerda**

Marine Science Institute
Federal University of Ceará
CEP 60165-081, Fortaleza, Ceará, Brazil

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ABSTRACT

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The Jaguaribe River drains the largest watershed of the Ceará state in northeastern Brazil, which, with a catchment of approximately 75,000 km^2, comprises more than 50% of the total state area. Land use and global climate changes are altering the river morphology, making navigation in the estuary difficult. Mapping of fluvial islands using images from the Landsat 5 between 1988 and 2010 showed that the existing islands in the estuary suffered great changes during this period. Overall, there was an increase of 24.15 ha in the area of the islands, which are presently being colonized by mangrove vegetation. The period of largest growth occurred between 1992 and 2003, when there was an increase of 13 ha at a rate of 2.7 ha y^{-1}. An estimate of the sediment loading from various land uses in the watershed showed that the main activity contributing to sediments to the estuary is agriculture (282,322 t y^{-1}), with the main contributions stemming from plantations of beans, cassava, and corn; the second-most important source of sediments is urban runoff (115,076 t y^{-1}), followed by shrimp farms (13,475 t y^{-1}) and livestock (1374 t y^{-1}). The increased rate of sedimentation in the estuary caused by land-use drivers is aggravated by the decrease in river flow caused by damming and the decrease in rainfall over the basin caused by global climate change.

ADDITIONAL INDEX WORDS: *Mangroves, geoprocessing, sediment budget, semiarid climate*.

INTRODUCTION

Mangroves occupy a significant fraction of the Brazilian coast—about 72% of the shoreline—extending from the north end in Oiapoque, Amapá, to its southern limit at Praia do Sonho in Santa Catarina. This ecosystem plays a key role in the stability of coastal geomorphology, biodiversity conservation, and maintenance of large fish stocks, generally used by the local population (Maia, Cavalcante, and Miranda, 2006).

In many places in the world, mangroves are showing a decrease in area of at least 35% (Feller *et al.,* 2010); in some places, however, such as New Zealand (Lovelock *et al.,* 2007, 2010), Florida (Ross, Obrien, and Sternberg, 1994), Australia (Wilton, 2002), and several sites in Brazil (Lacerda, Menezes, and Molisani, 2007; Lara *et al.,* 2002; Maia *et al.,* 2006), studies show an increase in mangrove coverage. A mixture of local and global drivers cause these alterations.

In an article on those drivers responsible for changes in the expansion of mangroves in NE Brazil, Lacerda *et al*. (2006a) argue that the changes result from the interaction of a number of factors, including river damming, water withdrawal, rising sea level, and a decrease of approximately 10% in the annual rainfall since the 1960s. These changes have resulted in a greater penetration of seawater into the continent and, consequently, a decrease in the rivers' capacity to export sediments to the adjacent continental shelf.

The Jaguaribe river hydrology was analyzed by Dias, Marins, and Maia (2009), who concluded that over the years, there has been a significant change in the river flow because of the construction of several dams. The construction of dams means the river discharge no longer corresponds to the rainfall; instead, the river flow is presently controlled by dam operations. Because of the reduced flow, several sandbanks have developed in the Jaguaribe River estuary, and the dams currently play an important role in controlling the discharge of the Jaguaribe River to the ocean. According to the Secretary for Water Resources of Ceará (SRHCE, 2010), the Jaguaribe River watershed has 87 large- and medium-sized dams. These dams are intended to provide water for both human consumption and the maintenance of regional economic activities.

This change in river flow can be seen by analyzing the data from the National Water Agency (ANA, 2010) for the station located in the town of Tabuleiro do Norte, in the margins of the river, approximately 100 km from the estuary (Figure 1). From the 1970s to the early 1990s, the river discharge followed the intensity of the rainfall, with periods of low discharge followed by several periods of peak discharge, which could reach 1000 m^3/s following rainy periods. Since the 1990s, with the construction of major dams, that flow was replaced by a flow pattern with less variation throughout the year, except for years with atypical heavy rainfall, as was the case in 2008 and 2009, when the Castanhão Dam, the largest reservoir in the basin located in the city of Jaguaribara, approximately 140 km from the Jaguaribe River mouth, was forced to open its

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*Corresponding author: mariodpgodoy@yahoo.com.br

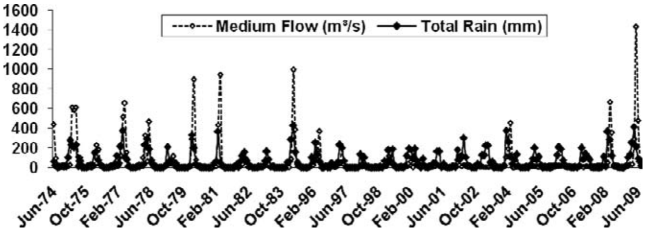

Figure 1. River flow and historical rainfall in the town of Tabuleiro do Norte (CE), Brazil. Source: Data from ANA (2010).

floodgates to prevent structural damage. In such years, the peak flows may even exceed previous peaks.

Dias (2007) stated that the decrease in the delivery of fresh water because of the damming causes the appearance of new areas of sedimentation, promoting the silting of the river in some places. The author also said that this sedimentation process along the estuary of the Jaguaribe River was straining navigation, restricting it to only two main access channels in the estuary. Marins *et al*. (2003b) showed that, even in years with atypically high rainfall, the rising tide caused an increase of suspended particulate matter within the estuary and a decrease in dissolved oxygen. That finding was evidence that flooding by seawater caused erosion and resuspension of bottom sediments, along with erosion of the estuary margins, creating new areas of sedimentation that could eventually be colonized by mangroves.

The fast growth of mangroves in high-sedimentation areas has been observed in other estuaries from northeastern Brazil. Lacerda, Menezes, and Molisani, (2007) conducted a study of the expansion of mangroves in the Pacotí River and showed that, in addition to colonizing old salt pits, mangroves also grew on progradated areas of islands and beaches. According to the authors, between 1958 and 1999, six new islands emerged in the Pacotí estuary. These new areas were quickly occupied and secured by mangrove trees, which increased in areal coverage from 71 ha in 1958 to 142 ha in 1999. After that period, mangrove areas continued to expand, reaching 144 ha in 2004.

