A GEOSTATISTICAL GIS MODEL TO IDENTIFY CADMIUM AND ZINC CONTAMINATION RISK AREAS IN SEDIMENTS OF SEPETIBA BAY, RIO DE JANEIRO - BRAZIL.

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ABSTRACT


This work presents two GIS models that evaluate Zinc and Cadmium contamination tendencies in the sediments of Sepetiba Bay, southern coast of Rio de Janeiro, Brazil. Both models were built upon geographical and environmental features. The natural surrounding areas (eg. mangroves and rivers) of industrial waste disposal usually present higher concentration of these metals. Where the predominant composition of the sediment is clay and/or silt, the metals also tend to be concentrated, since it easily adsorbs onto small particles. Additionally, The Port of Sepetiba's navigation channel needs constant dredging, which affects the bay's depth profile and moves the sediment from channel to other areas in the bay, moving together with it, the adsorbed metals. In order to assess the risk of contamination, models were developed using multi-criteria decision support based upon the analytical hierarchical process (AHP). In the first model (model one), proximity to adjacent areas of industrial waste disposal was considered the most significant condition to determine contamination risk, followed by the concentration of clay, silt and depth influence. In the other one (model two), sediment composition (clay and silt) was set as the most significant condition, followed by proximity to adjacent areas of industrial waste disposal and depth. Each model resulted in a fuzzy map (grid themes) that indicates where levels of risk contamination are higher. They were validated comparing the models to zinc and cadmium grid themes generated by geostatistical kriging over the metals samples. The cadmium contamination is better represented by the model one, indicating higher influence of the proximity to disposal areas. The model two represents very well the zinc distribution, appointing to the silt and clay higher concentration as the most risk areas.

ADITIONAL INDEX WORDS: Ecotoxicology; Spatial Analysis; Heavy metals.

INTRODUCTION

The Sepetiba bay is located in the southern coast of Rio de Janeiro, Brazil (Figure 1). Its 305 Km2 water body is influenced directly by the net of rivers and channels that drain the lower land of Sepetiba basin. This region, classified as area of metropolitan border (SEMA, 1996), is one of the most important industrial regions of the state. There is located the Port of Sepetiba, that according to Companhia Docas do Rio de Janeiro (2003), is the only port with natural physical capacity to become the greater of Latin America.

Since the 1960s, the growth of established industries in Sepetiba’s hinterlands expanded due to cheap land prices, its sheltered position from meteorological adversities closeness to water abstractions sources as well as for disposal of industrial waste (COSTA, 1992). This process unchained what today is one of the main environmental problems in the bay, i.e. contamination by heavy metals. These have been disposed in Sepetiba bay for over 25 years. Work by FEEMA (1980); SOUZA et al. (1986); LACERDA et al. (1987); FEEMA (1989); LACERDA and RESENDE (1996) and SEMA (1997) show metal presence in the sediment and biota, mainly zinc and cadmium, indicating levels of contamination higher than allowed in the current legislation.

According to SEMA (1997), these two metals can adsorb on clay or silt particles, which are led by sea currents and deposit in the seafloor. Moreover, the need to dredge the channel to maintain access to the port has contributed to removal of the sediment from
the channel bed to shallower areas of the bay, adjacent to the Restinga da Marambaia (Figure 2). This dynamic creates a distribution profile of these metals, where some areas tend to present greater contamination risk.

Recently the remote sensing (RS), geographic information systems (GIS) and global positioning systems (GPS) has been widely applied to acquire, store, process and manage large amounts of spatial and tabular data. This technology is also being used for coastal zone management (WRIGHT, 2001; WRIGHT and BARTLETT, 2000), aquaculture (ROSS et al., 1996; SCOTT et al., 2001; VIANNA et al., 2002), environmental (DOXARAN et al., 2002) and natural resource assessment (TSENG et al., 2001). All these authors agree that GIS is a very important and helpful tool for spatial analysis of marine and coastal data.

Thus, the objective of this study is to create and evaluate some GIS models, to identify areas with higher risk of contamination by zinc and cadmium, according to the proximity of the industrial waste disposal sources, nature of sediment and depth.

