Remote Sensing and GIS Integration for Modelling the Paranaguá Estuarine Complex -Brazil

M. A. Noernberg; L. F. C. Lautert; A. D. Araújo; E. Marone; R. Angelotti; J. P. B. Netto Jr. and L. A. Krug

Centro de Estudos do Mar
Universidade Federal do Paraná,
Pontal do Paraná
83255-000, Brazil
m.noernberg@ufpr.br

ABSTRACT

Before implementation hydrodynamical and ecological models in estuarine systems it is necessary a set of morphological and hydrological information at different spatial scales. The quality of this information will affect directly the model quality. A classification with three hierarchical levels was done for the Paranaguá Estuarine Complex focusing on both the morphological and hydrological characteristics. This classification allowed a physical characterization in different spatial scales, which is necessary for the watershed and coastal waters zonation, as well as the application of models, at each level. Remote sensing and GIS techniques were used to extract features from Landsat ETM such as the coastline, the upper limit of wetlands; the vegetated flooded area, composed basically of mangroves and salt marshes on upper areas; and mud flats. The top level in the hierarchy is the Paranaguá Estuarine Complex as a whole. The next level consists in a division of the system in five sections, and in the last hierarchy level seven sub-estuaries were delimited. Attributes were obtained for all the units defined in each hierarchy level, such as area, perimeter, depth (when available), water body area (without wetlands), wetlands area, tidal flat, drainage area, drainage density, hydraulic gradient and river discharge (when available).

ADDITIONAL INDEX WORDS: Coastal management, estuary, coastal water zonation.

INTRODUCTION

The social, economic and environmental importance of estuaries is already well known. In order to protect and to make a wise use of such environments it is necessary to know their dynamical characteristics. The use of ecological and hydrodynamical models became a powerful tool to give more accurate information not only of scientific nature, but also to decision makers and for the environmental management. The hydrodynamical models usually need morphologic and hydrologic information such as fresh water input, coastline morphology, bathymetry, tides, currents and winds. When the reduction of the spatial scale is performed there is, consequently, a larger need in details and definitions of boundary regions.

The use of remote sensing as a tool for studies in coastal areas is also well known. Its capability to obtain different kinds of information for a large area, at the same time, is one of the main characteristics. The diversity of applications using remote sensing in coastal studies is great, including qualitative and quantitative studies. These applications cover determination of bathymetry and coastline, studies and mapping of mangroves, water quality, chlorophyll a, sediment transport, subtidal habitats (JENSEN et al., 1991; KHAN et al., 1992; BANAN, 1993; TASSAN, 1993; SOOTHERAN et al., 1997; RAMSEY et al., 1998; DURAND et al., 2000; RYU et al., 2002).

Other useful characteristic of remote sensing is the possibility of studies about dynamic processes, thanks to the recurrence of images. Various products obtained from remote sensing, integrated with the capability of GIS spatial analysis, are important tools for the study and modelling of the estuarine and coastal environments.

The main goal of this work is to establish three hierarchies levels in the physical definition allowing the watershed and coastal waters zonation, as well as the modelling, for each level.

THE PARANAGUÁ ESTUARINE COMPLEX

Paranaguá Estuarine Complex (PEC), located at Paraná State coast, south-eastern Brazil (48º 25’ W, 25º 30’ S), is a large interconnected subtropical estuarine system, comprising two main water bodies (LANA et al., 2000). The population is 155.000 inhabitants, who live in three main cities, many fishermen villages and country homes. The system is connected to the open sea by three tidal channels. The structural properties of the estuarine system are typical for a marine ingression environment. An extensive coastal plain surrounds the Paranaguá Estuarine Complex, reaching up to 50 km inland at the piedmont of the Serra do Mar mountain range. Mangrove swamps and marshes mainly fringe the interior of the system, while ocean exposed areas adjacent to the mouth are composed of extensive sand beaches and some rocky shores (ANGULO, 1992). The mean tidal range is 2.2 m, with a tidal prism of 1.34 km³ and a tidal intrusion of 12.6 km. It is a partially mixed estuary with a residence time of 3.49 days and a mean fresh water runoff up to 200 m³ s⁻¹ (MARONE et al., 1995).

