THE PRESENT MIGRATION OF SÃO FRANCISCO RIVER MOUTH PART II

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Abstract – The paper describes, with emphasis on a collection of satellite images obtained since the 1980 decade, and considering also historical maps and aerial photos, the morphological changes in the mouth of São Francisco River, northeast Brazil. These changes were caused by the retention of sediments from continental origin to the river delta area, due to various dams constructed, since 1955, in the São Francisco River basin, and also due to the consequent regularization of the river flow. These subjects are covered in Part I of this paper, also presented at this Symposium. As a result, the mouth, once stable, is currently in a clear migration to SW, according to the dominant littoral drift. Semi-quantitative results of the regression of the coastline and the temporal variation of its alignment, considering the interface of the vegetation and the sand as reference for the erosion processes, are presented. It is recommended the measurement of morphological, sedimentological and hydrodynamic parameters in the region of the mouth and the use of already available data on river flows and the load of sediments from continental origin, to enable the application of mathematical models for the evaluation of the future morphological behaviour of the mouth region.

Keywords – São Francisco River; sediment retention in reservoirs; morphological response of river mouth.

INTRODUCTION

The description of the characteristics of São Francisco River (SFR) hydrographic basin, the sediment retention inside the reservoirs of hydroelectric power plants (HPP's) constructed along the river, the influence of the operation of the reservoirs on the decrease of river flow and considerations about the coastal sediment transport (littoral drift) in the region of the river mouth, have already been addressed in Part I of this paper, also presented at this Symposium.

Part II, here presented, focuses on the morphological changes experienced, due to the presence of the reservoirs, in the SFR mouth that was stable until the 1980s, and presently is migrating to SW, in the direction of the dominant littoral drift.

CONSEQUENCES OF THE INTERVENTIONS

The main consequences in the SFR mouth region, resulting from retention of sediments inside the reservoirs of the HPP's built along the river, and the regularization of the river discharge, are:

i) Drastic decrease (more than 90%) in the fish population in the low estuary and the region of the mouth, due to the reduction of fine sediment contribution, which carries nutrients and organic matter (PROJETO GEF – SÃO FRANCISCO, 2002);

ii) Erosion at the SFR mouth. This consequence will be seen, in more details, in sequence.

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Erosion at the São Francisco River mouth

With the decrease of the continental sediment load, the right bank of the mouth, in the Sergipe State, is suffering severe erosion. Why erosion only in this side of the mouth?

The sediment from continental origin, as soon as it leaves the mouth, is carried preferably in the direction of the Sergipe State coast due to the dominant littoral drift to southwest. With the decrease of this contribution, starting with the construction of Paulo Afonso HPP's in the 1950s of the last century, a long-term effect (of the order of decades) was felt: the waves and currents, with a certain capacity to transport sediments, but not having it fulfilled, started to erode the right margin, just downstream the river mouth, in relation to the dominant littoral drift. This erosive process tends to cease, as soon as the new coastline orientation, which is a function of the available sediment load, mainly sand load, becomes adjusted to the littoral transport capacity.

In the beginning of the decade of 1990, the erosion reached and started destroying the fishermen village of Cabeço. The first victim was the lighthouse constructed in the 19th century, near the village and 250 m inland from the shoreline. Figures 1 to 10 show the progress of this erosive process.

It can be observed (Figure 1) that the lighthouse was built 250 m inland from the shoreline surveyed in 1942. At that time no HPP had been constructed along the SFR and it may be considered that the mouth region was in a relative sedimentological equilibrium.

It was only after the beginning of operation of Paulo Afonso I (1955) to IV (1977) HPP's that the contribution of the sediment from continental origin started decreasing significantly. In 1978, Sobradinho HPP entered into operation, reducing even more this contribution. The HPP's of Itaparica and Xingó (downstream of Sobradinho) were built after 1978.