The Jaguaribe River (Figure 2) drains the largest watershed of the state, with a total catchment area of approximately 75,000 km^2; it is divided into five sub-basins (High Jaguaribe, Medium Jaguaribe, Low Jaguaribe, Banabuiú, and Salgado). It occupies more than 50% of the state area of Ceará and is located in the northeastern region of Brazil. Climate in the region is semiarid, characterized by two very distinct periods, a rainy season from January to May, which can extend to July in rainy years, and a dry season, typically from June to December, which can extend to February in extremely dry years.

The regional tidal regime is semidiurnal, with a maximum range of 3 m. The watershed has a diversity of land covers and uses, predominantly farmland, pastures, urban areas, and areas of natural vegetation, (Marins *et al.,* 2003). The right margin of the estuarine mouth is dominated by sand dunes, and the left margin is dominated by cliffs. The

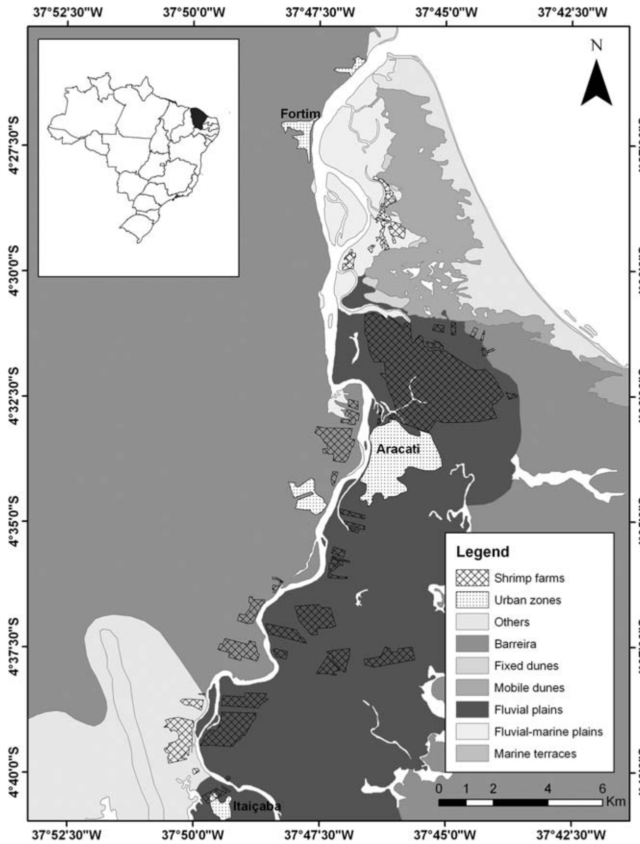

Figure 2. Map of the study area. Source: author's collection.

catchment is also responsible for 70% of all of the freshwater that reaches the Atlantic Ocean on the western portion of the northeastern coast of Brazil. Much of the catchment's hydrographic network is composed of intermittent rivers, with water flowing only during the rainy season (Dias, Lacerda, and Marins, 2011).

In this context, the objectives of this work were to measure the growth of the estuarine islands in the Jaguaribe estuary and, with the help of sediment-load estimates, to identify the principal drivers feeding those islands with sediment.

MATERIALS AND METHODS

Mapping

The first phase of this work consisted of mapping the lower estuary of the river from Aracati city, approximately 15 km from the sea, to Fortim at the mouth of the river. The software ENVI 4.0 and ArcGIS 9.2 were used to process Landsat 5 satellite images with 30-m spatial resolution from 1988, 1992, 2003, 2008, and 2010 (INPE, 2012). The dates were chosen to create intervals between the images that made it possible to identify the eventual changes in the surface area of the islands.

The images were digitally processed in ENVI, and composite images in RGB band 432 were generated. The composition of the images was chosen to facilitate differentiation of the

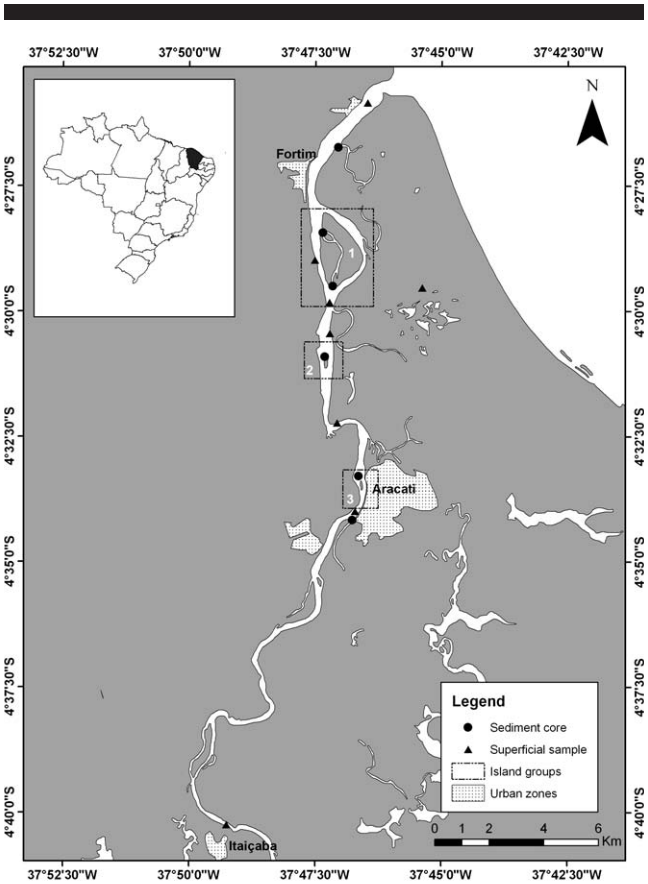

Figure 3. Map of sampling locations. Source: author's collection.

various environments in the study area. After this process, the images created were saved in Geotiff format to be used in the ArcGIS 9.2 program.

For the georeferencing of the images, control points were chosen by selecting artificial features recognizable in all of the images, such as road crossings and farm borders. This selection was made because these artificial features are more permanent on the landscape than trees, streams, and lakes, which can disappear from one image to another. The cartographic projection system used was the Universal Transverse Mercator (UTM), referenced to the geodesic horizontal datum World Geodetic System (WGS), 24 South Zone. The total Root Mean Square (RMS) error was below 10 m for all images.

