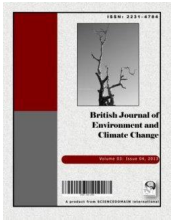

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Influence of Natural and Anthropogenic Processes in the Coastline Evolution at the Doce River Mouth (Espírito Santo, Brazil)

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Authors' contributions

This work was carried out in collaboration between all authors. All authors participated of the samples collection, date and statistical analysis and wrote the first draft of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Aims and Place: The Doce River is one of the largest rivers of southeastern Brazil, and has been target of strong environmental impact in recent decades due to mining and farming activities. Influenced by lithological factors and human disturbance, the Doce River has brought changes on the vegetation of the deltaic plain and increased the local sediment load transported
Methodology: Limnological analysis, textural characteristic of soils and sediments and TOC, TON and TP (ppm) were determined at the Doce River mouth during the dry and rainy seasons between 1993 and 2008. Cluster analysis, analysis of the sediment dynamic and bed topography of the mouth were applied to the results.
Results and Conclusion: The river shows accelerated bank erosion, especially during the rainy season. Near the mouth, erosion processes are enhanced by sediment dynamics, obstructing the main channel and modifying the coastal landscape. This research aims to contribute to a better understanding of fluvial geomorphology near the mouth of the Doce River, from nutrients flow analyze and sediment dynamics, without discarding the anthropogenic influence in the region.

Keywords: Erosion; saline wedge; sediment load; geomorphology; environmental changes.

NOMENCLATURES

TOC = Total Organic Carbon; TON = Total Organic Nitrogen; TP = Total Phosphorous; OM = Organic Matter; CEC = Cation Exchange Capacity.

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1. INTRODUCTION

Rivers are important carriers of minerals from the mainland to the sea. Many process-oriented studies of estuarine systems have focused on sediment-rich, often muddy systems, resulting from major fluvial sediment input. These disposal sites are characterized by high rates of erosion and sediment deposition, creating areas of accommodation sediments, resulting in the expansion or modification of the landscape.

The sediment dynamics that occurs on continental margins of estuaries is generally characterized by the presence of shallow water with high energy systems (fluvial dynamics) dominated by physical, chemical and biological processes, and intensified by anthropogenic activities. This scenario to contribute to modification of extensive lateral areas that are marked by the intensification of erosion processes [1,2].

The understanding of sedimentary processes in coastal regions, based on the characteristics of the sediments, has been limited by the interpretation of data related to grain size and some parameters of specific sediment composition [3]. Some advances have been made in the interpretation of data from grain size using statistical techniques on the distribution curves [4] and frequency of grain size and texture.

Nutrient transport in estuarine and marine systems is greater in the sediment-water interface where the redox gradients are elevated [5,6]. Studies on sedimentary analysis and nutrient composition in estuaries, especially involving the C:N:P balance as well as the construction of models of nutrient flow, may contribute to better understanding of the river flow to the ocean, and the anthropogenic activities influence in a specific region. Thus, we expect with this study to have better knowledge of regional geomorphology, classifying the sediment surface and marginal soils that make up the landscape of the Doce River mouth, from quantifying of the total nutrients concentrations in each compartment, and based on total solids transport, proposing a model of nutrient flow to this important southeastern Brazilian river.

2. MATERIALS AND METHODS

2.1 Study Area

Doce River mouth is situated in the municipality of Regency (19°35'-19°38'S and 39°47'-39°49'W), in Espírito Santo State, southeastern Brazil (Fig. 1). The climate ranges from subequatorial and tropical, with hot and humid summers and dry winters, with maximum rainfall between November and December (average 244 mm) and a minimum in July (average 50 mm), coinciding with the monthly average of temperature [7]. According to IBGE [8], the delta of the Doce River is the most important of the Brazilian coast with 2500 km^2 area. Near the mouth there is a wide plain with fluvial-marine terraces. The region has characteristics of destructive delta, with a single channel without meanders or tributaries, and with wave formation and transport of large amounts of suspended material into the ocean [9].

