REMOTE SENSING MONITORING OF ESTUARINE WATER FLUXES THROUGH A TIDAL INLET

Jarbas Bonetti Filho
Oceanographic Institute
University of São Paulo, Brazil
e-mail: bonetti@usp.br

Commission VII, Working Group 8

KEY WORDS: Coast, Landsat, Digital Image Processing, Water Quality Monitoring

ABSTRACT:

The practical application of Remote Sensing technologies in water quality monitoring has been increasingly attempted in the last few years. This paper presents an experiment on LANDSAT-5 digital image processing, applied to a time series, in estuarine water fluxes monitoring.
The chosen targets were the waters near Barra de Cananéia, a Brazilian tidal inlet located near to the Tropic of Capricorn. The main sources of dissolved and suspended materials are located at a 2.500 Km² coastal plain of the inner lagoonal-estuarine system. The associated vegetation is composed by mangroves and rain forests and are responsible for the input of dissolved organic matter (yellow substance) in the waters. Particulate suspended sediments in the column are essentially related to sandy terrace's erosion and to bottom sediment's resuspension.
Three LANDSAT-5 images were used in the study. They were co-registered and digitally processed in a computer system, following the steps: histogram's analysis; atmospheric correction; digital numbers surveying and densitometric transects; water/land separation; linear contrast enhancement; pseudo-color and color composition. Brightness temperatures were also obtained and quantified from TM-6.
The results clearly demonstrated time dependent variations in estuarine front's shape, dimension and spectral response. The April 1984 image indicated the predominance of inorganic suspended sediments in surface waters and the September 1986 image presented a large input of yellow substance from the lagoonal-estuarine system. A possible seasonal control is suggested to explain these variations.

1. INTRODUCTION

1.1 Motivation

Despite the increasing number of research works on estuarine water fluxes, the comprehension of suspended and dissolved matter transport in such systems is still weak. A good approach for its improvement is to focus the sampling areas near to tidal inlets, which seem to be the best places for the monitoring of inner waters' dispersion, since they represent the point of contact between oceanic and estuarine volumes. Nevertheless, the adversity for data collecting grows near these features, since navigation (and traditional data sampling by vessels) is often harmed by sea conditions.

The possibility to evaluate the enrichment of coastal waters and the paths of introduced waste disposals justifies the development of practical methodologies for estuarine fronts monitoring. Many authors have already demonstrated that the use of Remote Sensing in such investigations is highly satisfactory (Froidefond *et al.*, 1991; Nichol, 1993), since well-developed optical fronts are frequently associated to these areas.

The aim of the present work is to contribute to the comprehension of these fluxes. For this, a sequence of digital image processing steps were applied on a LANDSAT-5/TM time series. The test targets were the waters close to a Brazilian tidal inlet called Barra de Cananéia, the main mouth of a well-preserved lagoonal-estuarine system, located near to the Tropic of Capricorn.

1.2 Study Area

Cananéia-Iguape Lagoonal-Estuarine System is located at the southern coast of São Paulo State, being composed by several connected water bodies that were developed inside a 2.500 Km² Quaternary sandy coastal plain. It covers a 100 Km coastline and the inner waters are connected to the sea by three tidal inlets. Barra de Cananéia is the most important of them and exhibits the higher water exchange rates. A well-developed ebb tidal delta also occurs at this point, leading to great depth variations, with a maximum close to 22,0 m in its main circulation channel. The width of the inlet varies between 1.200 m and 1.500 m.

The input of fresh water is very limited, since no strong river reaches the system. Tides, which present a maximum amplitude of 1,20 m, are the main agents for estuarine circulation and for the mixture between chemical-physical properties. By the time of this experiment, a very small drainage basin, with an area of 1.339 Km^2, was responsible for most of the fresh water input. Tidal creeks also represent an important source for fresh water (collected basically from rain), and may present up to 8 Km of extension and maximum depths of 7,0 m.

These small water bodies were developed over Pleistocenic terraces, which are covered by tropical rain forests. Expressive mangroves have established in their margins, contributing for the high productivity of the area. The decomposition of leaves from these types of vegetation regularly promotes the "brownishment" of the water color, mainly after huge storm rains, which is related to the introduction of humic and fulvic acids in the system. These dissolved organic compounds are optically referred as "yellow substances".