With the images ready, the next step was to convert the images into vector representations consisting of lines and polygons. Because beaches and sand bars can change with the rising tide and the river flow, the increase in area of the river islands was measured based on the vegetation line because vegetation would fix the sediment, preventing its dispersion. The left and right banks of the river were also mapped in all of the satellite images.

The images interpretations took into account factors such as texture, tone, shape, and location. The estuarine islands were divided into three groups, according to their location in the estuary, to facilitate the explanation of the results (Figure 3).

To eliminate any doubts related to the mapping, field campaigns were conducted using a speedboat to visit the islands in 2009 and 2010.

Sediment-Loading Estimates

To better understand the changes in the margin morphology and the major drivers influencing the process of the silting of the estuary, estimates of sediment loading, namely, the amount of sediment emitted by each type of activity that occurs in the drainage basin of the estuary, were calculated. In that way, it was possible to better estimate the contribution of each activity to the perceived siltation of the estuary.

The sediment-loading estimates from different sources were based on information and emission factors from Tundisi (2003) as well as from regional data on the magnitude of local economic activities (IBGE, 2009) and, for shrimp farms, from data generated with the use of satellite images. The equations used are presented along with the results.

To calculate the sediment loading from the shrimp farms, we used data from Lacerda, Santos, and Madrid (2006b) and from Figueiredo (2005), who conducted studies on shrimp-farm effluents in the Jaguaribe Estuary. Based on their data, we calculated an average of their results of total suspended sediment (TSS) emission to the water; that value was used to calculate the emission factor and the estimate of the sediment loading from this river.

Sediment Analysis

To identify the potential sources of sediment that were responsible for the changes perceived in the estuary, six sediment cores were collected manually, using a rubber hammer to help insert the cores in the sediment, in different locations within the estuary. Four of the sediment cores were taken from the island beaches in the estuary, and the other two were taken from beaches in the river margin, one near the mouth and another near the city of Aracati. Those locations where chosen based on the results found during the mapping of the estuary and based on previous studies in hydrodynamics and sedimentology done in the area (Dias, 2007; Dias, Marins, and Maia, 2009; Marins and Dias, 2003; Marins *et al.,* 2003). The field campaigns took place in October 2009 using a speedboat to reach the islands and a handheld Global Positioning System to mark the sample locations. The sediment corers were made of acrylic material, 1.85 m tall and 0.56 m in diameter. Simultaneously, soil and modern sediment (0–5 m depth) samples from potential sources were collected, including dunes, fluvial–marine plains, fluvial plains, active cliffs, and samples from the bottom of the main channel. These samples were used as reference-area samples for the sediment cores and were collected and stored in plastic bags.

The sediment cores were taken to the laboratory, and the acrylic was marked where color and textural changes in the sediment layer were noticeable. Two sediment samples were taken from each layer. Those samples were labeled and dried at 80°C. After drying, the samples were ground and stored. A 25-g subsample from each sample was used for granulometric analysis: first, the samples were washed to remove the finer sediment, with the size limit of 0.062 mm. The samples were

Table 1. *Areas (ha) of Jaguaribe's estuarine islands and the changes in each island between 1988 and 2008.*

Island	1988	1992	Change (%)	2003	Change (%)	2008	Change (%)	2010	Change (%)
Group 1									
1	76.13	73.68	−3.22	75.45	2.4	75.9	0.60	75.25	−0.86
2	142.12	145.8	2.59	152.89	4.86	157.4	2.95	158.79	0.88
3	0.16	0.88	450	1.42	61.36	1.85	30.28	1.81	−2.16
4	1.61	1.85	14.91	1.52	−17.84	1.57	3.29	1.61	2.55
5	NA	0.12	100	NA	−100	NA	NA	NA	NA
6	NA	1.11	100	5.34	381.08	5.39	0.94	5.63	4.45
Group 2									
7	3.05	3.02	−0.98	3.64	20.53	3.67	0.82	3.79	3.27
8	NA	NA	NA	0.36	100	0.3	−16.67	NA	−100
Group 3									
9	3.32	3.05	−8.13	2.6	−14.75	4.02	54.62	3.66	−8.96
10	NA	0.41	100	0.57	39.02	NA	−100	NA	NA
Total	226.39	229.92	1.56	243.79	6.03	250.1	2.59	250.54	0.18

then weighed, and the material that was washed away was calculated as the difference of the initial weight from the sum of the weights of all of the other classes obtained during the dry granulometric analysis.

The dry granulometric analysis was conducted by passing the sediment into a succession of 11 sieves from 2.83 mm to 0.062 mm according to the Scale of Wenthworth, 1922 (in Suguio, 1973). The sediment within the 0.25-mm class was separated in Eppendorf microtubes to be used later in the grain-morphology analysis.

The values obtained in the granulometric analysis were entered in ANASED 4.3i, a granulometric analysis program developed at Federal University of Ceará, to obtain the statistical parameters. The grain morphology was analyzed using a microscope and comparing the analyzed sediment with the sediment morphology table of Krumbein and Sloss (1963).

RESULTS

Growth of the Estuarine Islands

We identified 10 islands in the estuary of the Jaguaribe River between 1988 and 2010. The islands' areas, obtained through the mapping of the various satellite images, are presented in Table 1.

From the beginning of the mapping in 1988 until 2010, there was a total increase of 24.15 ha (from 226.39 to 250.54 ha), or approximately 10%, compared with the initial area. The speed of that increase also changed during the period. From 1988 to 1992, the growth rate of the islands was 0.7 ha y^{-1}, and the rate increased to 2.7 ha y^{-1} between 1992 and 2003. From 2003 to 2008, the increased rate was 1.2 ha y^{-1}, and from 2008 to 2010, the rate was 0.22 ha y^{-1}. Overall, the average increase in rate between 1988 and 2010 was 1.09 ha y^{-1}.

Group 1

Group 1 presented a total increase in island area of 23.07 ha: in 1988, the island area was 220.02 ha, and in 2010, it was 243.09.