There is an extensive coastal plain of Plio-Pleistocene lands with sandy soil, and originally covered by sandbanks and coastal scrub vegetation [10]. This coastal band is mostly altered by agriculture, with construction of channels for drainage of excess water and reforestation. The result was the emergence of xeromorphic vegetation, alternating with grasses and dunes. A detailed map of the geological and morphological characteristics of the area was proposed by Aprile et al. [7].

2.2 Analytical Procedures

The mapping was conducted based on local observations with GPS, and through consultations provided by the National Institute for Space Research (INPE), the Brazilian Institute of Geography and Statistics (IBGE), Geographic and Cartographic Institute and Institute of Lands, Forests and Cartography State of the Espírito Santo. A program of sampling and measurements was deployed in the region in the last two decades (1991-2008), during the dry and rainy seasons, with collections and measurements ever undertaken by the morning. Six sampling stations of sediment and five of soil were distributed throughout the Doce River mouth (Fig. 1). In the water column were measured limnological variables: depth (m) with an Eagle fathometer; transparency of water (m) with Secchi disk; temperature of water (ºC), pH, electrical conductivity ($\mu S.cm^{-1}$), total dissolved solids ($mg.L^{-1}$), dissolved oxygen concentration ($mg.L^{-1}$) and oxygen saturation (%) via digital electrodes DMPH-2 and CD-2P Digimed, FAC 400 and YSI probes. Marginal soils and sediments were sampled with Ekmann dredge, at depths 0.0-0.2 m and 0.6-0.8 m, and placed in plastic bags and kept refrigerated at 4°C.