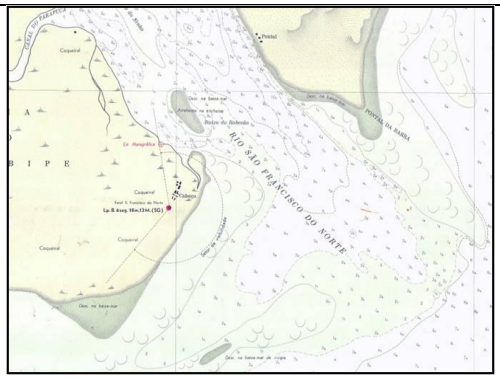

Figure 1 – Lighthouse distant 250 m from the coastline contour of 1942. (Brazilian Navy Chart – DHN 1002)

Figure 2 – Lighthouse at less than 100 m from the shoreline. Beginning of the 1990s.

Figure 3 – Church at "Cabeço" fishermen village, with the lighthouse already at the shoreline - 1998.

Figure 4 – Cabeço beach and the lighthouse offshore - Nov 2001 (Bandeira, 2005)

Figure 5 – SFR mouth & lighthouse – 2002.

Figure 6 – Lighthouse in 2/26/2004 at 235 m from the shoreline (Altitude of vision: 873 m)

Figure 7 – Lighthouse in 2009 at 430 m from the shoreline (Altitude of vision: 873 m)

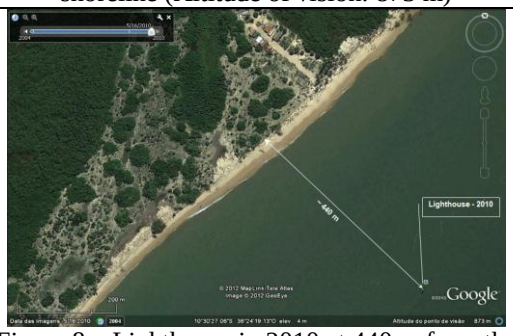

Figure 8 – Lighthouse in 2010 at 440 m from the shoreline (Altitude of vision: 873 m)

Figure 9 – Lighthouse in 2013 at 455 m from the shoreline (Altitude of vision: 873 m)

Figure 10 – Lighthouse in 2016 at 460 m from the original shoreline, and at 300 m from the new shoreline of sand spit (Alt. of vision: 873 m)

Considering the positions of the shoreline in relation to the lighthouse (figures 1, 3, and 6 to 9), and also the chronology of operation of Paulo Afonso I (1955) and of the subsequent HPP's, one can estimate the yearly average regression velocity (ARV) of the shoreline in this particular region of the coast, for different time periods, sizing up the long-term morphological impacts in the SFR mouth caused by the retention of sediments from continental origin, and also due to the regularization of the river discharge. Table 2 is a resume of the findings.

Table 2: Yearly average regression velocity of the shoreline in the region of the lighthouse

Time interval	Regression of shoreline (m)	Average regression velocity (ARV) (m/year)	Remarks
1955 to 2016	710	11.6	Start of operation of Paulo Afonso I HPP
1955 to 1998	250	5.8	Paulo Afonso I until lighthouse at the shoreline
1998 to 2004	235	39.2	Lighthouse at the shoreline till 2004
2004 to 2009	195	39.0	From 2004 to 2009
1998 to 2009	430	39.1	Lighthouse at the shoreline till 2009

1998 to 2010	440	36.7	Lighthouse at the shoreline till 2010
1998 to 2013	455	30.3	Lighthouse at the shoreline till 2013
1998 to 2016	460	25.6	Lighthouse at the shoreline till 2016

The ARV of 5.8 m/year for the period 1955-1998 increased 6.8 times, to 39.2 m/year, in the period 1998-2004. Above all, this sharp increase is due to the long-term effect of the beginning of Sobradinho HPP operation, 20 years before the beginning of this considered period. The ARV remained relatively stable between 2004 and 2009 and then began to decline. This gradual decrease in ARV is probably due to the new realignment of the main channel in the river mouth with the growth, to SSW, of the long sand spit on the left margin, which will be discussed later.