Group 1 (Figure 4) was closest to the mouth of the estuary and was the group with the largest islands. That group was located near the city of Fortim. In 1988, there were four islands in Group 1. In 1992, one of the existing island's area decreased by 3.22%, and there were three new colonized islands, resulting in six islands within the group. The result was a net expansion of 3.42 ha between 1988 and 1992, with an average growth of 0.68 ha y^{-1} in area.

From 1992 to 2003, there was a fusion of two existing islands, and the area of the islands increased from 223.44 ha in 1992 to 236.62 ha in 2003 with a growth rate of 2.6 ha y^{-1} and a total increase of approximately 13 ha.

From 2003 to 2008, all islands showed an increase in area, which ranged from 0.6% to 30% of each individual island, resulting in an overall increase of approximately 5.49 ha with a growth rate of 10 ha y^{-1}.

From 2008 to 2010, two islands showed a decrease in area from erosion. Even with those decreases, the overall behavior of the estuarine islands in Group 1 was of growth, resulting in a small expansion of 0.9 ha in 2 years.

The results of mangrove colonization (mostly by *Avicennia germinans* and *Laguncularia racemosa*), can be observed in both of the pictures in Figure 5, which shows the same beach at two different moments. The first picture shows the beach without any vegetation, and in the second picture, the same beach has been colonized by young mangrove trees of those two species.

Group 2

Group 2 presented a total increase in island area of 0.74 ha from 3.05 in 1988 to 3.79 in 2010.

Group 2 (Figure 6) is located between Group 1 and Group 3. There is no large urban center near the group, and the islands are much smaller than those in the first group. From 1988 to 1992, there was only one island in this region, and that island suffered slight erosion.

From 1992 to 2003, the area of this group expanded greatly, with the existing island area growing by approximately 20% and with the appearance of a new island. The new island was smaller than the first one but was already colonized with vegetation.

From 2003 to 2008, the largest island showed a small increase, whereas the smaller island showed strong erosion, losing almost 17% of its area.

From 2008 to 2010, the smaller island was incorporated by the largest and oldest island in the group. From 1988 to 2010, there was a net expansion of 0.74 ha or 24%.

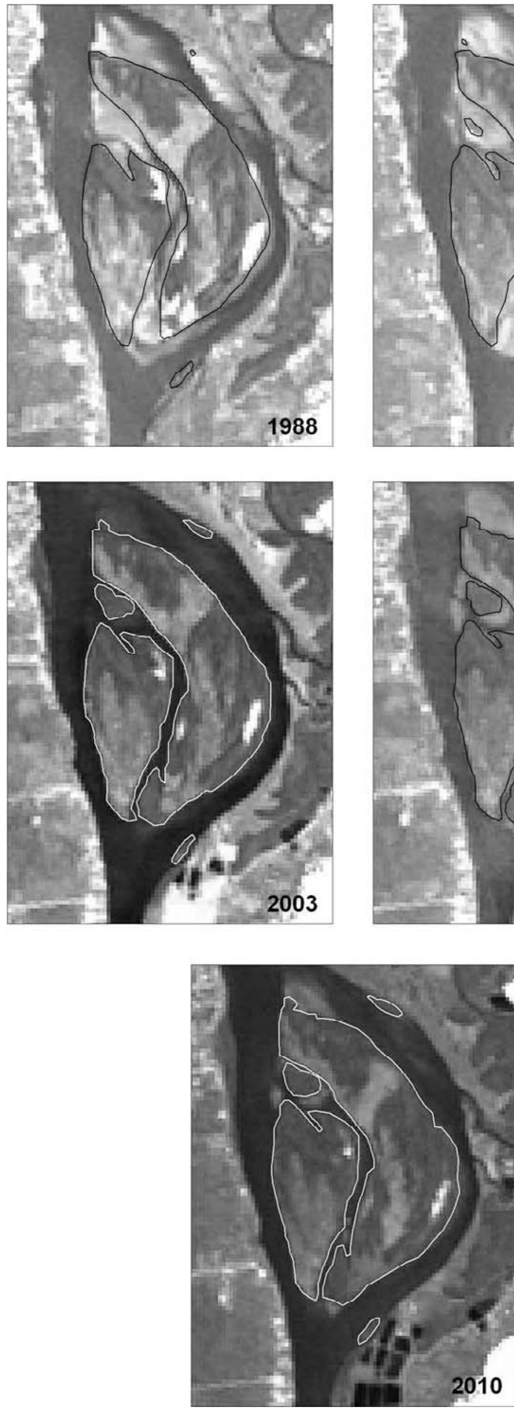

Figure 4. Map of islands from Group 1. Source: author's collection.

Group 3

Group 3 presented a total increase in island area of 0.34 ha from 3.32 ha in 1988 to 3.66 ha in 2010.

Group 3 (Figure 7) is, like Group 2, formed by small islands, but Group 3 is located in front of Aracati, the largest city in the study area, with approximately 90,000 inhabitants. In 1988, there was only one island in front of Aracati. In 1992, there was a new island, and just like in Group 2, that island was much smaller than the previously existing island. During this period, the oldest island suffered from erosion of 8% in area.