The particulate inorganic sediments in the water column predominantly come from Pleistocenic sandy terrace's erosion and from bottom sediment's resuspension, since river input is inexpressive. The highest concentrations occur near to the bottom, associated to maximum current speeds, both on ebb and flood tides. Bottom currents always present threshold velocities high enough to erode and transport fine and very fine sands, which predominate in the bottom (Bonetti Filho *et al.*, 1995). The water transparency in the area is rarely higher than 2,0 m and total suspended solids present an average concentration between 30 mg/l and 40 mg/l.

2. METHODOLOGY

Although ideal conditions for water quality monitoring from orbital platforms occur when simultaneous *in situ* data are available, many authors agree that a previous knowledge of the study site's oceanography may lead to a good qualitative approach (Robinson, 1984).

During this experiment, the extensive cloud coverage of the area did not permit the acquisition of real time data, and demanded the use of previously acquired LANDSAT-5/TM images for the investigation. Despite this, oceanographic data were collected aboard research vessels during two field trips, on August 1993 and February 1994.

In these occasions a series of water quality parameters was collected, following transects along the estuarine front and in 25 hour anchor stations inside the system, to help in the interpretation of the front's oceanographic characteristics. Suspended sediment concentration (fractionated on its organic and inorganic compounds), currents (speed and direction), salinity, temperature and pH were sampled and gave a very good support to the interpretation of orbital data.

The time series was composed by three continued years of images, generated in the following dates: April 17, 1984; May 22, 1985; and September 14, 1986. Their WRS reference was 220.77. For the three images, meteorological and tidal information were analyzed in detail. LANDSAT-5 bands TM-1, TM-2 and TM-3 were used for the study of water surface compounds, band TM-4 for water/land separation and band TM-6 for brightness temperature determination.

The images were co-registered and processed in full resolution (pixels with 30 x 30 m for reflected bands and 120 x 120 m for thermal band) and the working scale, in the system's monitor, was 1:85.333. The Brazilian SITIM-340 image processing system was used for digital treatment, which was composed by a number of steps previously described by Bonetti Filho *et al.* (1994). Basically, they were:

a) Histogram's Analysis: conducted to characterize digital numbers distribution and to determine the values for atmospheric correction;

b) Atmospheric Correction: applied to minimize the atmospheric contribution to the scene, following the method of the darkest pixel subtraction (Chavez, 1975);

c) Digital Numbers Surveying and Densitometric Transects: determined by direct digital reading along the estuarine front, perpendicular to the coastline, to help in the quantification of the differences detected in the time series;

d) Water/Land Separation: applied from the generation of a mask, derived from water classification on TM-4, used to maximize the performance of the posterior contrast enhancement;

e) Linear Contrast Enhancement: the function was determined from histogram's analysis, individually for each TM band, in order to increase visual discrimination;

f) Pseudo-Color: generated by the equalization of each band into 14 classes (5 classes for TM-6, due to its lower spectral dynamics) and the latter application of a mnemonic color palette;

g) Color Composition: obtained from the use of the enhanced bands TM-3, TM-2 and TM-1 (RGB), without land information.

In order to quantify the brightness temperature gradients observed in the images, the algorithm developed by Bartolucci & Lozano-Garcia (1985, *apud* Baban, 1993) was applied:

$$T(k) = 260{,}454218 + 0{,}294398DN - 0{,}000249DN^2$$

Where: $T(K)$ = brightness temperature, in Kelvin; and DN = digital number. The highest and lowest digital numbers of each image were used in the determination of their thermal gradients.

3. RESULTS

The images of 1984 and 1985 were acquired by the satellite in low-tide, while the 1986 one represented the beginning of flood tide. Tidal heights and amplitudes presented very close characteristics in the periods. The weather also exhibited similar conditions for all images, with the dominance of a continental hot and dry air mass in the Brazilian southeastern coast. This situation validates images' comparison.

All images demonstrated the great influence of the inner waters into the adjacent coast. The estuarine fronts were clearly visible and presented a strong variability in shape, dimension and spectral response in the time series. The observed extensions of the front, perpendicular to the coastline, were 6,5 Km (1984), 4,8 Km (1985) and 7,7 Km (1986).

The enhanced image from April 1984 (Figure 1) presented a very strong signal in the visible bands for the region of the estuarine front (mainly on TM-3). The lowest digital numbers, in relation to de adjacent waters, were verified in the September 1986 image (Figure 2), which indicated a strong absorption in the area of the front for all visible bands, remarkably on TM-1. The image of May 1985 seemed to represent intermediary conditions between the two extremes, and was not reproduced in this paper.

