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THE MIGRATION OF THE MOUTH OF SERGIPE RIVER IN NORTHEASTERN BRAZIL AND ITS CONSEQUENCES FOR THE DEVELOPMENT OF THE REGION - A CASE STUDY

By

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ABSTRACT

This paper intends to describe the evolution of the Sergipe River mouth since the last century, when the human occupation started in the lowest reach of the estuary with the settling of Aracaju, the new capital of Sergipe State, at the right margin, some 6 Km upstream from the mouth (Figure 1). The development of the city towards the mouth, in the early seventies, gave rise to some challenging problems due to the need to make its growth compatible with the migration of the river mouth to SW promoted by natural hydrodynamic forces.

For the occupation projects to be implemented, the natural ecosystem was severely impacted with the destruction of an extense mangrove area for land reclamation, initiated in 1977 (Figures 2 and 3).

1. INTRODUCTION

The commercial navigation across the mouth of Sergipe River started in the nineteenth century, with the installation of Aracaju, the capital of Sergipe State.

Sergipe river drains an area of about 3600 Km^2 having a small fresh water flow, with maximum measured values of 40 m^3/s (INPH, 1987), and opens into the Atlantic Ocean through a sandy coast, in a general direction of some 35° N. The local tide pattern is semi-diurnal and very regular. Amplitudes range from 0.8 to 2.3m, which gives an average tidal prism for spring tides of $108\times10^6m^3$ or a tidal flow of $4,831m^3/s$, measured at section Ac (Figure 1); the maximum value of the tidal current measured at this section during the flood phase of spring tides was 1.10m/s (PLANAVE, 1984). The influence of tides on coastal currents outside the zone of influence of Sergipe river mouth is negligible.

The estuary is a well-mixed one, offering stable depths of 8 to 10m and widths ranging from 600 to 1,000m in the stretch situated between the mouth and the Aracaju small harbour. Its entrance is restricted by a sand bar (situated some 2800m off the coast alignement), over which the control depth has remained at a value of 3.5+/-0.5m for the last decades (MOTTA, 1965) (Figure 1).

The winds in Aracaju are not so strong (maximum recorded wind speed is 8m/s) (MOTTA, 1966). They blow from 40° to 160°N (always from the ocean to the coast), with a predominance from E to SE and mean velocities around 5m/s. There is a marked seasonal variation in the wind regime. From October to March winds blow predominantly from E; from May to August, mainly from SE.

The beaches, stretching out to both sides of the estuary entrance, display a great bathymetric evenness, with a small slope of the bottom: the -10m line is located about 2.5Km off the coast.