METHODS

The Paranaguá Estuarine Complex is classified in three hierarchy levels (Figure 1). The top level in the hierarchy is the Paranaguá Estuarine Complex as a whole, a coastal plain estuary and its watershed, with geographic region containing comparable landform and climate.

The next level consists in a division of the system in five sections, including the main bays: Paranaguá, Antonina, Laranjeiras, Pinheiros, and a mixture section. The names of the sections follow the geographic denomination. The distal limits were determined in the zones of the shortest cross sections and the internal limits were defined at the wetlands boundaries.

In the last hierarchy level, the sub-estuaries of each section were delimited considering morphological features such as embayment, and specific drainage area.

A set of attributes were obtained for all the units defined in each hierarchy level (sub-estuary, section and estuarine complex), which are: area, perimeter, depth (when available), water body area (without wetlands), wetlands area (mangroves and salt marshes), mud flat, drainage area, drainage density,
hydraulic gradient and river discharge (when available).

The Landsat Image Processing

The morphological boundaries which present variations in distinct time scale were extracted from Landsat ETM+ image acquired in September 1999. The extracted features were: i) the coastline, considered as the upper limit of wetlands; ii) the vegetated flooded area, composed basically of mangroves and salt marshes on upper areas; and iii) mud flats. Each of these morphologic boundaries was obtained using a specific Landsat image channels composition. The different compositions allowed the enhancement of specific features, mainly the boundary between the specific feature and its neighborhood. However, the method for boundaries delimitation comprised the same: threshold, binary and vector transformation. The image processing software used was the Er-Mapper and the Spans program for GIS.

For the upper limit of wetlands extraction the channels composition used was the Landsat band 5 in the red channel, the Normalized Difference Vegetation Index (NDVI) in the green and the first principal components (PC1) of the Landsat bands 1, 2, 3, 4, 5 and 7 on the blue channel. With this composition the tidal inundation area of the basin was enhanced as well as its boundaries.

The mud flat areas were extracted using only the first principal components (PC1). The histogram image resultant was a bimodal shape, each one representing the water and land portions respectively. A linear stretch was applied for the water portion, enhancing the tidal flats areas.

These boundaries, extracted from Landsat images, were integrated in a previous GIS database (Noernberg et al., 1997).

RESULTS

The attributes obtained for top level in the hierarchy, the Paranaú Estuarine Complex (PEC) as a whole, are: watershed area 3870 km\(^2\), water body (without wetlands) 551.8 km\(^2\), vegetated flooded area 295.5 km\(^2\), drainage density 1.12 rivers/km\(^2\) and tidal flat area 136 km\(^2\), this tidal flat area represents 24.6% of the water body area.

The results for the sections and sub-estuaries levels are showed in Tables 1 and 2, respectively. The sections with biggest drainage area are Antonina and Laranjeiras, consequently in this sections there exists the higher number of sub-estuaries. The higher proportion between wetlands and water body is found in Antonina section followed by Pinheiros and Laranjeiras, respectively. The smallest relative tidal flat areas are found in Mixture and Paranagua sections.

The sub-estuaries with biggest drainage area are Antonina and Benito, although the highest drainage densities are found in Guaraquecaba. The sub-estuaries with highest proportions between wetlands and water body are, respectively, Nhundiaquara, Cachoeira and Medeiros. The smallest relative

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Table 1. Sections morphological and hydrological characteristics. (DA- drainage area; DD- drainage density; WLD- wetlands area; WBA- water body area; TFA- tidal flat area; RTFA- relative tidal flat area and MD- maximum depth).

<table>
<thead>
<tr>
<th>SECTION</th>
<th>DA (km(^2))</th>
<th>DD (rivers/km(^2))</th>
<th>WLD (km(^2))</th>
<th>WBA (km(^2))</th>
<th>TFA (km(^2))</th>
<th>RTFA (%)</th>
<th>MD (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antonina</td>
<td>1513.4</td>
<td>1.69</td>
<td>67.2</td>
<td>48.07</td>
<td>14.4</td>
<td>30.0</td>
<td>12.1</td>
</tr>
<tr>
<td>Paranagua</td>
<td>222.9</td>
<td>0.06</td>
<td>21.6</td>
<td>83.97</td>
<td>16.5</td>
<td>19.6</td>
<td>23.0</td>
</tr>
<tr>
<td>Laranjeiras</td>
<td>1462.1</td>
<td>2.06</td>
<td>99.7</td>
<td>159.65</td>
<td>57.4</td>
<td>36.0</td>
<td>11.2</td>
</tr>
<tr>
<td>Mixture</td>
<td>474.5</td>
<td>0.50</td>
<td>47.7</td>
<td>175.96</td>
<td>27.0</td>
<td>15.3</td>
<td>30.2</td>
</tr>
<tr>
<td>Pinheiros</td>
<td>272.6</td>
<td>1.56</td>
<td>50.4</td>
<td>36.48</td>
<td>20.7</td>
<td>36.7</td>
<td>17.5</td>
</tr>
</tbody>
</table>