In short, the benchmark of this drastic erosion at the mouth region of SFR is the lighthouse inclined, as the *Pisa Tower* in Italy (figures 3, 4 and 5), and standing, in 2013, some 455 m offshore (Figure 9). In 2013 there was a sand island almost reaching the lighthouse (figures 9 and 15). In 2016 this sand island had disappeared but a sand spit with orientation SW-NE had appeared in the right margin, in front of the Cabeço fishermen village (figures 10 and 16).

Figures 11 to 16 give an overall vision of the morphological impact on the SFR mouth region caused by the reservoirs built along its hydrographical basin. One observes in these figures the drastic change in the natural channel alignment, from NNW- SSE, in 1969 (Figure 11), to a present NNE-SSW direction (figures 15 and 16), due to the migration of the mouth to SW.

Figure 11– São Francisco River mouth 12/31/1969

Figure 12 – São Francisco River mouth 2/26/2004

Figure 13 – São Francisco River mouth 4/5/2009

Figure 14 – São Francisco River mouth 5/16/2010

Figure 15 – São Francisco River mouth 8/21/2013

Figure 16 – São Francisco River mouth 6/25/2016

Figure 17 shows the variation of deposition and erosion sites in the region of the mouth of SFR and in the nearby beaches, for the time interval 1988-2011, obtained by Boolean analysis of satellite images. Deposition occurred on a stretch of the right bank just before the mouth, and on the left bank in front of the mouth, forming the large sand spit that is growing to SW, according to the dominant littoral drift. It is observed, in addition to the heavy erosion on the right bank of the mouth, erosion of beaches located on both sides of the mouth. Figure 18 presents the coastal contours for 1988, 1995, 2007, 2011 and 2015. It shows, in great detail, the progress of the morphological modifications in the region.