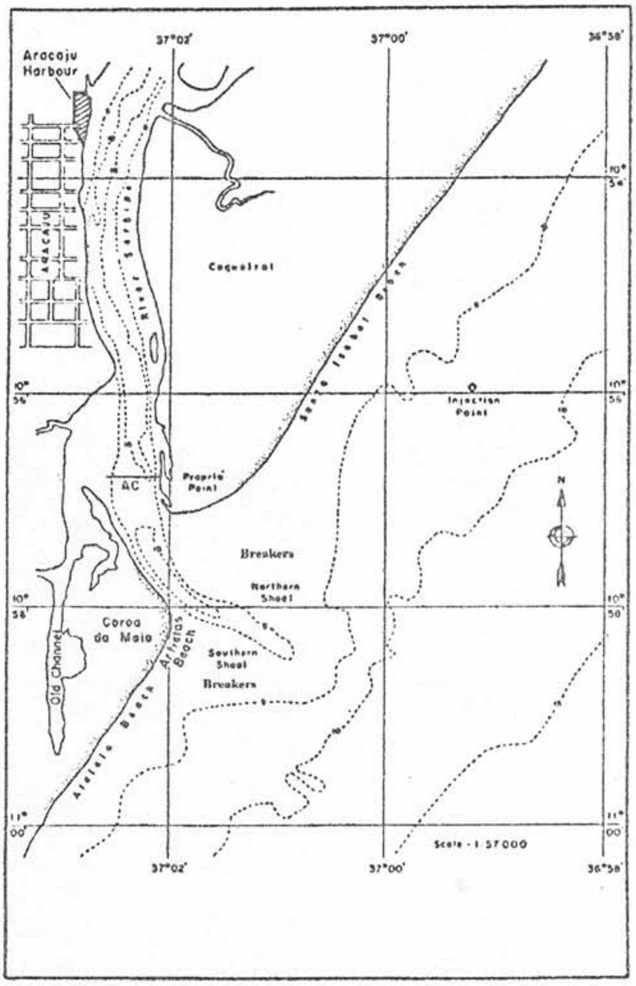

Figure 1: Key Map - Sergipe River Mouth, State of Sergipe, BRAZIL

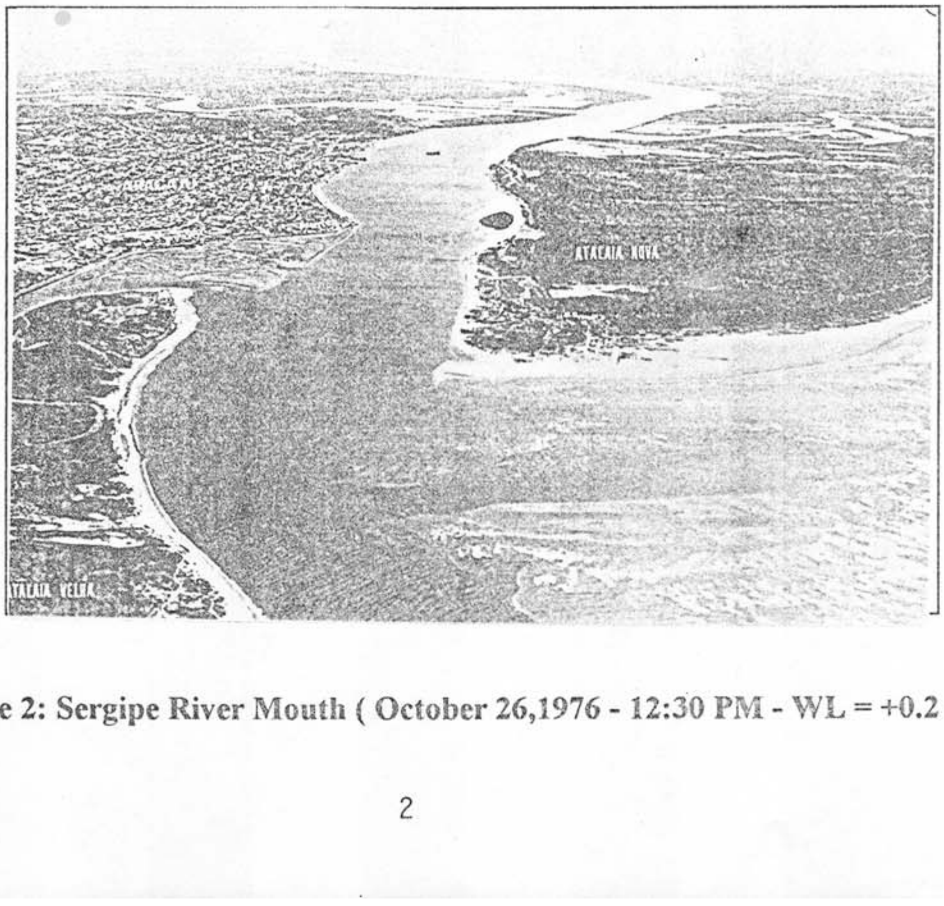

Figure 2: Sergipe River Mouth (October 26,1976 - 12:30 PM - WL = +0.2 m)

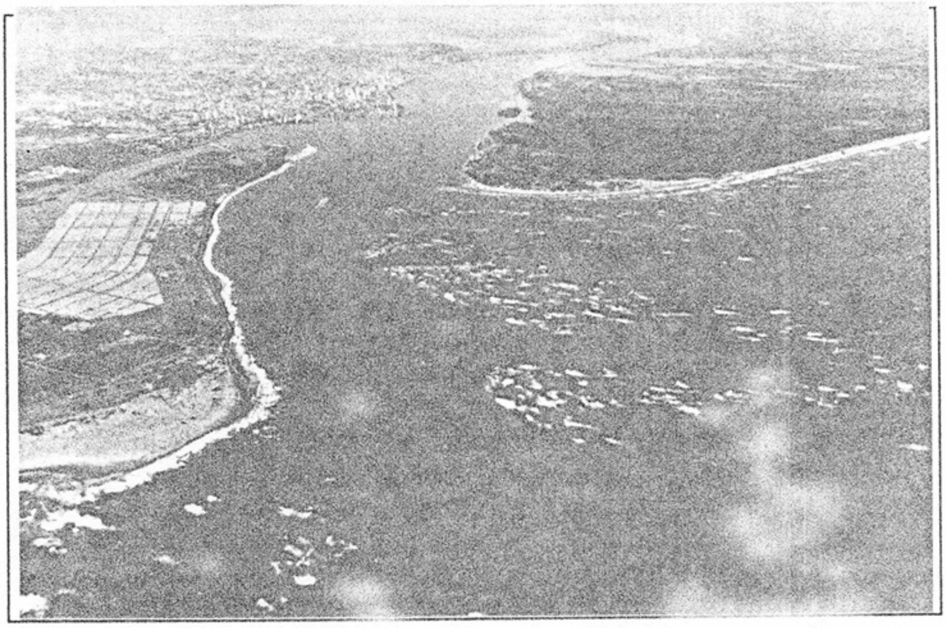

Figure 3: Sergipe River Mouth (December 1983)

The wave climate in Aracaju coast, based on measurements performed from September 1965 to August 1966 (MOTTA & BANDEIRA, 1974) and from May 1988 to September 1991 (PLANAVE & DHI, 1992), can be briefed as:

1- the waves come predominantly from the northern sector of the beach normal (azimuth of 125°), presenting a wider direction distribution than those propagating from the southern sector (Figure 4);

2- most frequent periods lie between 6 and 7 seconds, accounting for more than 70% of the observations; some swell with larger periods, between 10 and 15 seconds, were observed in the sector 115-135°N;

3- the waves present seasonal changes; periods are lower from September to March when compared with April to August; higher waves occur mainly from April to October than from November to March, coming mostly from the southern sector, associated to cold fronts; the most marked seasonal variation is the one associated with angles of wave attack at a given depth, as follows: from November to March the waves come from the north of the normal to the shoreline during practically all the time and from April to October come from both quadrants.