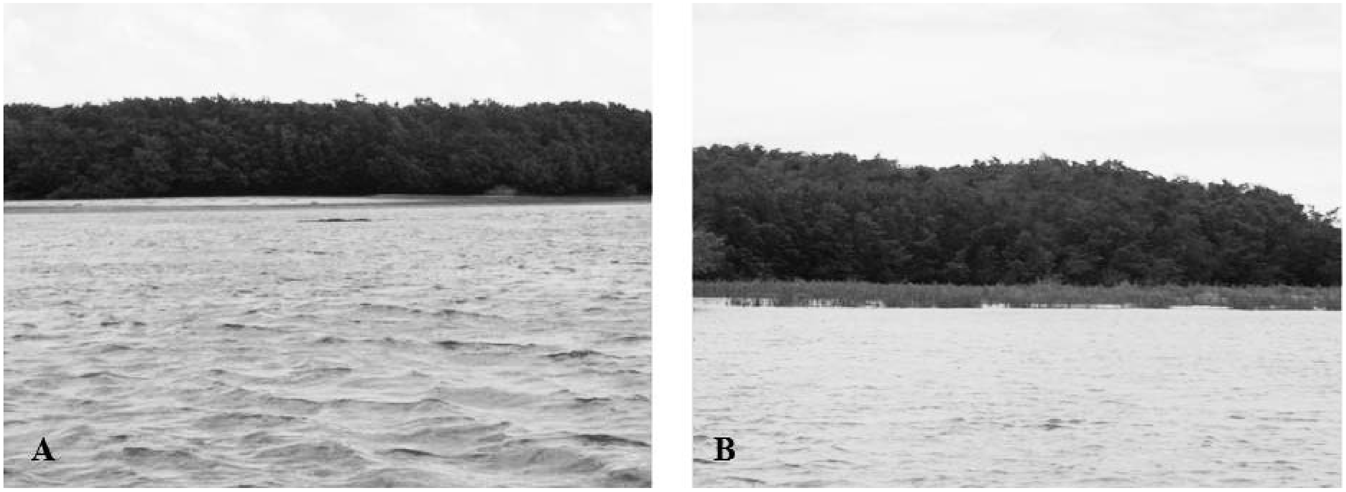

Figure 5. Mangrove spreading on a beach in the southern part of Pinto Island; photo A is from October 2009, and photo B is from August 2010. Source: author's collection.

From 1992 to 2003, the erosion of the oldest island worsened; during this period, there was a loss of 14% of the island area, whereas the newest island grew almost 40%. During this period, there was a decrease in the overall island area within this group of 8%.

From 2003 to 2008, the space between both of the islands was filled with sediment and was occupied with vegetation. Both islands turned into one island, with a growth of almost 27%.

Between 2008 and 2010, the island suffered from erosion and lost almost 9% of its area. However, from 1988 to 2010, there was a net increase of 0.34 ha, approximately 10% of the total area of the islands in this group.

River-Bank Erosion

The mapping of both of the banks of the Jaguaribe River estuary showed erosive processes. These processes were confirmed during the field campaigns, but one particularly deserved attention. In a stretch of the estuary, there is a curve located between the second and third island groups where the right margin of the estuary suffered from severe erosion during the studied period. Comparing the satellite images from 1988 and 2010, there was an erosion of approximately 115 m. That severe erosion caused large trees to fall into the estuary as can be seen in the Figures 8a and b.

Changes in Soil Use and Sediment Transport to the Estuary

The lack of emission factors for shrimp farms necessitated their calculation based on data gathered from previous studies performed in the region. The first estimates of the contribution of local shrimp farms are presented in Table 2 because there were no sediment-emission factors for this activity. The total estimates of sediment loads from all the studied activities are presented in Table 3.

Major drivers of sediment to the estuary are urbanization, agriculture, and husbandry, for which there where previous existing estimates (Tundisi, 2003), and shrimp farms, for which the estimates where calculated in this study using results gathered from other works (Figueiredo *et al.,* 2005; Lacerda, Santos, and Madrid, 2006) because there were no existing prior estimates available for the area.

Table 3 shows estimates of the soil loss from each of the soil-use categories present in the basin, indicating their relative contributions to the estuary. The main activity that contributed sediment to the estuary was agriculture (282,322 t y^{-1}), particularly beans, cassava, and corn. Agricultural contributions were followed by those of urban runoff (115,076 t y^{-1}), shrimp farms (13,475 t y^{-1}), and livestock (1,374 t y^{-1}). Unlike all other activities found in the study area, shrimp farming was the only activity in which the sediment load was released directly into the estuary. In that way, shrimp farms contribute to worsening siltation problem within the estuary.

Sediment Cores

The grain size of the cores showed a predominance of sands over the other grain-size classes (in some layers, almost 80% of the sediment was composed of >0.25-mm-class sediment) and also showed that there were different types of sediment, including layers with larger amounts of silt and clay and layers formed primarily of coarse grains. Of all the sediment cores, the one collected in Group 1 (Figure 9) showed a larger amount of silt and clay (60%) in the superficial layer. The subsuperficial layers also had a large quantity of silt and clay, but there were also coarser sediments (>0.5 mm), and in the layer between 40 and 70 cm, coarse sediment predominated by almost 50%.

DISCUSSION

Overall, the islands of the Jaguaribe Estuary are currently undergoing a process of areal increase because of the accumulation of sediment in the estuary. Once the sediment is deposited, it undergoes a rapid process of colonization by