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Figure 1. The Paranaú Estuarine Complex divided in sectors (1, 2, 3, 4 and 5) and sub-estuaries (6, 7, 8, 9, 10, 11 and 12). 1-Mixture; 2-Paranaguá; 3- Antonina; 4- Laranjeiras; 5- Pinheiros; 6- Cotinga; 7- Nhundiaquara; 8- Cachoeira; 9- Medeiros; 10- Itaqui; 11- Benito and 12- Guaraquecaba.
The tidal flat area is found in Cachoeira. The morphology of tide-dominated estuaries is characterized in plan view by a funnel-shaped geometry. The maximum width to length ratio (W/L) can give an idea of this geometry. This feature presents an inverse relationship with hydraulic gradient \( r = -0.85 \). Another relationship found with this ratio was with tidal flat area \( r = 0.84 \). Also, the hydraulic gradient have influence on the wetland \( r = -0.81 \) and tidal flat areas \( r = 0.65 \).

**DISCUSSIONS**

Although the Landsat image processing done with the objective of feature enhancement and boundaries determination presents subjective topics, it can be easily adapted for other places. Nevertheless, the study feature presents different spectral responses, which improve the quality of the results and, consequently, the delimitation of its boundaries. The wetlands areas are easily distinguished from the Atlantic forest area due to its high soil humidity; which provides greater visible and infrared radiation absorption. The spectral response of the tidal flat region is under the influence of the sea bottom, presenting a bigger reflectance in shallow waters than in deeper waters.

Earlier sectorization studies already have been applied in the PEC. However, these studies were concentrated on the axis E-W, not covering the estuarine complex as a whole. Among these studies, we can mention Knoppers et al. (1987) regarding the water stratification and physiographic characteristics; Netto and Lana (1997) regarding the hydrograph and the bottom sediments; and Lessa et al. (1998) related with the morphological and sedimentary characteristics.

The presented sectorization is defined not only by the physiographic features but also by the watershed. Among the comparable parameters of the previous sectorizations and the one presented here is the CEP water body. The previous estimative of the area was 612 km\(^2\) (Knoppers et al., 1987) and the new one is 551.8 km\(^2\). However, this difference due to distinct definition of the limit between the estuary and the ocean.

The sub-estuaries morphological characteristics are mainly

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**Table 2.** Sub-estuaries morphological and hydrological characteristics. \( DA \)- drainage area; \( DD \)- drainage density; \( HG \)- hydraulic gradient (elevation / river extension); \( W/L \) maximum width to length ratio; \( WLD \)- wetlands area; \( WBA \)- water body area; \( TFA \)- tidal flat area and \( RTFA \)- relative tidal flat area.