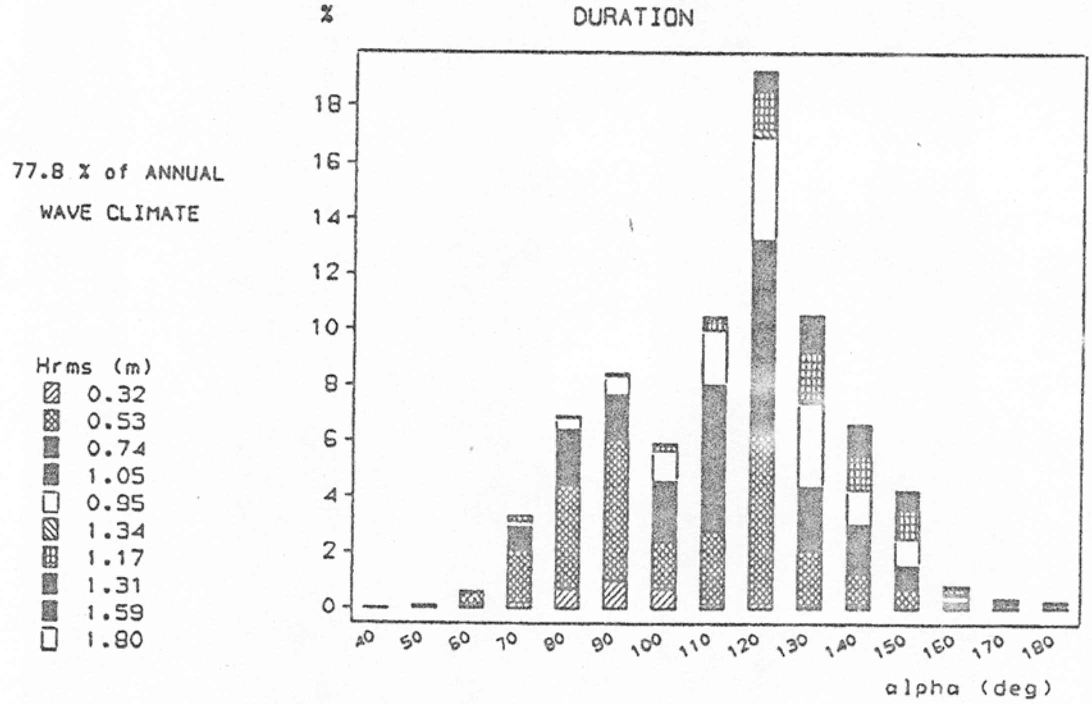

Figure 4: Offshore wave climate near Sergipe Marine Terminal from (PLANAVE & DHI, 1992)

Littoral drift occurs on both shoreline directions, being calculated as $800\times10^3 m^3$/year ($650\times10^3 m^3$/year in the NE-SW direction and $150\times10^3 m^3$/year in the opposite direction) (BANDEIRA, 1972) or 800×10^3 to $1{,}100\times10^3 m^3$/year (500×10^3 to $650\times10^3 m^3$/year in the NE-SW direction and 300×10^3 to $450\times10^3 m^3$/year in the opposite direction) (PLANAVE & DHI, 1992). It is constituted of fine sand with a mean diameter of 0.11mm. The southwestward net littoral drift is the cause of the migration of the river mouth in this direction, which has been known for the last 100 years.

In fact, a chart dated of 1894 (Figure 5) shows that the main entrance of the estuary lied at the southwestward limit of migration of the mouth, where presently the old channel can be found. Two secondary channels then existed, a central one limited by two shoals: Coroa Nova and Coroa do Meio, and a northern one, limited by the latter and Propriá Point. In 1895 the southern entrance became completely shoaled and the northern channel was naturally widened and deepened by the flow. The two shoals above mentioned were then incorporated to the right bank of the river, forming the present Coroa do Meio, with its Atalaia Beach. This migration cycle then ended.

Using bathymetric soundings and coastal contours data of the mouth region, obtained from 1947 to 1976, the average southwestward velocity of migration of the free mouth of the Sergipe river was estimated to be 3.0 m/month (SONDOTÉCNICA, 1978).

With the offshore oil exploitation in Sergipe State coast starting in the sixties as well as with the implementation of the production of fertilizers, cement and other products in the State in the seventies, the necessity arose to provide the region with adequate harbour installations. Feasibility studies were then performed with the objective of choosing an adequate alternative for the harbour: an estuarine solution or a coast terminal. As part of these studies hydraulic measurements were performed; a radioactive tracer experiment was carried out from January to April 1971 and showed the alongshore drift of the sand representative of the bar (D_{50} = 0.30mm) to be negligible seawards of the breaker zone (AUN et al, 1971); an experimental eight-metre deep approach channel was dredged across the bar and its accretion was monitored (MOTTA & BANDEIRA, 1974).