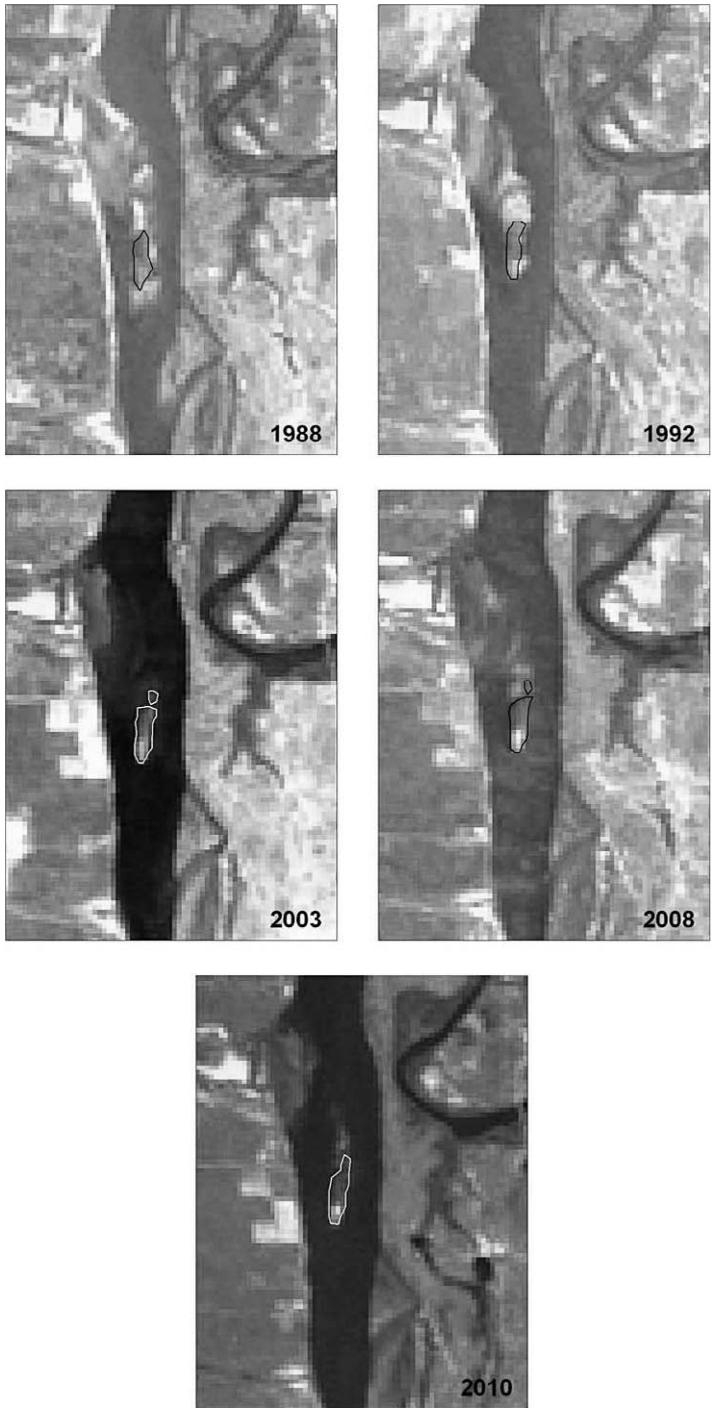

Figure 6. Map of islands from Group 2. Source: author's collection.

mangrove vegetation, which has a role in fixing the sediment. As stated before, the Jaguaribe River is far from being the only case where mangroves are expanding; there are several other cases like this in NE Brazil and in other countries. In a mapping study of mangrove areas between the states of Piauí and Pernambuco in NE Brazil, using satellite images from 1999 to 2004, Maia *et al*. (2006) compared the results with maps published by Herz (1991), who used aerial photos from 1978 from the project Radam, and showed an increase in mangrove area from 444 km^2 to 610 km^2, approximately 37% during a period of 25 years.

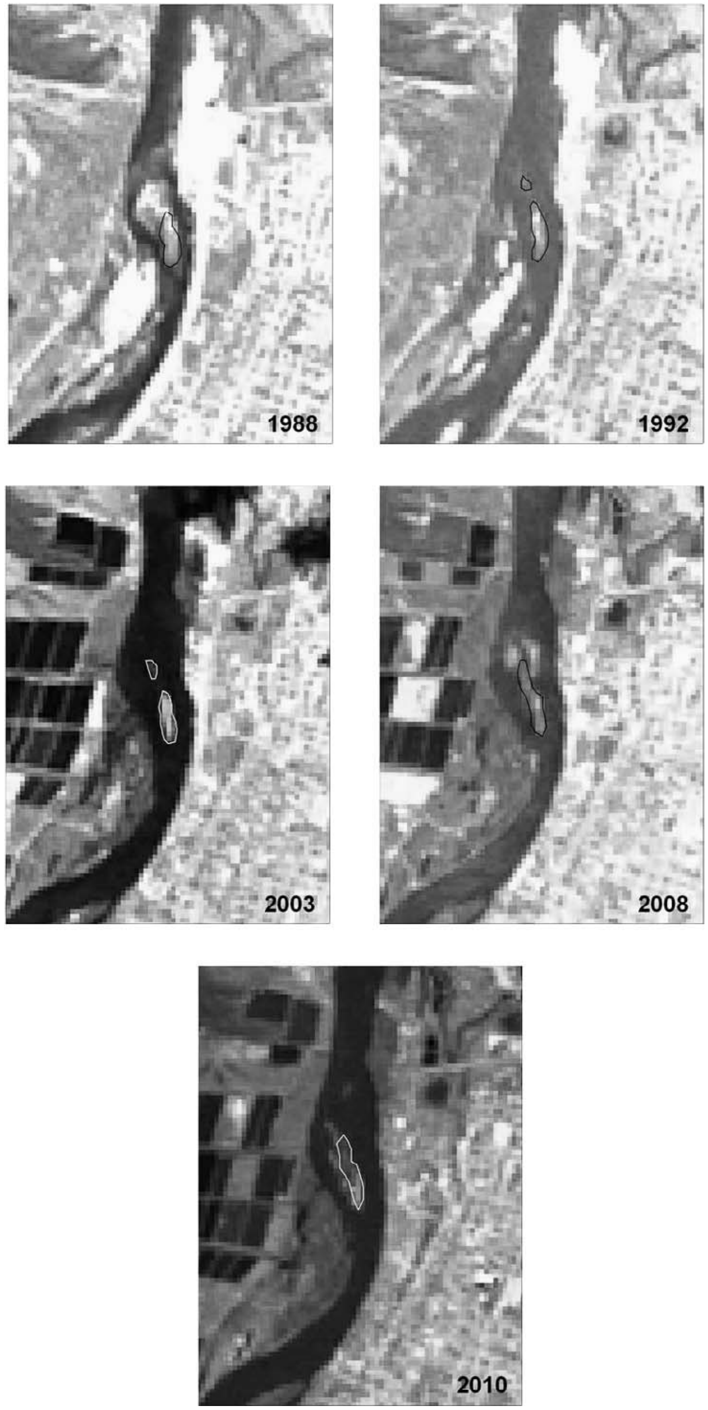

Figure 7. Map of islands from Group 3. Source: author's collection.