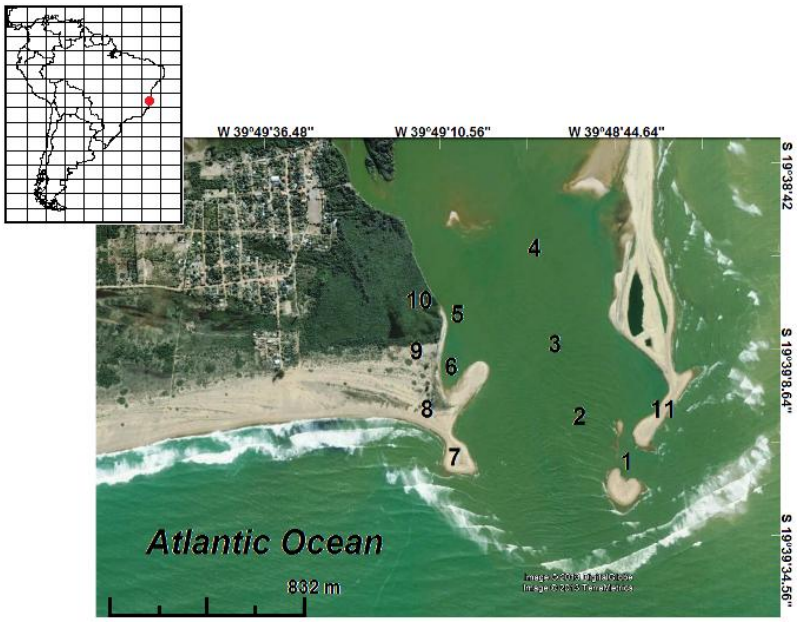

Fig. 1. Location of the Doce River mouth (ES, Brazil) with sampling sites

In the São Carlos Federal University (UFSCar), Pará Federal University (UFPA) and National Institute for Amazonian Research (INPA) laboratories, samples of sediments and soils were dried at 80°C for 24 hours, pulverized, homogenized and sieved to obtain the fine sand fraction (125-63 μm) and minor elements (silt and clay). The particle size distribution was determined by the classical method of fractional sieving. In the fine fraction of sediments and soils the organic matter content (OM%) was determined by acid digestion with hydrogen peroxide at 100°C for four hours [11], and from the results it was estimated the total organic carbon (TOC ppm). Cation exchange capacity (CEC meq.100g^{-1}) was determined by comparing the method of the acetic acid, pH control, and the method of absorption of methylene blue [11,12]. In soil and sediment samples were also analyzed the concentrations of total phosphorus (TP ppm) by the ascorbic acid method with spectrophotometric reading at 725 μm [13], and total organic nitrogen (TON ppm) by Kjeldahl method modified [14]. The results were statistically analyzed in order to confirm the sediment dynamics in the Doce River mouth.

3. RESULTS AND DISCUSSION

The channel flow on the surface waters of the Doce River have changed in many regions due to mining and agricultural activities. The limnological variables show a seasonal pattern marked by differences in precipitation and temperature. Fig. 2 shows the isovalue profile of this seasonal pattern, which is influenced by rainfall variation and also by human activities upstream the agricultural region where the drainage channels discharge during the heavy rainfall season. The high discharge increases the transport of fine sediments towards the mouth of the River Doce, reducing water clarity, especially within the small bay where stations 5 and 6 are located (Figs. 2B and 2E). The fine sediment transported accumulates especially along the right bank of the river. At stations 5 and 6 the electrical conductivity (Figs. 2C and 2F) and the suspended sediment load increased during the rainy season, contrary to what occurred in the main channel of the Doce river mouth, and this results from the accumulation of fine-grained sediments (silt and silt-clay) in the concave part of the river mouth (see Fig. 1), especially associated with sodium ions, and to a lesser degree with the magnesium and iron ions. Most of these sediments did not originate from erosion, but from river transport due to human activities in the middle Doce River between the state of Minas Gerais and Espírito Santo.

3.1 Sediment Dynamics

The main channel of the Doce River is characterized by alternating sequences of

sedimentary deposition of sand sediments and sand-silt sediments. The sediment layers have a high textural, compositional and structural variation, depending on the depositional environment where they occur. The sediments seen in the main axis of the channel are mostly composed of different sand layers, mainly consisting of detrital material and pebbles ranging between 4 and 2 mm in size. A more homogeneous layer skirts the main river channel, especially on the right bank, with changes in color and texture due to the presence of organic matter associated with sand sediments. Along this edge, the sediments become increasingly thin, with grain particles mixed between the sand, silt and clay.

Fig. 3 shows the soil and sediment texture characteristics at the mouth of the Doce River, according to the Shepard classification [15]. The summer rains greatly influence river erosion processes, which in the main axis showed predominantly sand-like grain size. The physical properties of the sediments such as transport and distribution patterns along the river mouth, and physicochemical properties such as cation exchange capacity were addressed in terms of particle distribution and size. Near the mouth, on the axis of the main channel, stations 1 and 2 predominantly showed very coarse sand to coarse sand grain size (ϕ = 2 – 1 mm) in 68.9% of the samples during the dry season and in 94.1% of the samples during the rainy season. In the small concave-shape bay the frequency of sand fractions was 3.9% during the dry season and less than 1.0% during the rainy season. The most effective contribution in these stations was fluvial deposition with high silt and clay values. Shepard and Moore [15] proposed the identification of the coarser fraction as a simple complementary technique, which can add relevant information to the interpretations of sediment distribution based on grain-size related parameters. This technique helped to differentiate the coastal environment from the continental margins. The sequence of sediments from station 1 towards station 4 was of very coarse sand with pebbles, coarse sand, fine sand and sand with silt fractions, respectively.