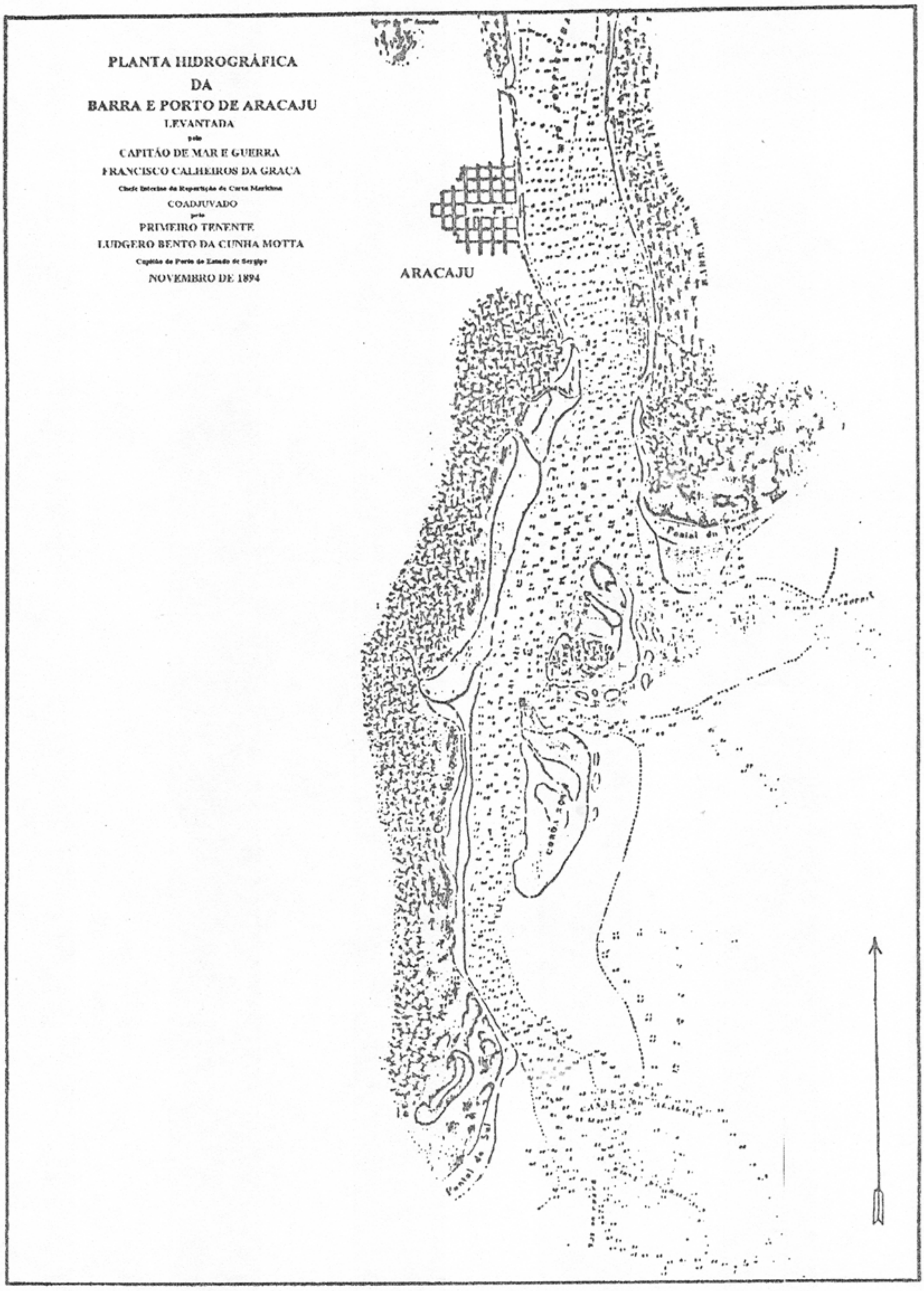

Figure 5: Sergipe River Mouth. November 1894 Nautical Chart, from (HIGESA, 1990)

A movable bed physical model of the mouth, at INPH laboratory in Rio de Janeiro, was employed to study the best solution to regularize the mouth and to assure good navigational conditions in a 10m deep dredged channel to Aracaju harbour, inside the estuary. Two long jetties (more than 4Km length each one) were considered in these studies. Nevertheless, the feasibility studies (SONDOTÉCNICA, 1978) pointed out to the coastal terminal solution. The Sergipe Port Terminal was then built 15Km northeastwards from the Sergipe river mouth. As a consequence, the fixation of the mouth fell to a secondary priority.

In the seventies, the expansion of the city of Aracaju had reached the Coroa do Meio region. A new district was planned and hundreds of houses and apartment buildings were constructed. Preventive coastal protection schemes in order to fix the right margin were not foreseen in the original project. As a consequence, some time after the construction of the Atlantica Avenue, in the late seventies, the first effects of the erosion appeared, threatening some reaches of this avenue (Figure 3). As a first corrective measure, a vertical concrete seawall along the affected area was built, with poor results. Afterwards, in 1983 a gabion seawall was also constructed with the same poor results. This destruction was caused by wave attack and scour by the river flow, because both structures had their foundations above the erosional level of the river in its migrational process.

In spite of the many studies already realized, which will be summarized in the next section, just corrective localized works and part of a stone jetty in the left margin have been constructed, guided mainly by the urgent need to protect some edifications along both margins. Much effort and money has been invested without a timely solution. In this way, erosion in the left margin, some hundred metres upstream from the mouth and a regression of some 200m of the coastline in some reaches along the right margin, impacting the new district, can now be observed. Among other important buildings, the new Atalaia Velha lighthouse lies in the destruction route of the river migration.

2. COMMENTS ABOUT SOME STUDIES, WORKS AND PROPOSALS PERFORMED

A sedimentological experiment was performed by CDTN in Aracaju, applying radioactive tracer (AUN et al., 1971). Its objective was to study the bed-load transport off the breaker zone with the material simulating that one representative of the bar: D_{50} = 0.30mm (GEOTÉCNICA, 1970). Ground glass labelled with Ir-192 (half life = 74.4 days) was injected at a point northeast of the mouth in 01-25-71 (Figure 1). The natural bottom sediment at this site is well sorted sand with D_{50} = 0.11mm.

The evolution of the material was surveyed by means of various detections, using a scintillation detector attached to a sledge trawled by a positioned boat, from January to April 1971. The experiment showed the alongshore drift of sand representative of the bar to be negligible seawards of the breaker zone. There was a sediment movement normal and towards the coast, with the labelled coarser material trying to find its equilibrium position in the beach profile (Figure 6). Quantitative results, applying the Count-Rate Balance Method (SAUZAY, 1967), were obtained, as follows:

Q = 5.03 ton/m/day (01-25-71 to 02-05-71)
Q = 2.19 ton/m/day (02-05-71 to 03-10-71)
Q = 0.10 ton/m/day (03-10-71 to 04-20-71)

showing a decrease in the bottom sediment transport rate as the material reached its crosshore equilibrium position. In reality, as soon as the material reached depths lower than 5m, in the offshore limits of the breaker zone, it turned southwestwards, being integrated to the dominant littoral drift. The experiment showed that the feeding of coarse sediment to the bar is done exclusively in the breaker zone, because the continental contribution of sediment through the Sergipe river is despicable.

An experimental channel has been dredged to a depth of 8m with a bottom width of 80m. After the dredging reached completion the channel was surveyed in December 1971, August an December 1972. The cubature showed an accretion of 564,000m^3 during the first year (MOTTA & BANDEIRA, 1974).

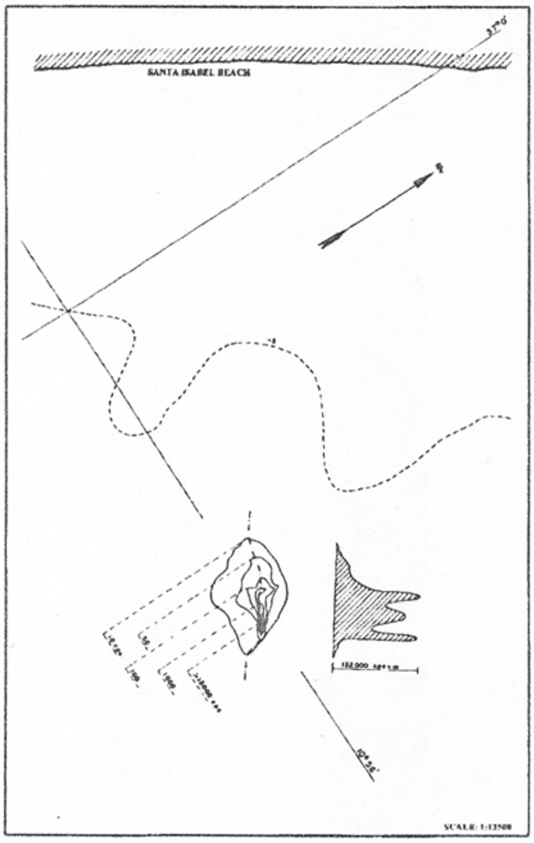

Figure 6a: (01/30/71)