The elaboration of the risk models was divided in three stages (Figure 4): i) input and treatment of the primary data; ii) spatial analysis, and; iii) elaboration and validation of the model.

**Input and Treatment of the Primary Data: Conceptual Model.**

According to the characteristics of the input, dispersion and deposition of these metals in the bay, the following data were selected:

1. Industrial waste disposal point sources;
2. Predominant nature of sediments (clay, silt or sand);
3. Depth.

It is necessary to know where the industrial effluents inputs are located in the bay because in its adjacent areas the contamination risk is higher. Moreover, the trend of these metals to be adsorbed by small particles of sediment (clay and silt) contributes so that areas with higher concentrations of these materials also present higher contamination risk. Similarly, the dredging process moves great amounts of sediment for flatter/shallower areas of the bay (Figure 2). Therefore, contamination risk is higher with decreasing depth. Thus, conceptually, the areas of higher risk are those next to the industrial waste disposal points sources, with high concentrations of fine sediment and with low depth.

**Spatial Analysis**

The study area and the limits for generation of the grid themes in the GIS had been defined according to the limits of the metals and sediment data (SEMA 1997) and the limits of the bay. To the north and the east limited by the shoreline, to the south by Restinga da Marambaia and the west by the imaginary line of the points of data collection (Figure 3).

All grid themes were generated with spatial resolution of 30m and fuzzy representation. The clay, silt, zinc and cadmium bathymetry points were analyzed in the geostatistical analyst module of ArcGis 8.2 and interpolation by kriging.

Because the data have different units of measure- clay and silt (%), zinc and cadmium (µg/g), bathymetry and distance (m) - it was necessary to standardize the units in a qualitative classification system. For this, all the generated grids were normalized.

The histograms of the clay, silt, zinc and cadmium data presented irregular curves. To adjust this, Log10 was multiplied to all the data. The result was used to interpolate the data and generate the distribution grid themes of these elements. These were normalized to values between zero and one, with zero representing minimum concentration value of the element measured in field, and one the maximum (Table 1).
The bathymetric data were interpolated in real values and the grid theme generated, normalized for values between zero and one. The values next to zero indicate areas with higher depth (lower risk), and the next values to one, the areas flatter/shallowest (higher risk) (Table 1).

The distance grid theme of the industrial waste disposal points was generated from the Distance tool of the Spatial Analyst module. This also was normalized and the values next to zero represent the distant areas (lower risk) while those next to one indicates the areas next to the effluents (higher risk) (Table 1).

Six normalized grid themes (fuzzy maps) were generated (Figure 6): clay (A), silt (B), bathymetry (C), distance of the industrial waste disposal points (D), zinc (G) and cadmium (H).

### Model Development and Validation

Two contamination risk models were developed. The difference between them is in the weights attributed to the grid themes indicating its influence as risk factor. In the first model, proximity to adjacent areas of industrial waste disposal was considered the most significant condition to determine contamination risk, followed by the concentration of clay, silt and depth influence. In the second model, sediment composition (clay and silt) was set as the most significant condition, followed by proximity to adjacent areas of industrial waste disposal and depth.

In order to assess the risk of contamination, the models were developed using multi-criteria decision methodology based upon the analytical hierarchical process (AHP). The AHP module of SPRING GIS was used to compare the grids and extract a relative weight for each one (Figure 4).

In model one, proximity to adjacent areas of industrial waste disposal normalized grid was weighted by 0.4345, clay normalized grid by 0.2785, silt by 0.1755 and depth by 0.1115. In model two, the weights were 0.4345 for clay, 0.2785 for silt, 0.1755 to proximity for adjacent areas of industrial waste disposal and 0.1155 for depth.