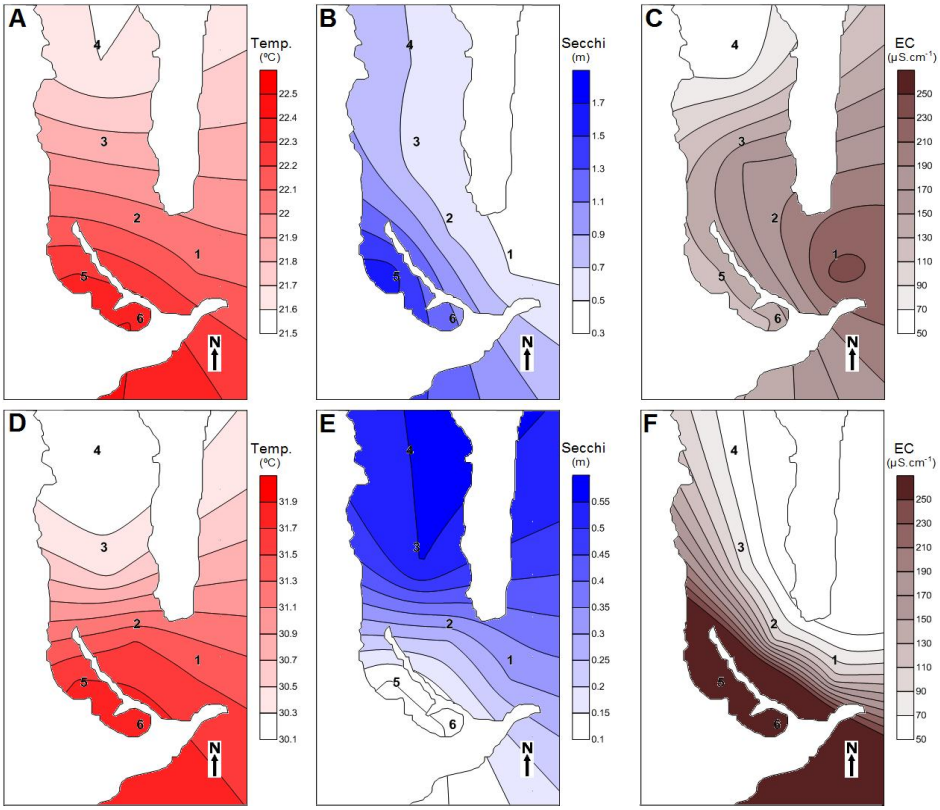

Fig. 2. Water temperature, transparency (Secchi) and electrical conductivity isovalues for the dry season (A, B and C) and rainy season (D, E, and F) at the Doce River mouth

The sequence found in the bay was of fine sand, silt-sand, and silt-clay. The sedimentation process in the middle of the main channel from the mouth is anomalous compared to the rest of the region. A river current flow with a high load of suspended sediment is pressed to the right bank of the main channel during the high tide season, interfering in the water transparency and also the sedimentation load within the bay.

Comparing the granulometric results with nutrient levels found in the sediments and soils of the sampled stations, it is noted that seasonality is maintained for the C, N and P patterns, and the sediment dynamics is one of the factors responsible for this seasonality. It was observed that in the dry season, in general, nutrient concentrations were higher than the levels analyzed in the rainy season, especially total organic carbon (TOC). The average C:N:P ratios were of 360:15:1 during the dry season, and 280:15:1 during the rainy season (Fig. 4), apparently when leaching of soils and the movement of coarser sediments were intensified by fluviomarine flows. Stations 5 and 6 were analyzed separately, as they are located in a fine sediment accumulation area (silt-clay sediments). Along this stretch, the average C:N:P ratios found were 3000:30:1 for the dry seasons and 1500:25:1 for the rainy seasons (Fig. 4).

The sedimentary characteristics and their physiographic distributions indicated a higher nutrient deposition, influenced by river currents on the right bank of the Doce river mouth, as observed in the particle-size analysis results. Emery [16] confirmed that permeable sands are a dominant type of sediment in continental shelves and generally contain a relatively small amount of organic matter. The low concentration of organic compounds in coastal sand sediments may reflect the high rotational rates [17], with high energy areas influenced by tidal zones.