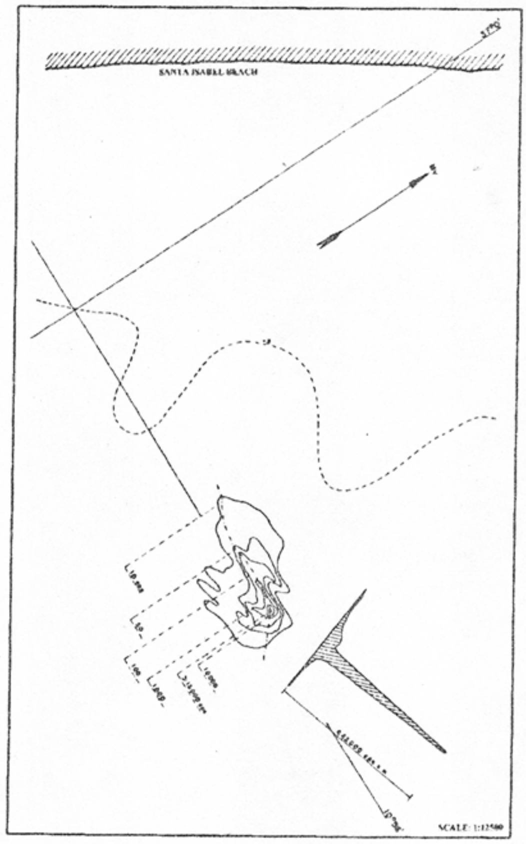

Figure 6b: (02/05/71)

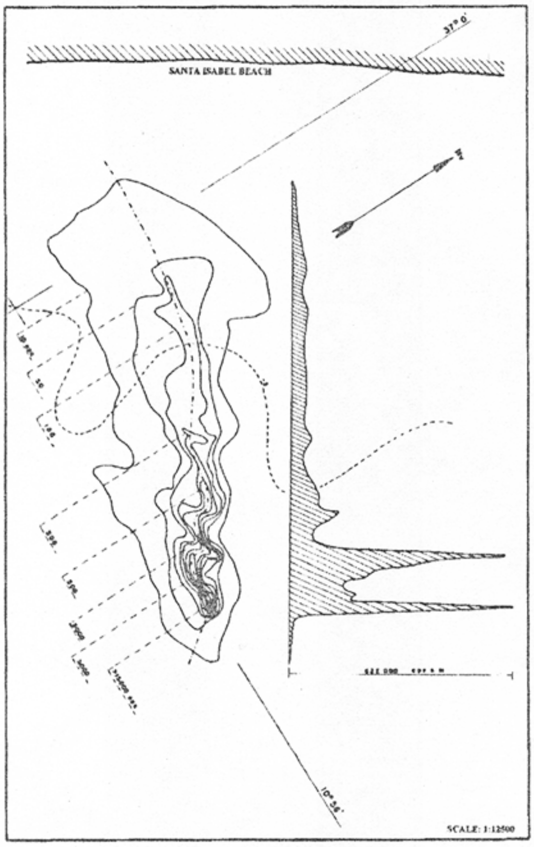

Figure 6c: (03/10/71)

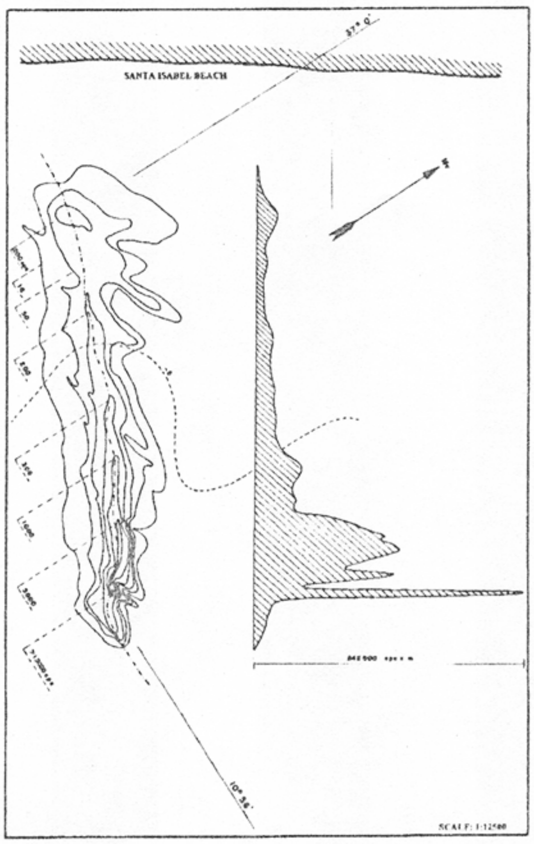

Figure 6d: (04/20/71)

Figure 6: Iso-counts contour lines and sediment transport diagrams,from (BANDEIRA,1972)

Relatively to the measures for the stabilization of Sergipe river mouth, other than the studies made at INPH considering the two long jetties solution above referred, proposals have been made during the last years, to protect mainly the right margin, taking into account the development of the new district at Coroa do Meio.

(PLANAVE, 1984) presented a study with the main objective of giving to the cross sections, downstream the section Ac (Figure 1), adequate dimensions by means of dredging, in order to equalize the amount of sediments transported during flood and ebb flows, attending the concept of stable mouths. The dredged material would be used for the construction of a sand spit aligned according to an artificial extension of Santa Isabel beach. This spit would have its seaward extremity protected by geotextile bags filled with concrete.

(WEGGEL, 1985) suggested the construction of a sloped stone training wall along Coroa do Meio margin, using the rocky material remaining from the old gabions protection. He also suggested the construction of adequately spaced groynes reaching depths of -3m. Sand with suitable grain size would be dumped between them, enlarging the beach.

Later on, another solution consisting of a stone jetty originating in the Propriá Point aligned 152° N, with a proposed length of 1800 m and a stone frontal protection of Coroa do Meio margin going down to -2 m datum level, was studied and designed (HIDROSERVICE, 1987). The jetty would have as a main function to minimize the effects of incident waves from NE, considered to be the agent responsible for the desestabilization of the right margin; their energy would be dissipated by this structure. The frontal protection would act in two ways: to protect the alignement of Coroa do Meio beach against the scouring action of the river currents and against attack of seas generated between the jetty and the beach. The construction of the jetty began in May 1990; only 850m were built, but the construction of the frontal protection, according to the project, never started.