<table>
<thead>
<tr>
<th>SUBSTUARY</th>
<th>SECTION</th>
<th>DA ( \text{km}^2 )</th>
<th>DD ( \text{river/km}^2 )</th>
<th>HG</th>
<th>W/L</th>
<th>WLD ( \text{km}^2 )</th>
<th>WBA ( \text{km}^2 )</th>
<th>TFA ( \text{km}^2 )</th>
<th>RTFA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cachoeira</td>
<td>Antonina</td>
<td>926.7</td>
<td>1.06</td>
<td>0.03</td>
<td>0.21</td>
<td>27.0</td>
<td>7.06</td>
<td>0.6</td>
<td>8.5</td>
</tr>
<tr>
<td>Nhundiaquara</td>
<td>Antonina</td>
<td>694.4</td>
<td>1.83</td>
<td>0.04</td>
<td>0.18</td>
<td>14.2</td>
<td>3.35</td>
<td>0.8</td>
<td>23.9</td>
</tr>
<tr>
<td>Cotinga</td>
<td>Mixture</td>
<td>397.4</td>
<td>0.67</td>
<td>0.00</td>
<td>0.63</td>
<td>34.8</td>
<td>21.38</td>
<td>7.3</td>
<td>34.1</td>
</tr>
<tr>
<td>Medeiros</td>
<td>Laranjeiras</td>
<td>44.6</td>
<td>0.98</td>
<td>0.07</td>
<td>0.14</td>
<td>9.1</td>
<td>4.12</td>
<td>2.6</td>
<td>63.1</td>
</tr>
<tr>
<td>Itaqui</td>
<td>Laranjeiras</td>
<td>122.8</td>
<td>1.88</td>
<td>0.04</td>
<td>0.27</td>
<td>8.6</td>
<td>7.74</td>
<td>4.2</td>
<td>54.3</td>
</tr>
<tr>
<td>Benito</td>
<td>Laranjeiras</td>
<td>884.9</td>
<td>2.18</td>
<td>0.01</td>
<td>0.36</td>
<td>25.6</td>
<td>16.54</td>
<td>7.8</td>
<td>47.2</td>
</tr>
<tr>
<td>Guaíraqueçaba</td>
<td>Laranjeiras</td>
<td>300.1</td>
<td>2.42</td>
<td>0.01</td>
<td>0.51</td>
<td>18.0</td>
<td>16.74</td>
<td>9.4</td>
<td>56.2</td>
</tr>
</tbody>
</table>

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**Figure 2.** Details of Cotinga subestuary.

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dominated by tidal range and drainage area energy (hydraulic gradient). This can be observed by the occurrence of tidal sand (mud) ridges elongated parallel to bidirectional currents and by the smallest relationship width to length ratio on sub-estuaries with high hydraulic gradient. These sub-estuaries with high hydraulic gradient also have bigger tidal flat and wetlands areas.

A distinct morphologic pattern is observed on Cotinga sub-estuary. It does not present the funnel-shaped tide dominated estuary characteristic. This sub-estuary is composed by many meandering creeks with extensive wetlands areas. This occurs due to the large coastal plain where the main river flow and present almost null hydraulic gradient. Because the Cotinga sub-estuary is to close to the PEC outlet its tidal range is smaller than that of the sub-estuaries located at the inner part of PEC. This occurs for sub-estuaries located on E-W (Figure 3) axis as well as on S-N axis (Figure 4). This effect is due to shallow waters and, also, the narrowing estuaries which can increase the tidal range to circa 2.7 meters on spring tides, whereas on the outlet it reaches 1.5 m (MARONE et al., 1995).

The sectorization also allowed a synoptic view of the actual PEC knowledge level. There is a marked difference in the knowledge level among the different sectors and sub-estuaries. The sectors with more number of environmental information are Antonina, Paranaguá and Mixture, all located on E-W axis. In these sectors there are a good number of nutrients, salinity, water quality, river discharge, currents, bottom sediments and biota surveys. On the contrary, sectors Laranjeiras and Pinheiros are less studied. For some places of Laranjeiras sector there are information about salinity, currents, bottom sediments and biota. However, the Medeiros, Itaqui and Benito sub-estuaries have few numbers of studies. The Pinheiros bay is the sector with the smallest number of information with few surveys of salinity, chlorophyll-a and zooplankton.

The identification of this information gaps is important to know how consistent is the estuarine water zonation on the PEC, as well as the hydrodynamic models implementation. In this way, we can consider the lack of river discharge data the most critical point, since consistent rivers discharge data are only available for Cachoeira e Nhundiaquara sub-estuaries. There are other parameters that need surveys, such as: bathymetry, salinity and temperature time series, nutrients and currents.

Figure 3. Details of Nhundiaquara and Cachoeira sub-estuaries.

Figure 4. Details of Medeiros, Benito, Itaqui and Guaraqueçaba sub-estuaries.

With the actual level of information it is possible to run hydrodynamical models for the different hierarchical levels. Some of the future steps are to integrate in the GIS the dynamical variability of water constituents (salinity, temperature, total suspended particulate matter, chlorophyll a, etc.).

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LITERATURE CITED