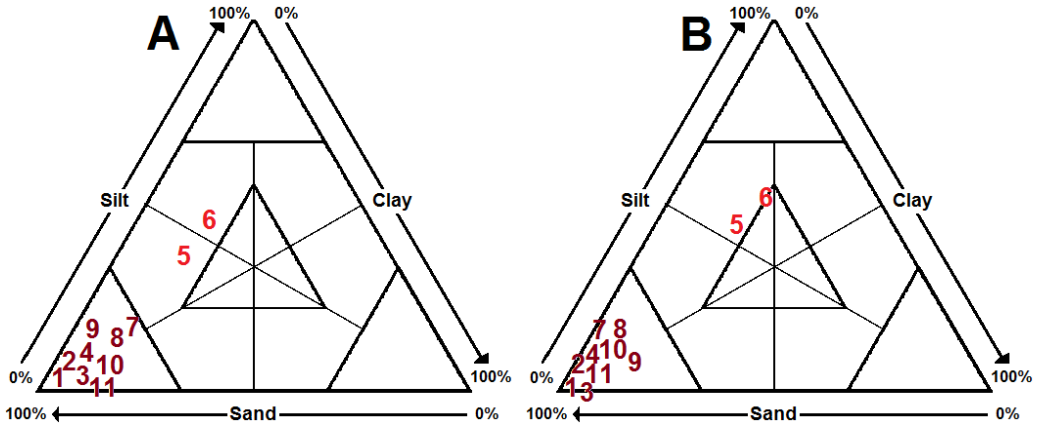

Fig. 3. Textural characteristic of soils and sediments at the Doce River mouth
Legend: A = Dry season; B = Rainy season

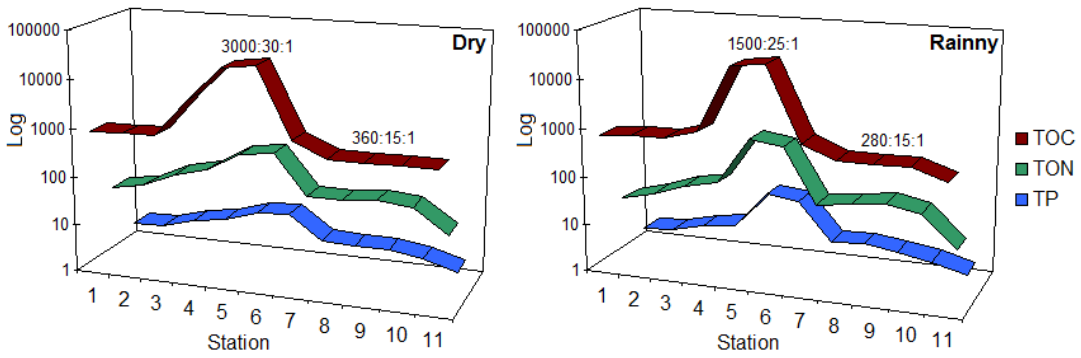

Fig. 4. Average concentrations of TOC, TON and TP (ppm) at the Doce River mouth during the dry season and rainy season between 1993 and 2008, with their respective average ratios

The spatial-temporal similarity analysis (cluster) was performed for a total of 16 environmental variables between 1993 and 2008, totaling n= 209 sampling sites, and showed a strong separation of the sampling stations 5 and 6 (Fig. 5), separating them from the other stations especially because of particle size and texture. The TOC, TON and TP nutrient levels also contributed to the findings at both stations. The results also showed a partial separation of station 4, located about 1 km inside the mouth of the Doce River, due to a higher concentration of fine silt and silt-sand sediments compared to stations 1 to 3, where the influence of marine sedimentation was more evident.