The external boundaries of the inner fluxes were clearly identified in the visible bands, always associated to higher digital numbers. The best band to individualize the front's body was TM-3 in the image of 1984, and TM-1 in the image of 1986. Very consistent results were also presented by the densitometric transects, which clearly delineated the estuarine front. Digital numbers for TM-3 were sensibly higher in 1984 image.

4. DISCUSSION

A satellite image from the ocean, in the visible bands, has its characteristics determined by the properties of the light interaction with water and with it's suspended and dissolved constituents.

The best spectral interval for the measurement of suspended sediments is located between 0.55 μm and 0,65 μm (Johnson & Munday Jr., 1983). This roughly corresponds to bands TM-2 and TM-3. The presence of high digital numbers on these bands strongly indicates an effective suspended solid's concentration at surface, as it was verified on 1984 image.

Yellow substances are well known for promoting an intense change in the color of coastal waters. The introduction of these organic acids increases the absorption coefficient of the water, specially in the lowest wavelengths (Witte *et al.*, 1982). Consequently, a high absorption (low digital numbers) on TM-1 may be interpreted as an indicator of dissolved organic matter, as it can be seen on the image of 1986.

Therefore, the strong differences detected in the time series seem to indicate a variability in the composition of the water flux through the tidal inlet, with an alternation in the predominance of suspended inorganic particulate or dissolved organic compounds.

These differences are possibly related to seasonal controlling, since in winter the pluviometric totals are very weak in the region and suspended solids' exportation decreases. The 1986 image, besides the absence of inorganics and the strong presence of yellow substance, also suggests a consequent higher exportation of organic matter to the adjacent coast. Another possibility of interpretation is to consider the existence of similar yellow substance concentrations in both images, which could be masked by the huge presence of inorganic matter in the image of 1984. Digital numbers' readings on TM-1 corroborate with this idea.

Local resuspension of bottom sediments was also verified in all dates, mainly on band TM-3, and confirmed by field investigations. A strong signal was always associated to the position of a submerged sedimentary terminal lobe, which is part of the ebb tidal delta, indicating a secondary source of inorganic material.

Offshore to the inlet, satellite data and *in situ* current measurements confirmed the influence of longshore currents in the redistribution of inner waters. Suspended sediment patterns suggest that the estuarine flux acts as a hydraulic jetty and induces a northeastward transport .

The highest brightness temperature gradient in the scene was obtained for the image of 1986 (with a variation from 20,8 °C to 24,0 °C). This was the only image that also presented, in the enhanced and pseudo-color images, a well-defined lens of warmer water in the position of the estuarine front. The lowest gradient was verified for the image of 1984 (20,6 °C - 22,7 °C), which showed no visual discrimination.

The wider thermal amplitude detected in 1986 is possibly a consequence of the higher heat capacity of the dark water, rich in yellow substance. The comparison between the obtained values with simultaneous *in situ* water temperature measurements (routinely recorded by a station of the Oceanographic Institute-USP) presented a very good correlation. Similar results were obtained by Nichol (1993), and validate the use of band TM-6 as a secondary indicator of organic dissolved matter in estuarine fluxes.

5. CONCLUSIONS

Although cloud coverage is a widely know limitation for optical remote sensing in many coastal areas, this study demonstrated that satellite time series can effectively be used in the evaluation of estuarine surface fluxes and matter exportation through tidal inlets, even without simultaneous field missions.

The importance in determining the main characteristics of these fluxes is multiplied in tropical and sub-tropical areas located in the western boundaries of the oceans, since the main source of nutrients that reach these coasts are related to the continental drainage.

The characterization of estuarine influence in the adjacent coastal waters, obtained from TM time series, may also be applied in the monitoring of eventual environmental impacts in the region. The presented methodology also demonstrated a potential application for planning later field investigations.

A previous knowledge of the oceanographic characteristics of the area is essential in this kind of work, and permitted the secure interpretation of the images. The synoptic vision offered by the satellite can lead to the identification of some geometrical aspects of the estuarine front that would be impossible to be obtained by traditional oceanographic sampling.