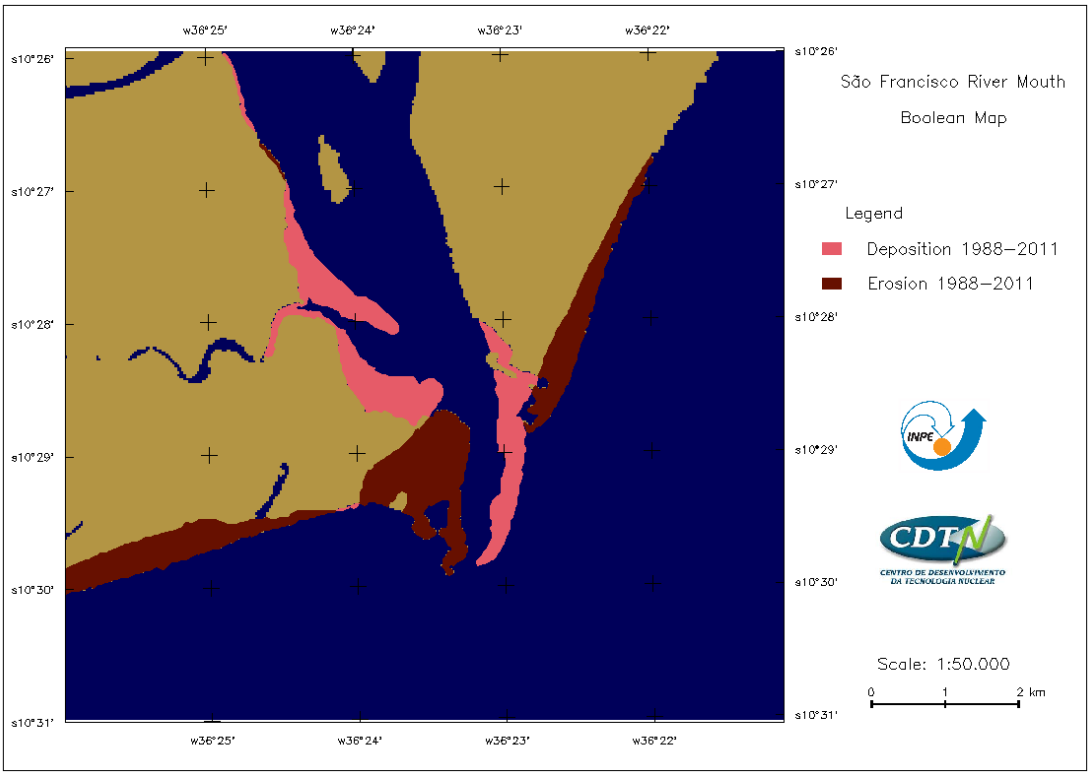

Figure 17 – Boolean analysis of the São Francisco River mouth for the period (1988-2011) based on Landsat satellite images. (Bandeira *et al.*, 2012)

The analysis of available images clearly indicates a dominant littoral drift towards SW, which tends to promote the migration of the mouth in this direction. However, the hydraulic flow through the mouth, comprising of both, the tidal flow and the riverine flow, acts as a "hydraulic jetty". This pre-dams construction flow, associated with the original contribution of the sediments from the hydrographic basin of SFR, kept stable the position of the mouth.

With the strong decline of the river flow, this hydraulic jetty weakened. Moreover, with the decrease of sediment contribution from continental origin the waves and currents, predominantly from E and NE, with a certain capacity to transport sediments, but not having it fulfilled, started to erode the right side, just downstream the river mouth, in relation to the dominant littoral drift. It seems that these two effects together are presently promoting the migration of SFR mouth.

With the migration of the mouth to SW, the hydraulic jetty previously oriented NNW-SSE (Figure 11), is now oriented NNE-SSW (figures 15, 16 and 18). With this change in orientation, the beach to the NE of the mouth increased by including the beach portion formed by the new sand spit. In consequence, a stretch of the ancient NE coastline, about 4 km long, with sand retention probably influenced by the old orientation of the flow ("hydraulic jetty") through the mouth, has been eroded (figures 17 and 18).