3.2 Spatial-temporal Influence on the Coastal Geomorphology

Historical records show that the coastline near the mouth of the Doce River has experienced changes in geomorphological patterns for centuries. Saint-Hilaire [18] noted the presence of sandbanks which lengthened obliquely in the river mouth, and also that the main channel, through which its waters were discharged into the ocean, constantly shifted. Aside from the sand spit where the river and marine waters meet, a dense forest was found along the length of the edge of the Doce River mouth, and as this forest gave way to agricultural activities, the erosion processes intensified. The depth of the Doce River mouth was also discussed in [18] and in the historical review of Zunti [19], in which both authors discuss that even during the highest tides or rainy seasons, only small boats could navigate the river channel.

The erosion-related wind activity caused by waves and tides shift the dunes, causing deltaic floods and burying certain regions, such as the area between the cities of Itaúnas and Conceição da Barra.

The seasonal variation (dry and rainy seasons), evidenced by sedimentary processes and biogeochemical cycles and confirmed in the spatial similarity analysis (cluster Fig. 5), showed the strong correlation between the coastal dynamics and the accumulation of fine sediments inside the Doce River mouth. In the rainy season the precipitation is associated with marginal erosion effects, in a system strongly influenced by regional lithological factors, which produced low soil retention and high transport capacity of clastic materials. This is a natural condition for the region, which is strongly influenced by the interaction of end of winter winds with low topography and the typical local vegetation. The action of ocean tides has a strong influence on shaping the Doce River mouth, alternating the orientation axis of the tides over the hydrological year. This enables to evidence the continuous construction and destruction of the sand banks along the NE-SW axis. Another important factor for the geomorphological construction of the Doce River mouth was the continuous human disturbance on this vegetation, reducing the retention capacity of marginal soils. The high total precipitation variation in the study region is a result of high evaporation rates of water masses of the Atlantic Ocean during the summer, as opposed to the cold ocean currents that reach the coast of the State of Espírito Santo between the months of June and August, and which are accompanied by strong trade winds.

The result of the interaction between the morphoclimatic and anthropogenic events in the region is a high sediment fluviomarine environment. It was observed that within a very short geological time a marine sedimentation area predominantly made up of sand sediments was formed in the eastern part of the river mouth (Fig. 6). The sequence of illustrations shows the continuous change patterns of the Doce River discharging to the Atlantic Ocean, with repercussions for navigation and fishing activities, as the main channel is continually being silted. It was observed over the last two decades that in several stretches of the river mouth the accumulation of sediment (deposition process) exceeded the natural erosion rate, as seen between stations 5 and 6.

The hydrological regime, the total solids flow in the water (dissolved/particulate), the biogenic material load and the ionic composition have all changed over the years, modifying not only the physical landscape and chemical composition, but also the terrestrial and aquatic biological structure. Undocumented information from local fishermen and coastal communities has shown that the volume of fish in the region near the mouth of the Doce River has fluctuated substantially over the years. The only solution to mitigate the advance of erosion and intense depositional processes in certain stretches of the river mouth is restoring the local preterit vegetation, emphasizing the preservation of the mangrove area, located further upstream the river mouth. The protection of the river banks in its middle course is also vital, by means of more rigorous control of agricultural and mining activities. The uncontrolled urban expansion in the region is another problem with serious

consequences for the biota, which could lead to a potential collapse of traditional fishing at the mouth of one of the most important rivers in southeastern Brazil.

3.3 Influence of Geomorphology and Seasonality on the Saline Wedge

The river flow speed is directly associated to the rain volume at the mouth of the Doce River. However, the ocean tide advancing towards the mouth of the river is due to a periodic acceleration during the occurrence of high tide or low tide events, on account of the changes related to the positions of the stars (Moon and Sun), distinctly recognized in high tide seasons and quadrature.

Throughout the study period, a water mass inversion situation was observed several times at the mouth of the Doce River (Fig. 7), always occurring during the dry season, when the absence of rainfall decreases the river kinetic energy, but which did not influence the marine kinetic energy. During these seasonal times, a less dense subsurface stream can be seen flowing below the thermocline, at low speed and inverse direction to the denser surface sea current, which during this time usually has a high penetrating power in the river mouth. This water mass inversion is known as inversion of the saline wedge.