Lara *et al*. (2002) conducted a study in Bragança, in northern Brazil, which measured the advancement of mangrove vegetation over inland vegetation following saline intrusion. According to the authors, from 1972 to 1997, there was an increase of 36% of the local mangrove area. In the United States, a study conducted in Florida (Ross, Obrien, and Sternberg, 1994) showed the replacement of pine forests by mangroves from soil salinization caused by a rise in sea level of 15 cm over 70 years. According to the authors, the original area of pine forests in the Sugarloaf Keys was 88 ha in 1935 and was reduced to 30 ha by the end of the study in 1991. In Australia, a study conducted in nine different locations by Wilton (2002) revealed that, in

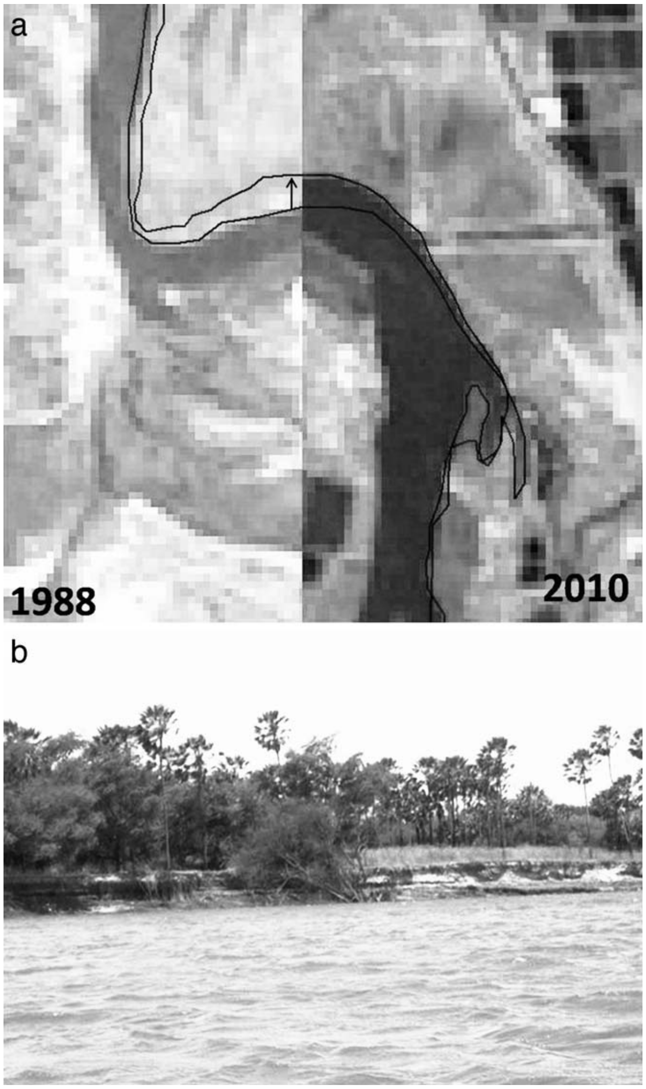

Figure 8. (a) Mapping of the riverbank erosion using Landsat images from 1988 and 2010. (b) Erosion in the riverbanks caused the trees to fall into the river. Source: author's collection.

almost all of the studied locations, the expansion of mangroves occurred at the expense of some other type of vegetation. From the 1940s to the 1990s, only 42% of the original area of the salt marsh remained, and the rest was occupied by mangrove forests.

In New Zealand, a study conducted at the Firth of Thames by Lovelock *et al*. (2010) showed an accretion of mangrove forest of 1 km seaward over 50 years (an average of 20 m y^{-1}). There were two major periods of mangrove expansion, one in 1978–81 and another in 1991–95. Both of the periods coincided with periods of sustained El Niño activity. Another study from Lovelock *et al*. (2007) showed that, in two other estuaries in New Zealand, mangrove coverage was increasing because of fertilization and high sedimentation rate.

Table 2. *Estimated Total Suspended Sediment (TSS) from shrimp farm emissions in the Jaguaribe River estuary*.

Sample	Emissions per Cycle (t ha^{-1})	Emissions per year (t ha^{-1} y^{-1})
Inputs		
Input of filling water[a]	9.08	19.07
Input of refilling water[b]	1.05	2.1
Total input	10.13	21.17
Outputs		
Output of filling water[c]	7.66	16.08
Output of emptying water (80%)[d]	1.61	3.23
Output of emptying water (20%)[e]	4.21	8.41
Total output	13.48	27.72
Total	3.34	6.54

[a] 5% of the average pond volume (7.5×10^5 L) × TSS in the entering water (70 mg L^{-1}) × 173 d.
[b] Average pond volume (1.5×10^7 L) × TSS in the entering water (70 mg L^{-1}).
[c] 5% of the total pond volume (7.5×10^5 L) × TSS in the output water (59 mg L^{-1}) × 173 d.
[d] 80% of the total pond volume (1.2×10^7 L) × TSS in the superficial water in the tanks (134.5 mg L^{-1}).
[e] 20% of the total pond volume (3×10^6 L) × TSS in the bottom water (1402 mg L^{-1}). Sources: Farm operation from Nunes *et al.,* 2005. The TSS values and shrimp-pond measurements are from Figueiredo *et al*., 2005 and Lacerda, Santos, and Madrid, 2006.

As seen above, mangrove expansion is not limited to NE Brazil. Several other studies around the world have shown similar trends, mostly because of damming and water withdrawal, along with sea level rise, such as in the Jaguaribe River estuary.

In the Jaguaribe River estuary, the period of major siltation corresponds to the period of the construction of the Castanhão

Table 3. *Estimate of the sediment emission from each soil use in the estuary of the Jaguaribe River*.

Source	Area (ha)	Soil Loss (t ha^{-1} y^{-1})[a]	Total Soil Loss (t y^{-1})
Natural vegetation[b]	16,792	0.4	6716
Urban area[c]	115,076	1	115,076
Agriculture[d]			
Banana	58	0.9	52
Sweet potato	10	0.9	9
Cashew nuts	19,602	0.9	17,641
Perennial fruits	528	0.9	473
Watermelon melon	1580	0.9	28,395
Corn	3330	12	39,960
Sugarcane	30	12.4	372
Cotton	406	24.8	10,068
Tomato	22	26.7	565
Cassava	1850	33.9	62,715
Beans	3204	38.1	122,072
Agriculture total	30,620		282,322
Livestock[d]	3437	0.4	1374
Shrimp[e]	2061	6.54	13,475
Total	167,986	—	418,963

[a] Soil loss from Tundisi (2003).
[b] *Natural vegetation = Total area − (Urban area + Agricultural areas)*.
[c] Area from Ceará (2010).
[d] Area from IBGE (2009).
[e] Area and soil loss from this study.