The shoreline, on both sides of the river, is reacting to the partial jetty construction and the progression of the erosion in the Coroa do Meio bank remains, threatening buildings and streets. Another erosion process got started on the left bank of the river, a few hundred metres north of the jetty origin.

The report "Study of the Environmental Impact of the Protection Works at Coroa do Meio Beach" (HIGESA, 1990) deals with the interventions proposed in (HIDROSERVICE, 1987). The environmental impact report was discussed in (BANDEIRA, 1991) and some questioning about the future performance and stability of the frontal protection to be constructed at Coroa do Meio bank arose.

Firstly, as pointed out in (INPH, 1990) the utilized movable bed model with scales 1:500H and 1:80V was not adequate to represent the localized erosion effects in the right margin (Coroa do Meio bank) after the construction of the jetty and the frontal protection. This model was originally built to study the coastal portion of the Sergipe river mouth where the two long jetties solution for its stabilization were tested. In this way, (INPH, 1990) suggested that a new model with adequate scales should be used to represent the hydraulic and sedimentological aspects of this localized region. Nevertheless, the design of the burying depth (-2m) of the frontal protection was made (HIDROSERVICE, 1987) considering the results of the available model.

Therefore, there were uncertainties about the stability of the frontal protection, should the erosive process due to the action of the river currents reach depths greater than -2m. If this protection were to be constructed according to the proposed design, the river bottom should be surveyed by means of regular bathymetric soundings, to make sure that the -2m depth contour would not dangerously approach the frontal protection. This contour line should be kept at least 100m away from the wall foundations, for safety purposes. This could be accomplished by dredging bottom material in the reach of the left margin opposed to the eroded one, and by dumping it where needed, in the right margin.

Secondly, the frontal protection should be extended 560m to the north of the 1822m originally proposed to comply with the observed length of erosion (July, 1991) along the right margin.

More recently, mathematical modelling has been used to study the impact exerted by the jetty under construction on the littoral transport regime, and to present proposals for the protection of the southern beaches (PLANAVE & DHI, 1992). The following models were applied for this purpose: a) DHI's LITPACK computer model was used to study littoral transport and coastal evolution north of the river mouth, as well as to evaluate different coastal protection schemes for Atalaia Beach, south of the mouth; b) DHI's 2-D modelling system MIKE was applied to determine wave-, current-, and sediment- transport as well as the bypass conditions in the region of the river mouth.

The simulations considered the initial shoreline without the jetty and the presence of this structure with three different lengths (850m, 1200m and 1800m). The evolution of the coastline in a ten-year period together with the sediment budget was evaluated for each of these scenarios. Some of the main conclusions were: a) little difference is estimated between the coastal evolution north of the jetty whichever length be used (1200m or 1800m); b) the 1200m long jetty marginally reduces the wave heights in the region of Coroa do Meio, compared to the original situation, especially for waves propagating from the northern sector; c) the effect of the jetty on the tidal- and wave-induced flows has a local character, influencing mostly the wave-driven currents on the northern river bar; maximum flow velocities are concentrated against the shore of Coroa do Meio, following the location of the talweg of the river, both for flood and ebb flows; d) the jetty significantly reduces the trend for sedimentation along its southern side, which would, in turn, reduce the trend for southward migration of the northern bar and, consequently, reduce the trend to force the talweg against Coroa do Meio; nevertheless, this reduction is limited to the extension of the jetty; e) the influence of the jetty is rather limited to control the trend for erosion of the shoreline along Coroa do Meio and Artistas Beach; therefore, apart from its construction, any solution intended to fix the river mouth should consider some kind of coastal protection for the right margin; f) if the effects of protection works at Coroa do Meio and of the 1200m long jetty at Propriá Point are added together, a lack in sediment supply to the beaches south of the river mouth is to be expected, which may induce erosion and shoreline retreat; g) three protection schemes for the Atalaia Beach have been studied, namely, short groynes with large spacing, short groynes with small spacing and longer groynes with large spacing; the second scheme appeared to be the best solution.

Comments were made in (PLANAVE & DHI, 1992) about alternative protection schemes previously considered by PLANAVE for the right margin: a) dredging of the northern bank of the river channel, to reduce the current velocities along the right margin, dumping the dredged material along the eroding coasts; shore-normal groynes along the Artistas Beach with the purpose of forcing the river talweg away from the shore (Figure 7); b) marginal protection consisting of a rubble-mound structure for the upstream end of Coroa do Meio, extending downstream for approximately 2200m; c) groynes combined with rubble-mound marginal protection at Artistas Beach.