From the integration of oceanographic and orbital information it was clear that the inner waters of Cananéia-Iguape Lagoonal-Estuarine system influenced the coastal area by the exportation of suspended sediments and dissolved organic matter, although local resuspension also occurs. The preferential northeastern redistribution of waters was also demonstrated. Further studies may confirm if there is a real seasonal control in the determination of the nature of transported material.

6. ACKNOWLEDGEMENTS

The author sincerely thanks Prof. Dr. Valdenir Veronese Furtado and Prof. Dr. Teodoro Isnard Ribeiro de Almeida, from the University of São Paulo, for their genuine incentive and support to this research.

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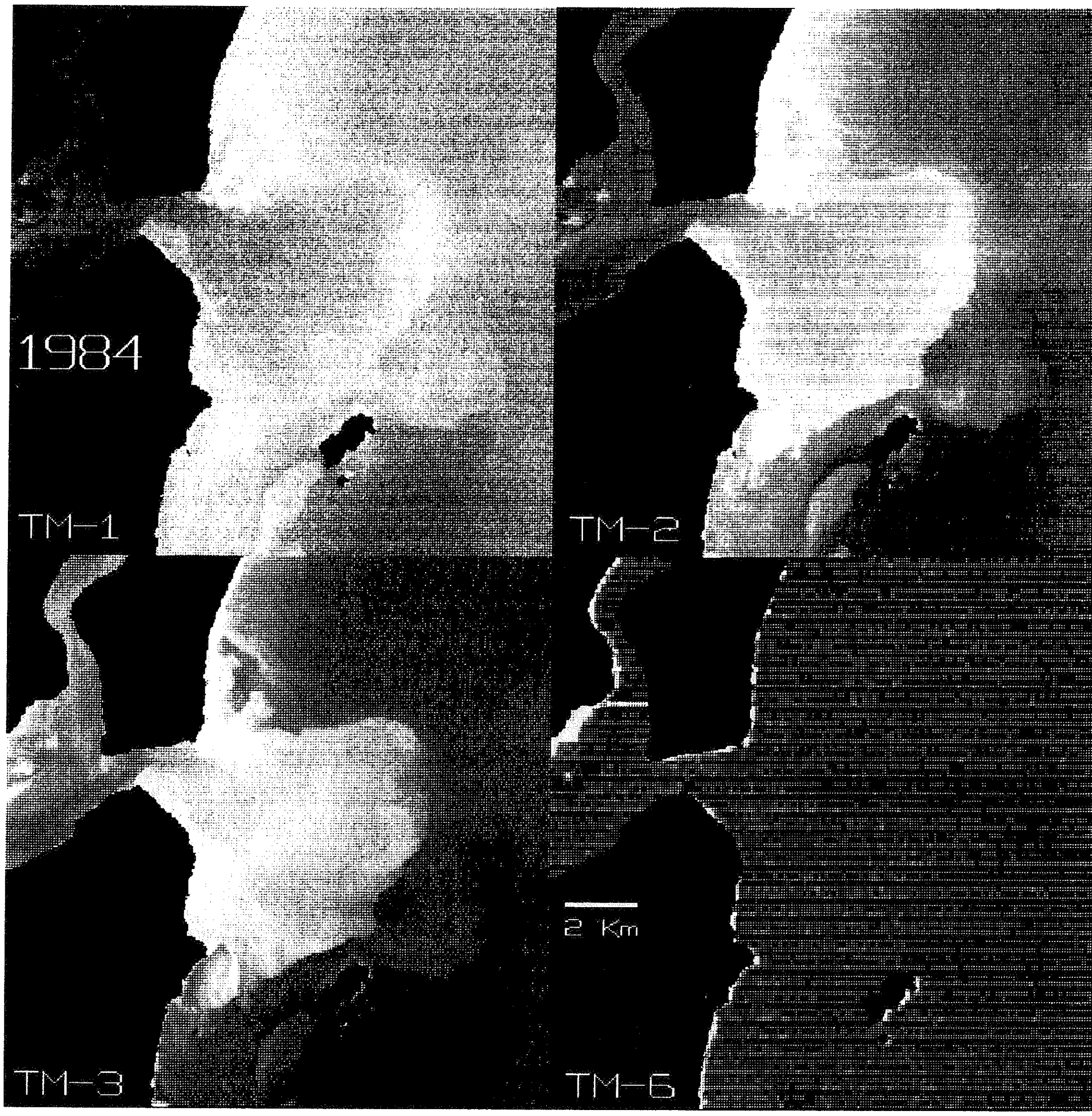

Figure 1 - Enhanced LANDSAT-5 bands TM-1, TM-2, TM-3 and TM-6. Image acquired on April 17, 1984.