The validation was made through a comparative analysis between the metals and models grid themes. This analysis

### Table 1: Minimum and maximum measured and normalized values used to classify risk areas.

<table>
<thead>
<tr>
<th>Theme</th>
<th>Measured</th>
<th>Normalized</th>
<th>Contamination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>30 µg/g</td>
<td>0</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>8,720 µg/g</td>
<td>1</td>
<td>Higher</td>
</tr>
<tr>
<td>Cádmio</td>
<td>1 µg/g</td>
<td>0</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>33 µg/g</td>
<td>1</td>
<td>Higher</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Theme</th>
<th>Measured</th>
<th>Normalized</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0 %</td>
<td>0</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>89 %</td>
<td>1</td>
<td>Higher</td>
</tr>
<tr>
<td>Silt</td>
<td>0 %</td>
<td>0</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>62 %</td>
<td>1</td>
<td>Higher</td>
</tr>
<tr>
<td>Depth</td>
<td>50 m</td>
<td>0</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>0 m</td>
<td>1</td>
<td>Higher</td>
</tr>
<tr>
<td>Effluent distance</td>
<td>22.161 m</td>
<td>0</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>0 m</td>
<td>1</td>
<td>Higher</td>
</tr>
</tbody>
</table>

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**Figure 4**: Risk model methodology

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consisted in the subtraction of the metals grid theme for the models grid theme. The results were four grid themes with values between -1 and 1: Model one for zinc; Model two for zinc; Model one for cadmium and Model two for cadmium (Figure 8).

In the validation grid themes, the values next to -1 indicate areas with low metal concentration and high risk of contamination pointed for the model. The values next to zero indicate consistency between the level of contamination and the risk. And the values next to 1 suggest areas with high metal concentrations and low risk (Table 2).

### RESULTS AND DISCUSSION

The sediment of Sepetiba bay is composed in its majority of clay and silt as can observed in the figures 6A and 6B. Clay is more concentrated in the central zone of the bay, where values were found next to 90%. Silt is distributed more homogeneously, with a maximum concentration of 62%. The presence of great amounts of these materials in the composition of the sediment is because the fluvial influence and the land use and occupation process of Sepetiba basin. The deforestation and launching of organic dejections without treatment in the rivers and channels have contributed over the past 25 years, for a speeding up of sedimentation process, mainly in the northeastern shore. The great amount of effluent contaminated with metals and the capacity of these to adsorb onto particles of clay or silt, contribute to higher contamination risk in those areas where clay or silt is more concentrated.

Another characteristic of the bay is low mean depth (5.8m). The center-east is flat and with little depth variation, while the deepest regions are located in the southwest and west, in areas next to the main navigation channel to the port and around some islands (Figure 6C). The dredging process to maintain the channel navigable removes the bottom sediments and deposits them in the flat shallow areas of the bay, next to Restinga da Marambaia (Figure 2). So the areas of lesser depth are those where the contamination risk is higher.

The areas next to industrial disposal point sources are located in the northern area of the bay (Figure 6D), mostly in and around the industrial zone (Figure 2). This proximity also increases contamination risk.

The sediment contamination level by zinc and cadmium is very high, between 30 and 8.720µg/g for zinc and 1 and 33µg/g for cadmium (Table 1). In this case, the areas max of low risk cannot be seen as free from contamination, but as areas with trend towards lower concentration of these metals.

According to model one, (Figure 6E) the areas with higher risk are located in the north, next to the industrial zone. The regions in South and southwest are those where the risk is lower. By analyzing the histogram one (Figure 5A) even with the distribution approaching to that of the normal curve, its average (0,68) and standard deviation (0,14) slightly dislocates the curve towards the right, indicating that there are more areas of medium risk than of low risk.

In a different way, model two presents average 0,77 and standard deviation 0,13 (Figure 5B), indicating that great part of the area presents medium to high risk of contamination. In the figure 6F the areas of higher risk extend for all the central portion of the bay, and some distant areas present high risk of contamination. The risk only diminishes in the regions where the depth is higher and the concentration of fine sediment is lower.

In both models there is an area in the Southeast of the bay where the risk was considered low (Figures 6E 6F). This is because the sediment samples in this point indicated the total nonexistence of clay or silt (Figures 6A 6B). There is an area of strong influence of sand dunes which exist in Restinga da Marambaia, where the sediment is sandy.