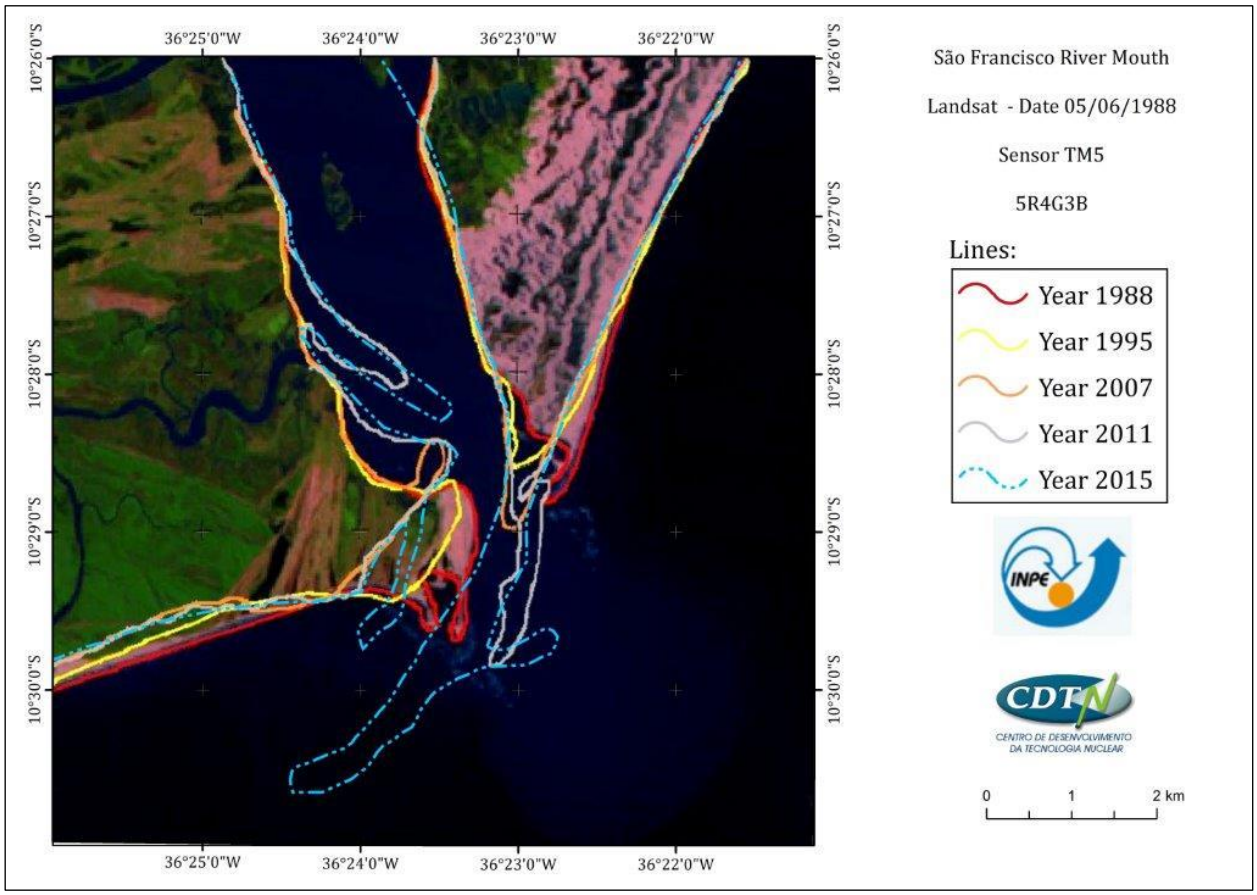

Figure 18 – Coastal contours of the São Francisco River mouth (1988, 1995, 2007, 2011 and 2015) based on Landsat satellite images (Bandeira *et al*., 2016).

Beach erosion in both sides of the mouth was also studied by Formoso (2008) and Bittencourt *et al*. (2009) and corroborates the previous observations.

CONSIDERATIONS ABOUT THE USE OF MATHEMATICAL MODELS TO STUDY THE FUTURE BEHAVIOUR OF THE SÃO FRANCISCO RIVER MOUTH

Coming back to the present SFR mouth behaviour (Figure 19), some questions arise:

i) How far will it migrate?

ii) How may this migration affect the beach and the existing set of tidal channels in the coastal region SW of mouth?

In order to answer these two questions it is necessary to predict the behaviour of the mouth in its migration process, which has never happened before. Therefore it is necessary to make use of predictive models and, in this case, the most suitable ones are the mathematical models.

Morphological changes pictured in the mouth of the SFR over the last 28 years are the result of the interaction of waves, tidal and coastal currents, and river discharge with the sediments of marine and fluvial origin. They reflect the decrease of sediment from continental origin and the river regularization caused by the anthropic intervention, due to the construction of reservoirs along the river. These changes, represented mainly by the intense process of erosion that has hit the village of Cabeço, resulted in the resettlement of the population. Impacts of this nature, which reach populations living in areas of major coastal and estuarine changes, could have been predicted with the use of mathematical models and the social impacts therefore minimized.