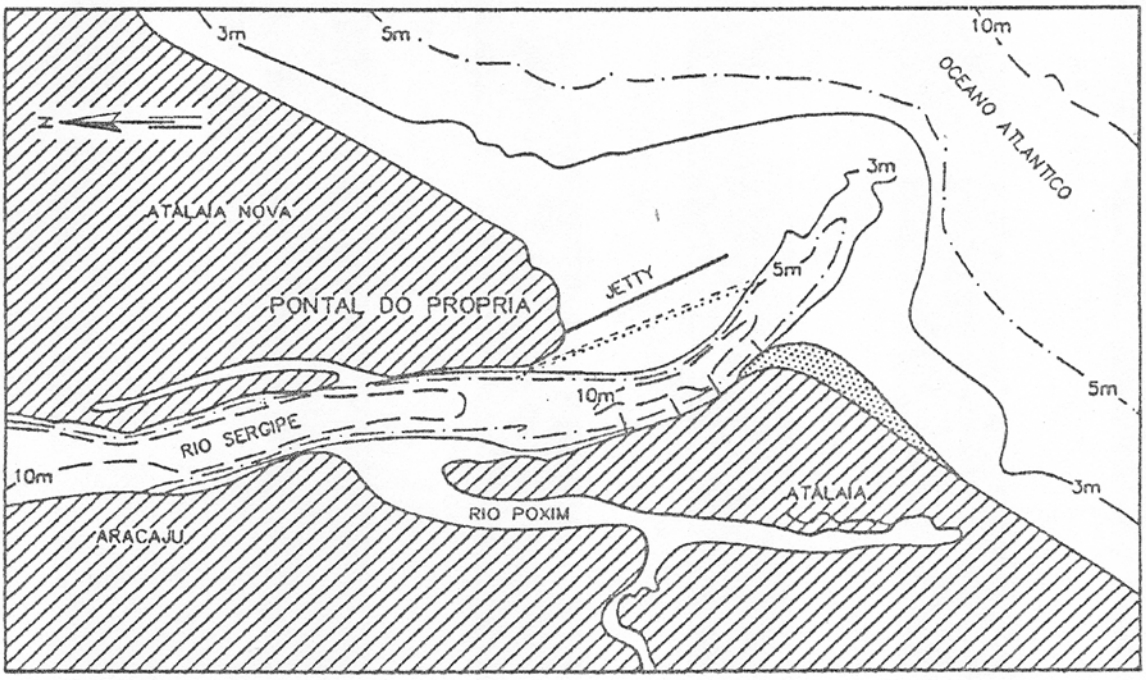

Figure 7: Sketch on recommended interventions, from (PLANAVE & DHI,1992)

Regular monitoring of the evolution of the shoreline south of the river mouth was strongly recommended, before and after the construction of any protection works along Atalaia Beach. A final consideration was that the effect of any solution scheme proposed for the stabilization of Coroa do Meio and of Artistas Beach should be carefully considered before taking any action. For this purpose, the MIKE modelling system, which has already been set-up for the region, could be applied.

3. PRESENT STATUS OF THE REGION AROUND THE MOUTH OF SERGIPE RIVER

A field inspection was carried out by the authors in April 1995. The photo (Figure 8) shows that a great extension of the 850m long jetty is now covered by sand, with its northern side almost filled up. Due to the intense eolian sand transport over the jetty (not considered in the previous studies) and the contour of its extremity by the littoral drift, also the southern side of the structure is already strongly accreted for some 400m to SW. This accelerated growth of Propriá Point has been promoting the talweg migration and forcing the tidal currents more and more against the right margin, worsening the erosive process at Coroa do Meio. It can be seen in Figure 8, by observing the breaking of the waves, that the region of the deeper and narrower portion of the tidal channel through the mouth, is dangerously close to the right margin.

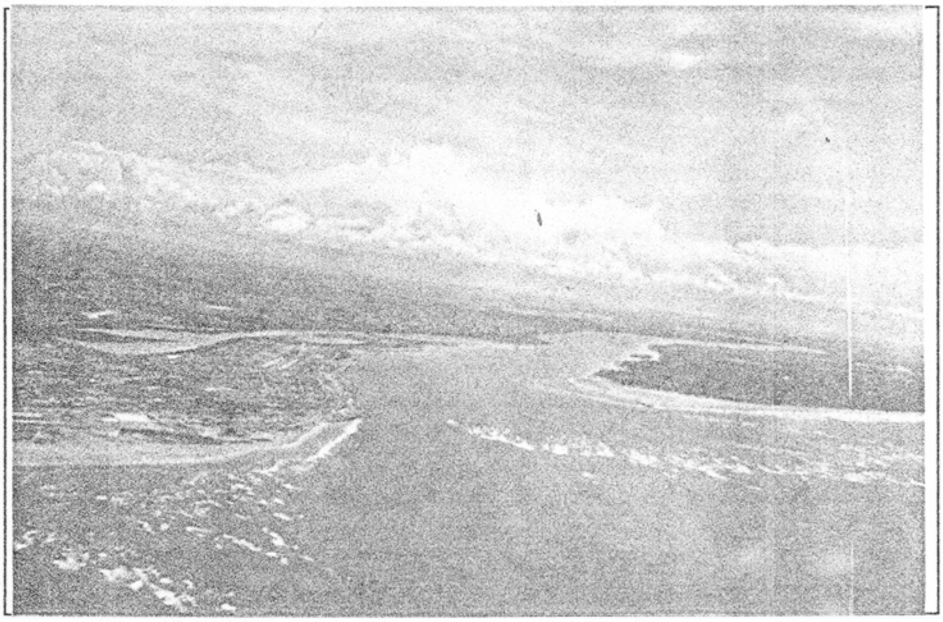

Figure 8: Sergipe River Mouth (April 4,1995 - 11:40 AM - WL = +0.4 m)

The intensive erosion process is critical along all the right margin. At its northern region, where a shopping centre and many new buildings are located, a strong erosive process (Figure 9a) has been halted by the construction of a frontal protection with an approximate length of 500m, not in the original alignement of the Atlantica Avenue, which is the same of the old sea wall, but advancing some 50m to NE (Figure 9b). Southern region of Coroa do Meio and Artistas Beach experience nowadays a severe erosion situation. Some localized stone dumping has been made according to urgent erosion controlling needs, but the construction of a complete rubble-mound marginal protection combined or not with groynes, as proposed in (PLANAVE & DHI, 1992) (Figure 7) is far from being implemented.