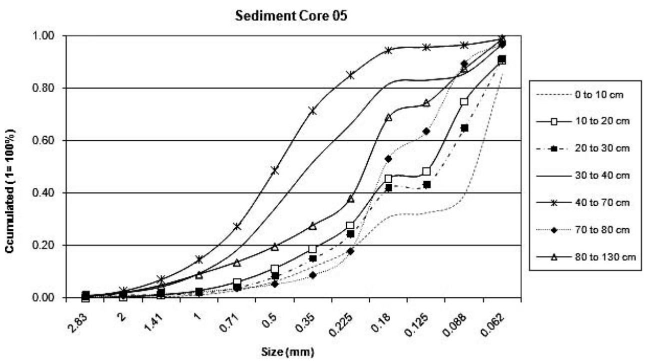

Figure 9. Granulometric analysis of sediment taken from Core 5.

Figure 10. Erosion in the margins of the estuary caused by the water expelled from local shrimp farms. Source: author's collection.

Dam, the largest dam in the state of Ceará, which was completed in 2003. In addition, construction of the Worker's Canal began in 1993. With 113 km of extension, this canal was built to drain water from the Jaguaribe River watershed to the Pacajus Reservoir. The Irrigated Perimeter of the Jaguaribe–Apodi was established in the late 1980s and is based on the water withdrawal from the Jaguaribe River.

Apart from local drivers, such as damming, water withdrawal, and diversion, the decrease of annual rainfall at a rate of 5.6 mm y^{-1} (Moncunill, 2006) and the salt-water intrusion contaminating the underground water supply of the region caused by sea-level changes (Maia *et al.,* 2004) are examples of local drivers caused by global changes. These drivers are caused by factors outside of the Jaguaribe River watershed but can influence the growth of islands and mangroves in the estuary.

The effects of water withdrawal for human consumption, the construction of dams along the river's course, and the alterations caused by climate change decreased the ability of Jaguaribe River to export materials to the sea, which in turn caused grain sedimentation of smaller sizes as seen in the analysis of sediment-core samples taken from the islands and the river channel at various locations within the estuary.

From the results on sediment loadings from shrimp farms (Table 2), it is clear that these farms serve, most of the time, as large sedimentation pools because the amount of suspended sediment measured in the output during the normal operation of the tanks is lower than the amount of suspended sediment measured at the entrance. However, the stage that contributes the most sediment to the estuary is the emptying of the shrimp ponds, when all of the water that was stored during the growing period is released into the river without any treatment. At that stage, the water leaves the tank with enough force to create currents that are capable of eroding the walls and bottom of the tank. Because of that erosion, the deepest layer of water (corresponding to the last 20% of the tank volume) has a suspended sediment concentration 10 times greater than that of the surface water (Figueiredo *et al.,* 2005; Lacerda, Santos, and Madrid, 2006). Apart from the force of the output water, which can cause river-margin erosion (Figure 10), tank water has a significant amount of suspended sediment ($>$1000 mg L^{-1}), resulting in the siltation of local tidal creeks (Costa *et al.,* 2013).

The results presented in Table 3 show that the main activity contributing sediment to the estuary was agriculture (282,322 t y^{-1}), particularly beans, cassava, and corn. The contribution from agriculture was followed by that of urban runoff (115,076 t y^{-1}), shrimp farms (13,475 t y^{-1}), and livestock (1,374 t y^{-1}). Unlike the other activities in the study area, shrimp farming is the only activity in which the sediment load is released directly into the estuary. The other sediment loads reach the estuary *via* sediment runoff. In this way, shrimp farms may contribute more to the siltation of the estuary than the other activities do; furthermore, comparing the results found in our estimate with other studies, it becomes clear that the farms in the Jaguaribe River estuary produce more sediment than farms located in other places, such as New Caledonia Lagoon (Thomas *et al.,* 2010) and some farms in Mexico (Casillas-Hernández *et al.,* 2006).

The lack of regulations for effluents from shrimp farming can become a major problem in the future because this activity is growing at a rapid pace, and its effluents have a large amount of organic material that can be easily consumed in the estuary. This large amount of organic matter is a great risk to the ecosystem because it can trigger the eutrophication of estuarine waters.

The results found in the sediment-core analysis reinforce the idea that the damming of the Jaguaribe River removed its ability to export sediment generated in the basin; those sediments are only exported when the dams are required to open their gates in rainy years, generating the sedimentation pattern found, with coarse sediment layers (mostly sand) interleaved with layers of fine sediment (fine sand with clay).

Furthermore, the shape and size of the sediment, with coarse grains showing little signs of weathering, implies that the sediment was recently deposited, which is consistent with the results from the sediment-load estimates, showing that most of the sediment that reaches the estuary originated from soil erosion that occurred in the lower portion of the watershed or in the estuary itself because the sediments generated in the higher portion of the basin are trapped by the Castanhão dam in Jaguaribara city and are only liberated when the floodgates are opened.

To calculate the absolute contribution, in terms of sediment mass, to the buildup of islands, one should compare emissions before 1988. Unfortunately, there are no detailed databases on husbandry and agriculture available for that period, which would allow a calculation of the past contributions of those activities to the silting process. However, it is safe to affirm that agriculture and shrimp farms have a large role in the silting of the estuary because the shrimp farms did not exist in the region before the 90s and large-scale irrigated agriculture was largely developed after the creation of the Irrigated Perimeter of Jaguaribe–Apodi because of the earlier lack of water in the region to feed those activities. As such, the siltation of the Jaguaribe Estuary is probably due to the increase in these drives, but also, indirectly induced by damming.

CONCLUSION

The mapping clearly showed that there was an increase in the area of the islands located within the estuary of the Jaguaribe River, and the speed of the increase was not the same throughout the period analyzed. The largest increase occurred between 1992 and 2003. Those years also correspond with the period when the Jaguaribe River basin underwent the greatest changes in land use, including river damming and water diversion.

Therefore, it is possible that the major works that have occurred in the watershed entrapped a large amount of sediment within the estuary, contributing to the increase of the islands in the lower estuary. However, sea-level changes and decreases in rainfall may be global factors that can affect the whole basin and exacerbate the effects of regional changes.

The estimates created showed that the activity that contributed the most to the silting of the estuary was agriculture. This information was further sustained by the granulometric analysis, which showed that most of the sediment found on the islands was derived from soil erosion. However, shrimp farms have the potential to become an environmental problem in the future if no additional regulations are enforced, especially because of the rapid growth of that activity within the region and because the effluents from the farms are discharged directly into the estuary without prior treatment.

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