INPE-5328-PRE/1726

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SÃO JOSÉ DOS CAMPOS
Junho de 1991

SECRETARIA DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

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Aceito para apresentação no 24th International Symposium on Remote Sensing of Environment, Rio de Janeiro, Brazil, 27-31 May 1991

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MODELING SUSPENDED SOLIDS CONCENTRATIONS BASED ON TM/LANDSAT-5 IMAGES AT GUANABARA BAY, RJ, BRAZIL*

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ABSTRACT

This paper presents a distribution of Total Suspended Solids (TSS) for the Bay obtained through the expansion of a stepwise regression resulting model from in situ and TM/Landsat-5 data. Water samples from 12 sites in the Bay were collected simultaneously with a TM overpass on Sept/09/86. TSS was related to nine different TM bands and band combinations through simple correlation analysis. Bands 4 (760-900nm) and 6 (10400-12500nm) had the highest and statistically significant correlation coefficients ($r=0.87$ and 0.74, respectively), and were selected for stepwise linear regression analysis. Determination coefficients (r^2), with 95% confidence level, were 0.69 for dependent variables bands 4 and 6 and 0.72 for band 4 alone. Therefore 72% of the TSS variability in the surface water of the Bay is explained by band 4. Based on this result a map of concentration levels for about 400 Km^2 of estuarine waters at the Bay region was digitally produced in an interactive multispectral image analyzer. The results show a potential application of orbital remote sensing to water quality monitoring and could provide environmental agencies with complementary continuous information for estuarine areas with few or missing water sampling points.

1.0 INTRODUCTION

The rapid growing of cities and populations in coastal regions usually brings considerable polluting sewage discharges to local water bodies. The organic pollution initially causes blooms of phytoplankton resulting in depletion of oxygen in the water. As a consequence, all life chain is adversely affected, eventually reducing the number and diversity of individuals in the original water communities. The accompanying excessive input of toxic substances brings immediate damage to the living forms

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*Presented at the 24th International Symposium on Remote Sensing of Environment, Rio de Janeiro, Brazil, 27-31 May 1991.

and ultimately also to man and his activities.

Many estuaries in Brazil have severe pollution problems and very often are the scenery for environmental disasters with losses of human lives and long-lasting effects to surrounding areas. Camaçari (BA), Cubatão (SP), Rio de Janeiro (RJ), Vitória (ES), for example, have large petrochemical, chemical, and mineral processing industrial complexes, whose effects in the water bodies were never properly understood. (IBGE, 1990). Environmental impact reports were seldom prepared and little concern for the actual impacts has been the common stand. Considering the large surface of these estuaries, their environmental monitoring is a complex and costly undertaking.

Guanabara Bay estuary, located at Rio de Janeiro State, Brazil, encompasses an area of about $400Km^2$ and receives the waters of 24 sub-basins. It receives domestic sewage of over seven million inhabitants with only about 25% of their volume treated prior to discharge. Over six thousand industries contribute with 25% of its organic pollution and also release toxic wastes with heavy metals, and various nutrients. Two large harbors with a traffic of some three thousand ships/year, fifteen oil terminals and two airports of intense activity also contribute to the release of pollutants and the general environmental decay of the Bay. (FEEMA,1984 and IBGE,1990).

Notwithstanding this massive discharge of pollutants in the Bay very little has been done in the past to control the effluents or even to assess the extent of contamination. Limited existing data shows that dissolved oxygen, organic nitrogen and phosphorous, and coliforms, have exceeded critical standards in up to 100% of the cases in many sampling points in the tributary rivers (FEEMA, 1984).

In such situation, where field data is scarce and the area to be studied is relatively large, orbital remote sensing should be considered as a potential source of information. For example, Klemas and Hardisky (1983), showed that remote sensing can provide synoptic multispectral views at relatively low costs and in short time. Saitoh et al. (1979), and Muralikrishna (1983) used the ratio of LANDSAT/MSS bands 4 and 5 to estimate total suspended solids (TSS) in coastal waters. Tassan (1981) used the difference between CZCS bands to detect and develop an algorithm to map TSS and chlorophyll concentrations. More recently high resolution LANDSAT/TM images were also used to detect coastal pollutants and Jensen et al. (1989) developed a model to estimate salinity and TSS concentrations.

For the Guanabara Bay, Braga (1988) examined water quality data simultaneously acquired with two TM overpasses and found a strong dependence on the tide conditions. Significant correlations for the twelve stations during the high tide (Sept/09/86) were: TSS and band 4, TSS and band 6, Secchi depth and band 4, Secchi depth and band 6, secchi depth and the ratio of bands 2 and 3, and temperature and band 6. During the low tide condition (Aug/11/87), correlations for the thirty-six stations were significant for: Iron contents on TSS with bands 2, 3, 4, 6, and with the ratios of bands 1/3 and 2/3, and with the second channel of a principal component analysis product.