<table>
<thead>
<tr>
<th>Validation value</th>
<th>Zinc Class</th>
<th>Cadmio Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>Low zinc and high risk</td>
<td>Low cadmium and high risk</td>
</tr>
<tr>
<td>0</td>
<td>High zinc and high risk or Low zinc and low risk</td>
<td>High cadmium and high risk or Low cadmium and low risk</td>
</tr>
<tr>
<td>1</td>
<td>High zinc and low risk</td>
<td>High cadmium and low risk</td>
</tr>
</tbody>
</table>

The grid themes mean of zinc and cadmium were 0.85 and 0.50 and standard deviation 0.05 and 0.20, respectively. The higher zinc mean and its lower standard deviation indicate that the contamination for this metal is high in the entire bay (Figure 6G). On the other hand, the lower cadmium mean and higher standard deviation indicates a different contamination distribution, having areas with high concentrations and others not (Figure 6H). In this way, it is possible to distinguish the process of distribution of these metals in the sediment of the bay. Zinc is found in high concentrations all over the bay, while the higher cadmium concentrations are limited to areas close to the industrial point sources.

The results of the validation for the models indicated this difference in the metals distribution (Figure 8). The histograms of validation for zinc presented positive means, while for the means for cadmium were negative (Table 3). This is because the amount of existing zinc in the sediments is much superior to that of cadmium.

Table 3: Validation grids statistics data

<table>
<thead>
<tr>
<th></th>
<th>Model one</th>
<th>Model two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn</td>
<td>Min -0.03</td>
<td>Max 0.55</td>
</tr>
<tr>
<td>Cd</td>
<td>Min -0.50</td>
<td>Max 0.08</td>
</tr>
</tbody>
</table>

Figure 5: Histograms: (A) Model one; (B) Model two; (C) Zinc; (D) Cadmium.

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In relation to the distribution of cadmium, model one showed more consistent (Figures 7C and 8C), while model two better represented the risk of contamination for zinc (Figures 7B and 8B). The means next to zero indicate consistency between the amount of metal and the added risk of contamination and values of 0.07 for zinc and 0.17 for cadmium. The low standard deviation of model two for zinc (0.09) indicates that most of the values are next to the mean. It corroborates the importance of the relation of zinc distribution to the type of sediment. As for cadmium, the highest value found in model one (0.12) demonstrates that the biggest influence in the contamination risk is the proximity to industrial areas.

CONCLUSIONS

The Sepetiba bay currently presents a serious problem of contamination of zinc and cadmium. These metals concentrate in the sediment and arrive directly to bottom of the bay through the point sources of industrial discharge sites into the rivers and drainage canals.

Through the modeling of environmental and spatial data that influence directly in the process of distribution of these metals, it is possible to identify and to characterize areas for contamination risk. For this, GIS is well suited as an efficient and practical tool assisting with high accuracy the spatial analyses.

The models developed in the present study have shown efficiency in identification of the risk areas in the Sepetiba bay.

![Figure 6: Fuzzy maps: (A) Clay concentration; (B) Silt concentration; (C) Bathymetry; (D) Distance from disposal; (E) Model one; (F) Model two; (G) Zinc contamination; (H) Cadmium contamination.](image-url)
Model one, which considered the distance of waste disposal areas as the main risk factor, showed a better representation for the distribution of cadmium, and indicated a trend of this metal to concentrate in certain areas.

Model two, better represented the distribution of zinc, and pointed the areas with higher concentration of fine sediments as being those where the contamination risk is higher.

The metals distribution grid themes have demonstrated different behaviors, with zinc being found in great amounts in all the center-north region of the bay, and cadmium concentrating next to industrial areas.

To improve the quality of the model and understand why this difference exists between the distribution of zinc and cadmium, would be important:

(i) To increase the number of points, intensify the samples in the channel and waste disposal areas;

(ii) make a survey of the historical launching of these metals to know how long both comes being disposed in the bay, and;

(iii) make a chemical evaluation to know if the molecular and/or atomic characteristics of these metals influences in the distribution process.

Figure 7: Validation histograms: (A) Model one to zinc; (B) Model two to zinc; (C) Model one to cadmium; (D) Model two to cadmium.

Figure 8: Validation grid themes.
LITERATURE CITED