Another factor that may be correlated with the inversion of the saline wedge is the topography of the Doce River bed near its mouth. Granulometric and morphometric studies by Aprile et al. [7,9] showed an irregular formation of this bed, with the presence of medium to large sized sandbanks during the dry season, which may have contributed to the change of current patterns, as suggested by [20] in their hydraulic geometry studies (Fig. 7).

Even in the water mass inversion period, a slow and gradual mixture was observed as it moved from sampling station 1 to station 3 (see Fig. 1). Changes in temperature patterns and in the concentration of dissolved oxygen and the main dissolved cationic ions, in the vertical and horizontal profile, show the slow homogenization tendency of the water masses into the mouth of the Doce River during the dry season. In other words, two distinct water masses were initially observed at the mouth of the Doce River, which due to density differences remained as such for a period of time, occasionally the inversion that occurred in winter (dry season) was due to the imbalance of three associated factors: current speeds, different temperatures and concentration of total solids. After a trajectory, resulting from the exchange of thermal and kinetic energy, the density differences tended to balance out, with the occurrence of an initial partial mixture followed by water masses.

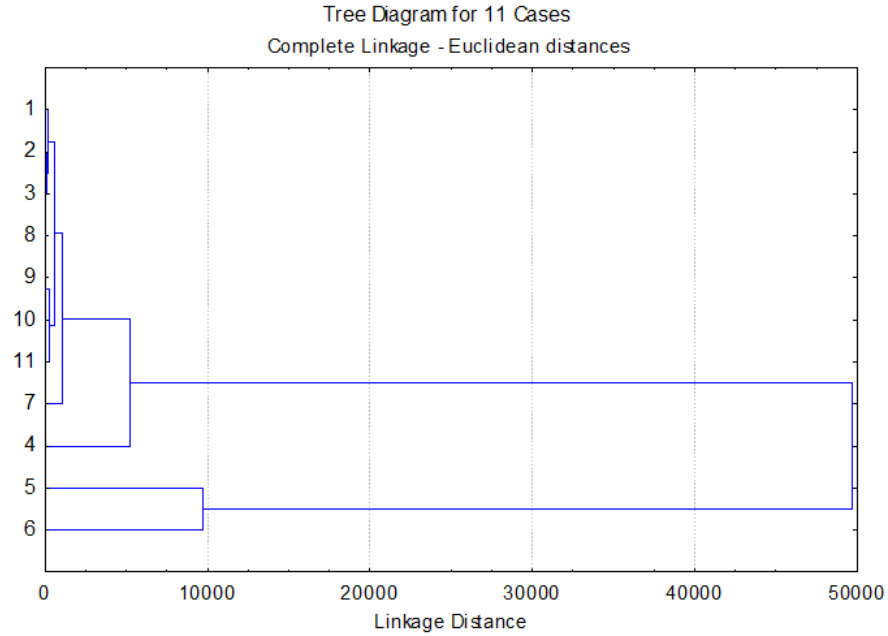

Fig. 5. Cluster analysis of sampling sites analyzed at the Doce River mouth

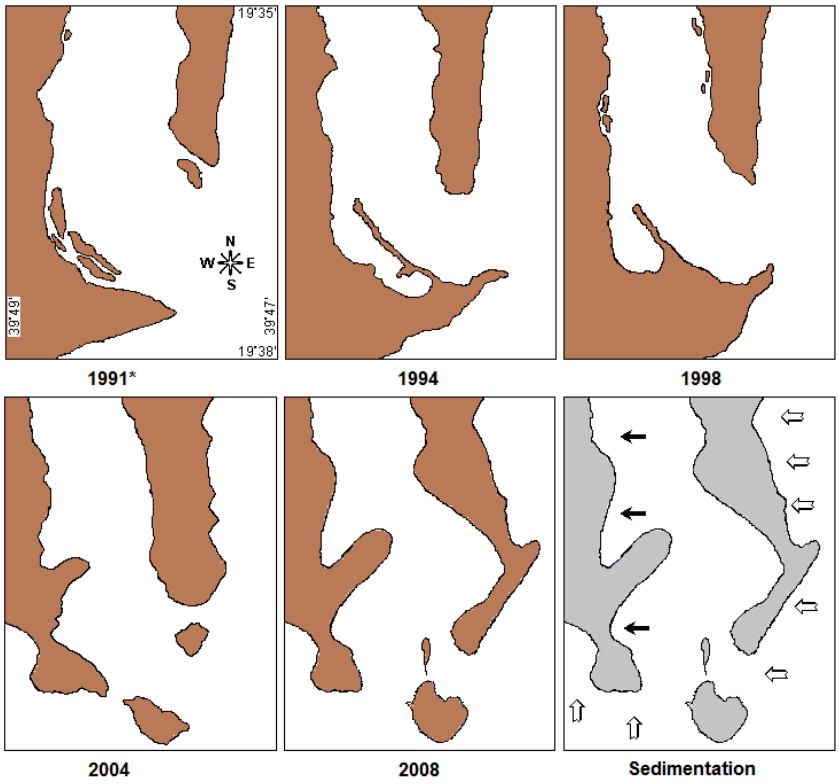

Fig. 6. Change in shoreline patterns according to sediment dynamics in the Doce River mouth for the period between 1991 and 2008

Legend: White arrows = Marine sediments; Black arrows = Fluvial sedimentation

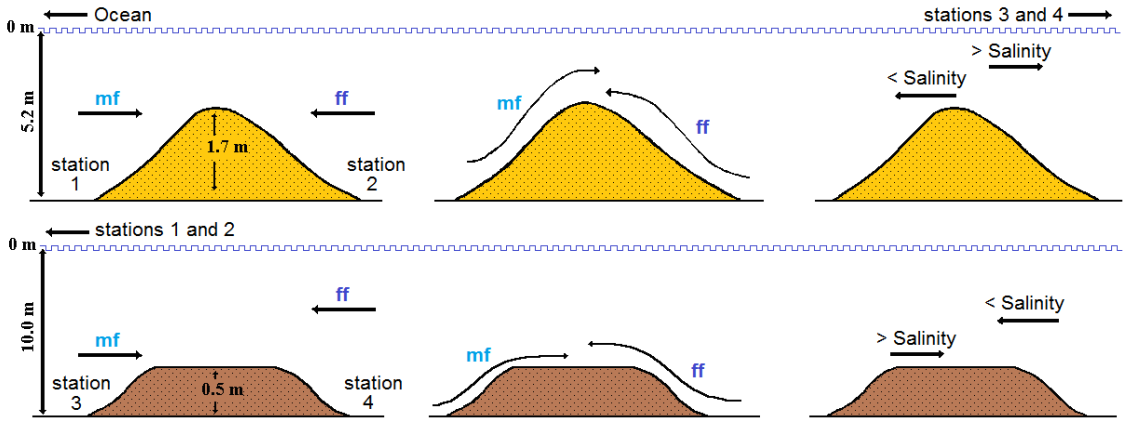

Fig. 7. Bed topography influence of the Doce River mouth in reverse water masses river and sea, according to the model suggested by Leopold and Maddock (1953)

Legend: mf= Flow marine; ff= River flow

4. CONCLUSION

The strong environmental impact from mining and farming activities has influenced changes in the geomorphology and sediment composition at the Doce River mouth in the two last decades. As result, an increase of the fine sediment load in the secondary channel was observed. Erosion processes with high sand deposits also were observed in the coastal line affecting the navigation and the marine water flux. The studies confirmed that there is a high dynamic fluvial and

marine at the region, changing continuously the mouth geomorphology.

CONSENT

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ETHICAL APPROVAL

It is not applicable.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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