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Hydrodynamic and Morpho-Sedimentary Characterization of the Potengi Estuary and Adjacent Areas (NE Brazil): Subsidies Towards Oil Spilling Environmental Control

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ABSTRACT

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This study presents the Environmental Sensibility Mapping to oil spilling on the Potengi estuary and adjacent coastline. Located on the eastern coastline of the Rio Grande do Norte State and being inserted in the geological context for the Pernambuco-Paraíba coastal basin, this estuary shelters the Natal harbor zone and an oil terminal, centralizing, therefore, important oil transport operations that can cause accidental spillings. This study has the aim to collaborate for the increase of informations about the estuarine environment and contribute to a better management of the question: environment/polluting loads. The methodology used included remote sensing data, collecting, processing and integration of the geomorphologic, oceanographic (temperature, salinity, density, direction and intensity), meteorological (wind speed and direction) and high resolution seismic (bathymetry and sonography) data. Important variations of the salinity mean values (36.32 psu), temperature (28.11ºC) and density (22.96 kg/m^3) in the estuarine waters presented features belonging to low latitude regions. The water temperature follows the air temperature variations, in the region, with expressive daily amplitudes. In this study, the identification of the estuarine bed morphology through bathymetric and sonographic analysis had the purpose to evaluate the influence of the superficial and bottom currents for the bottom shaping. The estuarine channel is filled by holocene sandy- to silty sediments. The distribution of these textural facies apparently oscillates owing to the tidal cycle and flow intensity.

ADDITIONAL INDEX WORDS: *Oil spilling, environmental sensibility, northeastern Brazil.*

INTRODUCTION

The estuaries are coastal sedimentary environments whose evolution depends on the interaction between hydraulic, sedimentary parameters and morphological features and where the biological activity is an essential conditioning. Being excellent sediment depositing means, where the evolutive processes are fast, the estuaries are important research areas for the present morphodynamics and depositing facies of the recent geological history.

The estuarine systems are also attractive means for an anthropic action where the development of the harbor and marine activities are increasing. They constitute, therefore, important poles for the development of geology and marine geophysical studies related, above all, to waterway maintenance, behavior of dredging and rejecting zones and building and maintenance of the works. In all of them, besides the knowledge of the hydrodynamic parameters and understanding of the flow patterns, the kind of the materials and the sedimentary dynamics constitute determinating components for the foreseing of the operating processes, owing to the evolution in a recent past being analysed in accordance to the understanding of the future evolution.

In this context it is inserted the Potengi estuary (Figure 1) where is located the Natal harbor which centralizes important operations such as oil transport and an oil terminal that can cause oil spillings. Such accidents, although rare, are difficult to be controlled and can produce serious material and ecological damages.

In case of environmental accidents, the damages brought to this region usually are quite enlarged not only by the economic and esthetic consequences, easily evident, but also by the higher sensibility inherent to the environments here shown such as mangroves and tidal plains which suffer, in the event of accidents, the most serious initial impacts and have a slower recovery.

Meanwhile, the inexistence of accurate and updated cartographic maps is often one of the main problems to accomplish the mapping of the Coastal Sensibility Index (CSI). This problem is still more serious in developing countries due to the lack of opportunities or economical resources to prepare a database for maps updated in scales, in accordance with the necessity of specific informations. Though it may exist a generally acceptable map cover to identify the main roads and cities, the mapping quality of wide land extensions such as mangroves is often hardly trustworthy.

The first studies that used remote sensing and geographical information system (GIS) to make environmental sensibility maps for oil spillings date from beginning of the nineties (JENSEN *et al*., 1990; 1993) and were afterwards used by the National Oceanic and Atmospheric Administration (NOAA) in the south of Florida, USA and in Abu Dhabi Emirate, United Arabian Emirates, this methodology was adapted to environmental of the Rio Grande do Norte State (CASTRO, 2002; FRAZÃ O *et al*., 2002; 2003).

In this context, the main purpose of this research is to analyse the hazard situations due to eventual oil spillings in the Potengi estuary. This kind of analysis is essential to reduce the spilling environmental consequences (MMA, 2002), to make the contention and cleaning/ removal efficient in the Natal harbor, by simulating the hydrodynamics forced by wind and the simultaneous performance (currents and wind) in the transport of oil spots as a support to the contingency plan.