The present work uses the above results of Braga (1988) for the image of 09 September 86 to model the distribution of total suspended solids in the Guanabara Bay and adjacent sea areas. The methodology is then suggested to regular assessment of TSS at the Bay and in other polluted estuaries of the country.

2.0 METHODOLOGY

Results of correlations between total suspended solids (TSS) and TM/LANDSAT data for the Guanabara Bay on 09 September 86 were used on a stepwise multiple regression analysis. The TM data consisted in the digital information from bands 1, 2, 3, 4 and 6, band ratios 1 to 3 and 2 to 3, and the first two channels of the principal component analysis of bands 1, 2, 3 and 4. The bands that correlated with TSS were used as independent variables in the stepwise regression, employing the "Statgraphics" statistical software for PC computers. The backward procedure was chosen with a confidence level of 95%. The software selected a final model for TSS with the independent variables that better explained TSS variability.

The final model was then applied to extend the TSS regression results to the whole Bay and adjacent areas. This was achieved using a geographical information system (GIS) coupled to a digital image analyzer (SITIM) developed at the National Institute for Space Research (ENGESPAÇO/INPE, 1990). The expansion of the model produced an image where the digital values represented TSS concentrations. Next, the image was classified based on a supervised separation of its histogram. The manual procedure was used instead of an automatic or equal range separation to account for noticeable features of the histogram that allowed a more clear distinction of classes. The GIS/SITIM then produced a map of TSS ranges

3.0 RESULTS AND DISCUSSION

Results of the correlations that were the basis for this work indicated that TM bands 4 and 6 (TM4 and TM6, respectively) correlated with TSS (Braga, 1988). These bands were thus used as independent variables in the stepwise regression and the first model fitting results are presented in Table 1 below.

Table 1. First Model Fitting Results

Variables in model	Coefficient	Standard error	R-squared (adjusted)
CTE	14.329	64.106	
TM4	1.878	0.700	0.69
TM6	-0.082	0.476	

Since the correlation between TM4 and TSS was higher than between TM6 and TSS, in another stage of the stepwise regression a test was done removing TM6 from the model (Table 2).

Table 2. Final Model Fitting Results

Variables in model	Coefficient	Standard error	R-squared (adjusted)
CTE	3.266	3.764	
TM4	1.773	0.326	0.72

With TM4 included as the only independent variable the results showed a slightly better fitting model with an adjusted coefficient of 0.72. Considering the small difference between this coefficient and that relative to the model with both TM4 and TM6, it was decided to use as few independent variables as possible, so that less variance would be introduced in the model. This last model for TSS was then implemented in the GIS, and TM4 digital values were converted into values of TSS concentration. Land features were initially screened from TM4 to avoid spurious classification by the model.

The supervised classification based on the histogram of the "TSS image" resulted in six classes corresponding to six ranges of TSS. Table 3 summarizes the results, including limits and cover areas of each class.

Table 3. TSS Image Classification Results

Class number	Lower limit (mg/l)	Upper limit (mg/l)	Area (Km^2)	Area (%)
1	04	09	12.82	2.03
2	10	26	489.46	77.31
3	27	32	67.07	10.60
4	33	37	39.48	6.23
5	38	43	20.98	3.30
6	44	(open)	3.34	0.53

The lower limit of the first class was set equal to 4mg/l because this was the minimum value found in the resulting image. The histogram could be easily partitioned since TSS levels were well separated in classes. The only spectral confusion occurred initially with the second, third and fourth classes out of a total of eight, and classified as three different classes. An overall exam of this first classification, however, clearly showed that classes three and four were actually stripping effects of class two. Such stripping is caused by defective TM signal acquisition and has been reported in the literature (Desachy et al., 1985) for example). Therefore, these three classes were unified resulting in a total of six classes - see Table 3.

Class 1, from 4 to 9mg/l, was found only in some places upstream the tributary rivers of the Bay, and therefore this class was not included in the thematic map presented in Figure 1. Class 2, from 10 to 26mg/l, predominated in the Central and Central-East areas of the Bay and also in the open sea, evidencing relatively clean sea water. From class 2 towards the internal margins in the Bay a gradient in TSS was observed, with concentrations reaching more than 44mg/l. Figure 1 also shows that the Western side of the Bay, which receives most of the urban and industrial effluents, is the most polluted, presenting larger areas identified as class 6. This result also agrees with field data obtained in the same area in other studies (FEEMA,1984).