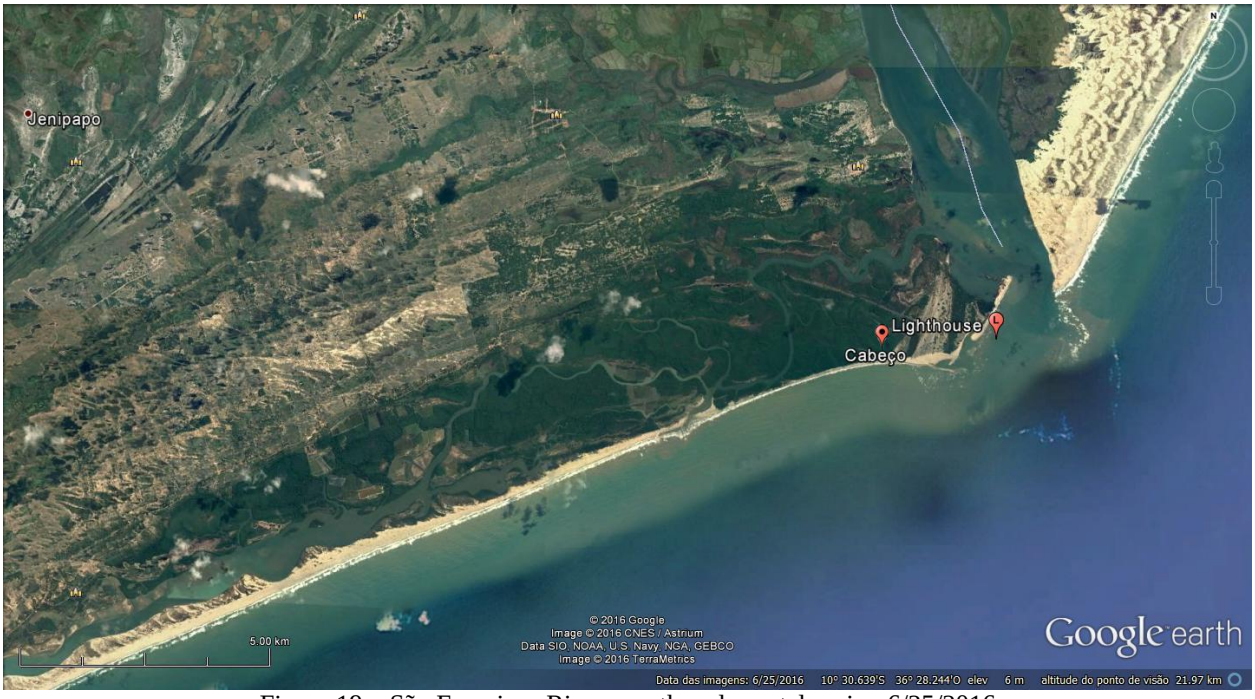

Figure 19 – São Francisco River mouth and coastal region 6/25/2016

There are currently powerful mathematical models, like DELFT3D (Leonardi *et al*., 2013), TELEMAC (Delgado, 2011), LITPACK (Thach *et al*., 2007), etc., which simulate the physical processes in open coasts and estuaries. By coupling a number of modules, which include a large number of interacting processes, it is possible to simulate the hydrodynamic circulation, sediment transport and the consequent morphologic evolution of the region. Thus, knowing the morphological, hydraulic and sedimentological parameters of the region, changes continuously suffered by this region could be predicted, preventing the displacement of populations and equity losses.

CONCLUSIONS

The main impacts in the region of the mouth of SFR, due to the retention of sediments inside the reservoirs of the HPP's built along the river, are: a) Drastic decrease (more than 90%) in the fish population in the low estuary and in the region of the mouth, due to the reduction of fine sediment contribution, which carries nutrients and organic matter; b) Erosion at the São Francisco River mouth caused by the lowering of sand contribution from continental origin and river discharge regularization.

In order to enable the application of mathematical models to evaluate the future morphological behaviour of the mouth region, it is recommended the measurement of morphological, sedimentological and hydrodynamic parameters in the region of the mouth of SFR and the use of already available data on river flows and the load of sediments from continental origin.

It should be stated that foreseen decadal or long term variabilities associated with climatic changes should be taken into account in modelling efforts. Lower precipitation rates associated with stronger and more frequent storms in the coastal areas (with increased wave action, and possibly changes in the direction of propagation of wind sea and swell) could have major impacts over the coastal ocean affecting human activity and infrastructures in the littoral zone.

Finally, in order to avoid future environmental impacts like the ones in the SFR basin and other basins around the world, it is advisable that an Integrated Water Resources Management (IWRM) should be established together with an Integrated Coastal Zone Management (ICZM), forming an Integrated Coastal Area and River Basin Management (ICARM).

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