This study has the purpose of helping to increase the estuarine environment knowledge and to contribute for a better management of the question environment / polluting loads, by subsidizing the elaboration of Environmental Sensibility Maps (ESM) to oil spillings, so that the protection priorities may be established and the strategies of contention and cleaning / removal previously sketched out.

The mapping of sensitive areas stands out, therefore, as an important tool for the planning decisions, development and

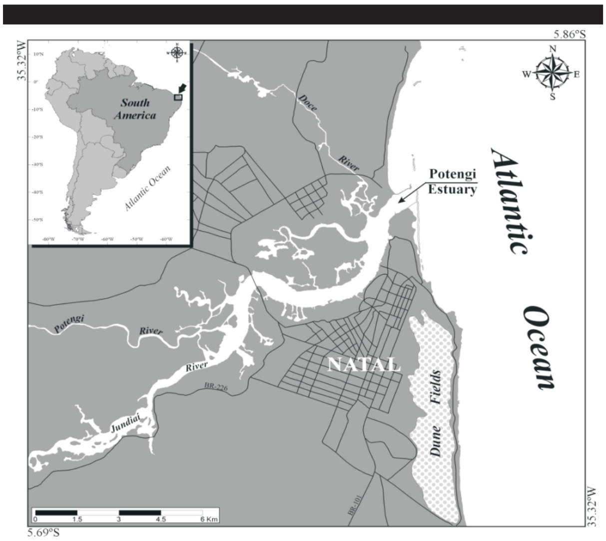

Figure 1. Study area location.

environmental monitoring of the oil industry, specially the regulation and hazard management.

METHODS

The used methodology has included the use of remote sensors (2 images from the Landsat Enhanced Thematic Mapper Plus - ETM+), field data and later on processing.

The field works were accomplished in three stages: (1) the first consisted of an aerial survey made with a Fox ultralight, with the purpose of taking oblique photos of the main echosystems along the coastline and identification of specific targets to help in the separation of the oil spilling sensitive segments; (2) the second has included an "in situ" investigation with a Land Rover DEFENDER 110 4x4 jeep to characterize and separate the segments with the help of a DGPS. In each segment sensitive to oil spillings, were performed beach profiles, hydrodynamic data collecting (waves, currents, tides), sediment and socio-economic samples; and (3) the third consisted of bathymetric and sonographic surveys (Odom Hydrographic Systems and Sonar's HYDROTRAC, EG&G's model 272T), water physical parameters (VALEPORT'S 108KIII current sensors and AANDERAA's DCS 3500, VALEPORT's CTD 108 MKIII and AANDERAA's 3231) and bottom sediment collecting (van veen type drag) in the Potengi river estuary. As floating means were used boats borrowed from the Capitania dos Portos do Rio Grande do Norte - CPRN / Brazilian Navy and all the research area was performed by DGPS.

The imagery pre-processing and processing were accomplished through the *ER-Mapper v.6.0* software (Earth Resource Mapping Pty Ltd.). First of all the Landsat 7 ETM+ images were rectified so that they could be efficiently used as an updated digital cartographic base. Using maps with 1:100.000 and 1:50.000 scales, the ETM+ satellite images were rectified to an *Universal Transverse Mercator* (UTM) projection bearing system.

The square root mean error (RMS) for all the images was 1 pixel (30 m and 15 m), being used an algorithm of the nearest neighbour.

The used Coastal Sensibility Index (CSI) was based on the Specifications and Technical Norms for the Elaboration of Oil Spilling Environmental Sensibility Charts (Charts SAO) elaborated by MMA (2002), based on the classification of environmental sensibility adopted by NOAA (1997).

RESULTS

From the water physical parameters collected in this research the Potengi estuary was classified by applying the stratification-circulation diagram, deduced by HANSEN and RATTRAY (1966) and known to be the best method for the estuary classification by several authors (DYER, 1986; 1997; PRITCHARD, 1989; among others).

The Potengi river estuarine channel was classified, in this diagram, as a 2 type (moderately stratified) during spring tide with the salt rate ruled by the advective and dispersing processes. Besides these processes, it occurs the tidal turbulence effect which destroys the saltwater wedge interface producing a salinity gradient which takes place from the bottom to the water surface through advection and diffusion mechanisms based on salinity and water density.