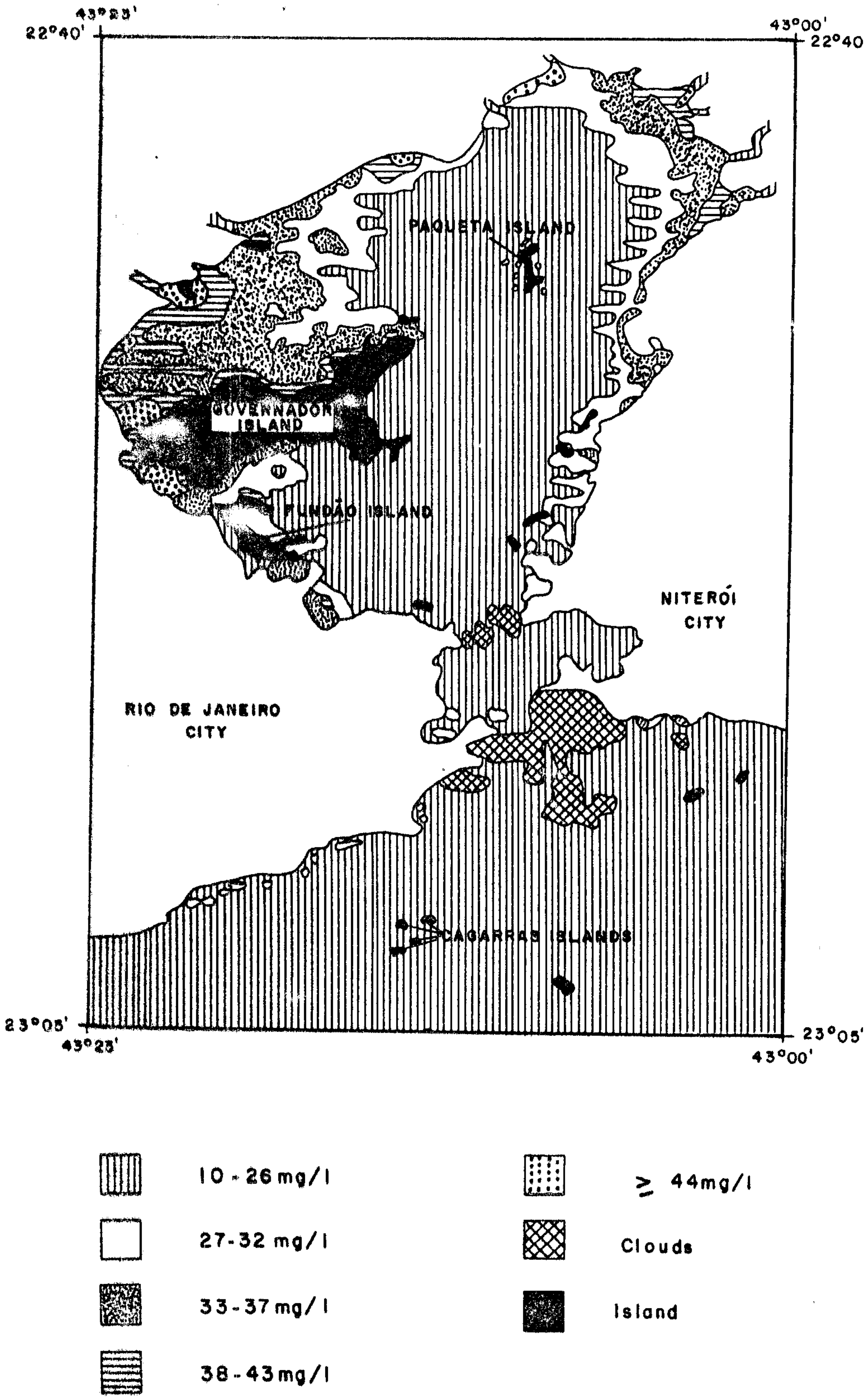

Figure 1. TSS Concentrations Thematic Map

In the North-East region concentrations of TSS were also high, probably resulting from sediments brought by the tributaries and originating mainly from agricultural activities. At adjacent beach areas outside the Bay some regions with class 3 are also noticed, and correspond to the existing outlets of domestic sewage from the cities. It is important to notice that no in-situ sampling took place at these regions, and their location was found solely by the model applied to the TM image.

The general distribution of TSS in Figure 1 also indicates that the inflow of sea water occurs more along the central channel of the Bay, and the polluted fresh water outflows underneath and closer to the margins, towards the open sea. Similar findings were reported elsewhere by Braga (1988). A small area in the South-West margin is shown erroneously as class 2, possibly because of its black color caused by the extreme load of mud and lack of circulation in that place. Being dark, this water tends to absorb all the incoming near-infrared radiation, resulting in the same response as that of clear waters.

4.0 CONCLUSIONS

Modeling of total suspended solids (TSS) using a TM/LANDSAT band 4 image calibrated with in-situ measurements was done for the Guanabara Bay, Rio de Janeiro, Brazil. The results produced useful information, indicating that this method can be used to extend local data to synoptic-scale areas. TSS model results for the Bay varied from 10mg/l in relatively clean sea water to above 44mg/l in areas with heavy discharges of urban and industrial effluents.

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6.0 ACKNOWLEDGMENTS

The authors thank Mr.Moacir Godoy Jr. from LTID/INPE for assisting the image processing and algorithm implementation, and also Mr. Joaquim Godoi Filho from DSM/INPE for the drawing.