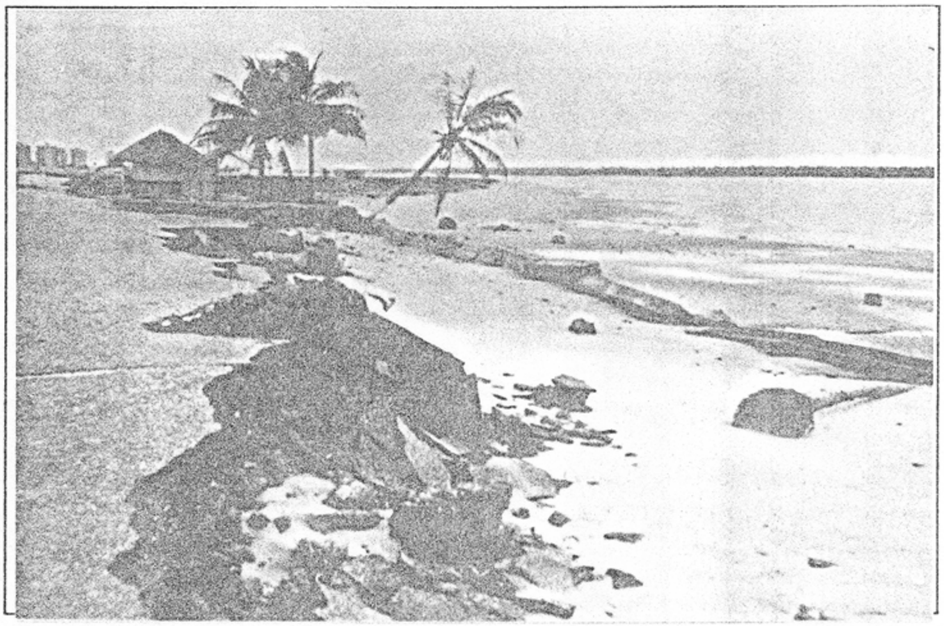

Figure 9a: Erosion at northern extremity of the right margin - Coroa do Meio Beach Atlântica Avenue and RT - 11 street - (July 26, 1991 - 11:25 AM - WL = +0.6 m)

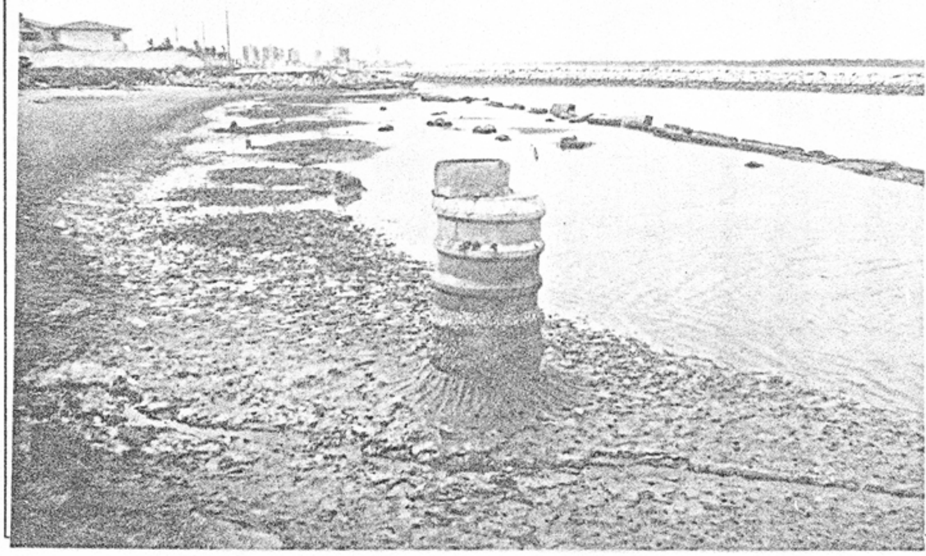

Figure 9b: Erosion at northern extremity of the right margin - Coroa do Meio Beach Atlântica Avenue and RT - 11 street - (April 5, 1995 - 01:30 PM - WL = +0.3 m)

With the construction of the jetty at Propriá Point, an interesting sedimentological process can be observed at the left margin. The presence of the jetty interrupted temporarily the feeding of sand to the portion of the northern bank just southwestwards of the jetty. (PLANAVE, 1984) calculated, by means of field measurements, that the net drift of sediments through the Sergipe River mouth is towards the interior of the estuary. In this way, the "source" of sediments to the region of the left margin, some hundred metres upstream the jetty, was depleted and an erosion process got started. Many houses and a boat terminal were threatened of destruction and, as a remedial measure, a long rubble-mound protection was built (Figure 10). Presently, with the return of sand supplying to the bank, just SW of the jetty, the erosion problem is gradually disappearing and it is expected that in a near future the southern part of this protection will be covered by sand.

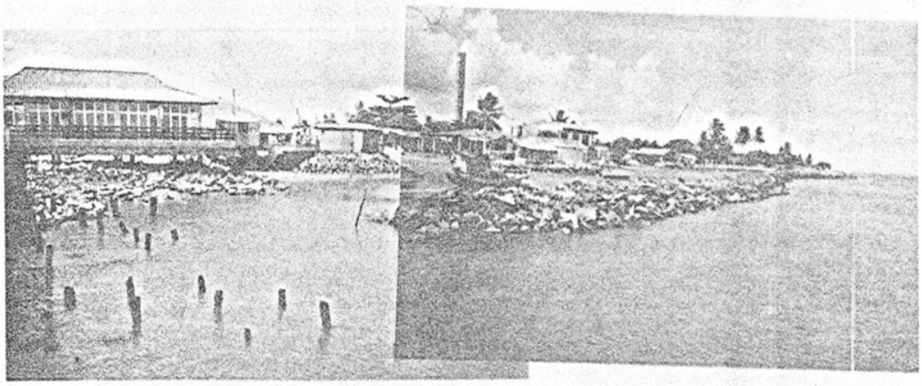

Figure 10: Stone protection at the left margim (note sand deposition by the southern face of the jetty) April 5,1995 - WL = +0.6 m

4. CONCLUSIONS AND RECOMMENDATIONS

Doubtlessly, the surroundings of the mouth of Sergipe River is one of the most intensively studied coastal areas in Brazil, in its hydrodynamic and sedimentological aspects.

Nevertheless, very few of the technical recommendations yielded by this vast set of studies have been adequately implemented, in time and space, to cope with the stabilization of the river mouth. For how long will this situation persist?

The migration of the river mouth southwestwards, with its associated erosive process along the right margin are in due progress, causing loss of reclaimed areas, buildings and localized protection works. The authors are convinced that, if feasible and definite solutions to the problems related in this paper are to be implemented, integrated and well coordinated efforts must be made. So far, much effort, time and money have been invested in a discontinued way, without taking into account the overall problem.

The parts involved with the stabilization of the mouth of Sergipe River, an important problem since the seventies, must be gathered together, discuss plans and solutions already proposed, stablish priorities, have funds provided and attack works with no more delay.

Nature will follow its course and man must keep pace with it!

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