The estuarine water thermic stratification shows itself independent from the tidal action, producing an up to 0.8C temperature zone between the surface and the bottom and can change more widely with time and the place depth. This thermic stratification is emphasized mainly during the afternoon and early in the morning. During the night from 21 o'clock on, it can occur a stratification thermic reversal when the superficial water temperature shows itself lower than the bottom one at the bottom.

Regarding to the temperature vertical distribution, it was observed in the Potengi estuary, a quite steady distribution, without thermic variations, so that this fact can be related to the water turbulence process which spreads heat through all the water.

However, towards the mouth, it was detected a temperature decrease in all the water column. This is directly related to the Potengi river estuarine bottom gradient, where zones with a lower water column and higher concentration of suspended matter are under the influence of the daily high insolations giving rise to temperature high values.

The measures tooken in the Potengi estuary, within the purposes of this work, show that the salinity achieved from the conductivity changes according to the tide, where the salinity peaks occur together with the slack water.

The salinity vertical distribution during the spring tide is shown partially stratified with a 4.86 psu variation (minimum of 32.57 psu and maximum of 37.43 psu) and an average of 36.32 psu, occurring an increase towards the mouth. The concentration distribution of this parameter is controlled mainly by the small freshwater discharge coming from the Potengi and Jundiaí rivers, showing, that in the studied region, occurs only the predominance of sea waters in all the water column which is related to the lower fluvial influence.

The T-S Diagram for the Potengi estuarine channel (RN), with the hydrographic data sampled during a spring tide cycle of 13 hours, 8.4 km far from the mouth, shows a small dispersion of the estuarine water mass. In that diagram, it was identified only the presence of a coastal or mixed water mass (CW) along the estuary between the Igapó bridge and the mouth.

The classification map of the sediment textures, produced for the study area, is related to the bathymetric map shape, the sandy facies was the main sedimentary facies found in the estuary between the Igapó bridge and the mouth. The muddy facies is restricted to the estuary margins, while the estuarine channel deepest areas are covered with coarser sediments, usually pebble and gravel sand together with fragments of limy shells.

In a few words, the Potengi estuary bed is characterized by small to large dunes, with wavelengths at the rate of 2.87-95.12 m, heights up to 4.3 m and with diverse sinuousity and overlay.

The bedform classification here used follows ASHLEY'S indications (1990) and comprises DALRYMPLE and RHODES revisions (1995) based upon the morphology. According to this classification, all transverse bedforms in large scale (except ripples and antidunes) occupy a similar rank in the sequence of the lower flow regime being later modified by data such as grain size, shape and superposition. The wide variety of shapes shows the several hydrodynamic conditions as well as the sediment types. In the main channel zone, the recorded dunes were mainly medium to large ones concerning wavelength and height, besides showing another features belonging to a simple superposition.

By using the log-log diagram of height (H) versus wavelength (L), proposed by FLEMMING (1988), it was possible to make the distinction between ripples and dunes, both of them belonging to the lower flow regime. The smallest bedforms were identified as dunes with a small wavelength.

Most dunes, recorded by the two types of side scan sonar, have revealed strong asymmetries what shows the influence of flood and ebb tide flows. The bedform asymmetry along the estuarine channel is a strong evidence of the marine influence on the estuary, being, therefore, the main ruler of these environments dominated by tides.

The side scan sonar survey has shown abrupt changes, till then not identified, in the bedform morphology within the study area; both the dune wavelength and specially the height have changed in size along distances of a few meters. This situation allows the dune type large bedforms found in the Potengi estuary up to 95 meter long and 3 meter high to become natural traps for the spilled oil capture.

The more sensitive areas were mangroves and tidal plains while the less sensitive ones were the artificial structures built by man and beachrocks. The less sensitive coastlines can often be cleaned by wave action or machines. On the contrary, areas as mangroves and tidal plains are very difficult to be cleaned and the access is restricted. Each of these sensitive areas shows its grade of environmental sensibility to spilled polluting agents and distinct response and cleaning recommendations.

The oil spilling environmental sensibility map here showed (Figure 2), was elaborated according to a strategic detailing level on a 1:75.000 scale owing to the used Landsat imagery resolution. For larger scale detailing levels (tactic and operational charts), it may be applied the same methodology using Spot or Ikonos images.