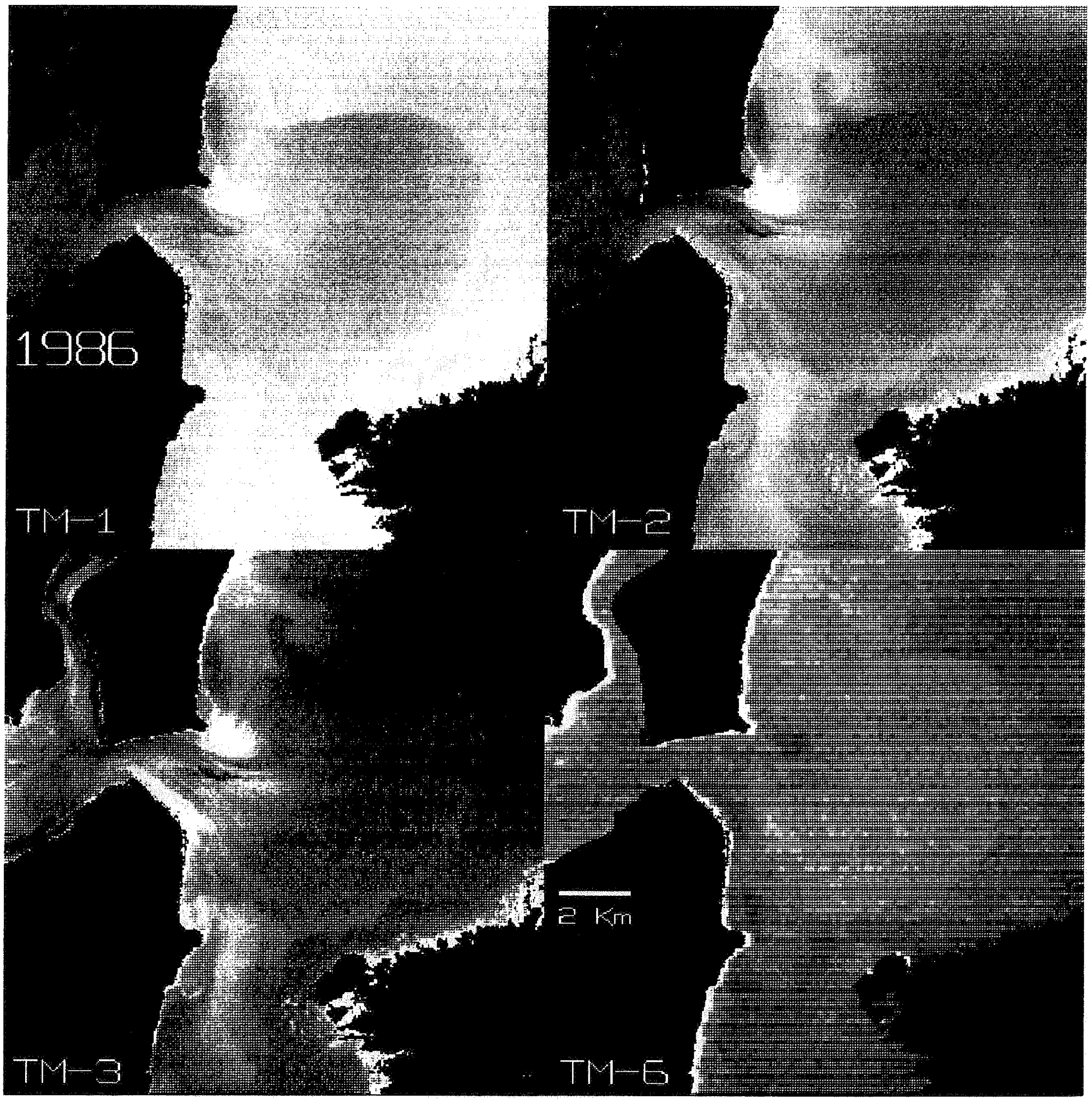

Figure 2 - Enhanced LANDSAT-5 bands TM-1, TM-2, TM-3 and TM-6. Image acquired on September 14, 1986.