The main results can be seen on figure 2, which is an environmental sensibility map to oil spillings built from satellite imagery with the coloured compositions RGB and RGBI 432 combined with the Terrain Digital Model (TDM) for the Potengi estuary. It were identified some coastal ecosystems showing a better result on the discrimination of Barreiras Formation exposed cliffs (CSI-3), dune fields (CSI-3), beachrocks (CSI-5), exposed rip-rap (CSI-6), exposed sandy tidal plain (CSI-7), sheltered muddy tidal plain (CSI-9), mangroves (CSI-10) and mangrove preceded by muddy low tidal terrace (CSI-10).

According to FRAZÃO *et al*. (2003), the obtainment of oblique aerial photos and *in situ* data collecting were essential to identify and discriminate the coastal features that couldn't be right mapped with the ETM+ data. However, the ETM+ data were efficient to map the location and spatial distribution of several more sensitive segments as mangroves and tidal plains. While the CSI traditional mapping couldn't show the presence of those segments, the use of remote sensing techniques was able to measure accuratly their length area.

CONCLUSIONS

The superficial waters of the Potengi estuary and neighbouring sea areas, even under weak winds, are characterized as a relatively unquiet system, above all by the tidal flow action, with high frequency of irregular waves, determinating clearly a turbulent flow regime.

Based on the intensities and direction of the tidal flows it was possible to elaborate flow charts for the Potengi estuary every 2 hours before and after high tide. These data are extremely important in the event of a scattering of oil spots, since it is necessary to know the hydrodynamic conditions at the same time an oil spilling is happening. They are therefore, an important tool for the contention and cleaning teams, in the identification of the most sensitive areas to oil spillings, such as mangroves and tidal plains, as well as to map the oil scattering route.

The water temperature in the estuary is a control factor for life and chemical processes that take place in the aquatic environment. In the studied area, the temperature superficial distribution is typical of low latitude regions, presenting a well mixed homogeneous layer with mean temperature of 28C. The high temperatures contribute, in the event of oil spillings, to a better evaporation and decrease of the spilled oil viscosity.

The salinity of the Potengi river estuarine waters, between the Igapó bridge and its mouth, showed a superficial distribution, directly influenced by climatic and oceanographic factors, presenting a maximum of 37.43 psu in the mouth and decreasing upstream as far as the Igapó bridge to 32.57 psu. Concerning the density distribution of the Potengi estuary waters, it was possible to observe that the salinity influences more strongly the density distribution than the temperature in the studied region.

The salinity is one of the important parameters which control the scattering and the density increase of the spilled oil. The salinity high values found in the Potengi estuary are going to contribute for a smaller oil scattering due to the increase of the waterish environment density.

The quantity of suspended matter in the water deriving from the nearly steady resuspension of the fine sediments from the banks and margins, due to the tidal flows, contributes for a higher or lower scattering of the spilled oil, since, in areas with higher concentration of suspended matter, the scattering through flocculation will be more efficient owing to the favourable conditions.

The Potengi estuary classification was important, because, in the event of scattering polluting agents such as oil derivatives, it is necessary to know, among the dispersion and advectiv processes, which one is dominant or what combination of these processes may be used in the estuarine hydrodynamics.

Since the Potengi estuary was classified as partially mixed or 2-type, in accordance to the stratification-circulation diagram, the mixture process of the Potengi river waters with spilled polluting agents such as oil happens through piercing, advection and turbulent dispersion. So, in case of oil spillings in the Potengi estuary and neighbouring areas, a more serious factor in the oil mixture along the water column would be the effect of the turbulent dispersion produced by the tide which would play an important part in the mixture processes of the estuarine water mass with the spilled material.

The differences in the morphology of the transverse flow bedforms mapped in the Potengi estuary reflect the response dimension to the drainage system, water floating level, speed and direction. Since these bedforms also appear as a size continuity, we can then say that the variations observed in the bedform morphologies reflect the influence of the hydrodynamic condition variation as well as the tidal effects.

It is an important factor to know accurately the several types of bottom morphology in case of oil spillings with more density than the water such as grease and paraffin oils. Because, in these situations, the dune type large bedforms, found in the Potengi estuary up to 95 meters long and 3 meters high, can become natural traps for the spilled oil capture.

The main sedimentary facies which covers the Potengi estuary, between the Igapó bridge and its mouth, is the sandy facies. In sites with moderate flows, it can be seen fine to medium sands and in the navigation main channel where the flows are extremely strong, mainly during the floods, the bottom is covered by sparse gravel sand and gravel sand. The fine fraction lies on little depth zones as the estuary margins, the tidal channels and tend to increase upstream owing to the loss of the tidal flow intensity.

This research showed how the components of a mapping digital system of the Coastal Sensibility Index (CSI) may be built by using *in situ* data and remote sensing techniques, ordered in a GIS and discussed using a suitable logic. These techniques showed to be efficient on the mapping of location and spacial distribution of areas with difficult access and more sensitive to oil spilling.

The orbital digital images associated to oblique aerial photos are very important to the SAO Chart elaboration. The correct use of these charts will allow the oil spilling fighters to optimize the distribution of the oil spilling control and the protection resources.

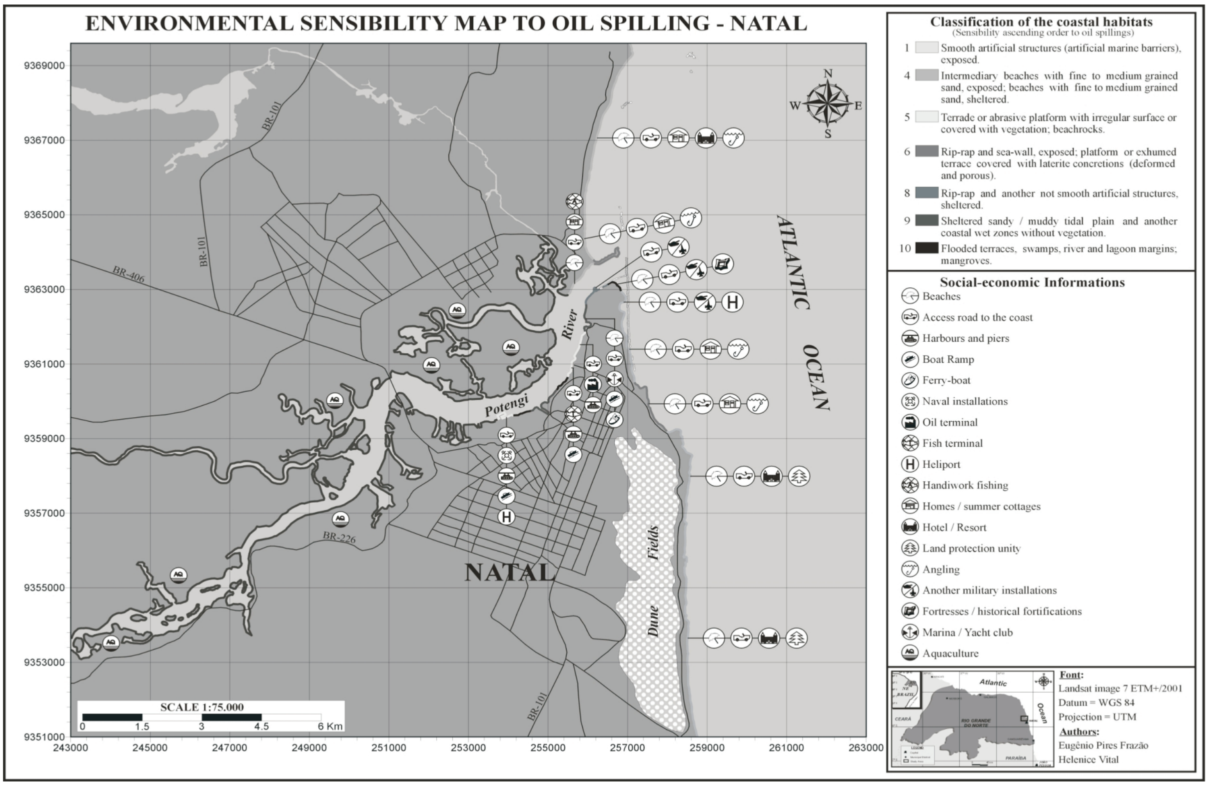

Figure 2. Environmental sensibility map to oil spillings for the Natal City region.

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