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Water Quality Assessment with Simultaneous Landsat-5 TM Data at Guanabara Bay, Rio de Janeiro, Brazil

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This study aims at determining relationships between water quality parameters and digital data from the Landsat-5 Thematic Mapper (TM). The study area was the Guanabara Bay, in Rio de Janeiro, Brazil. Water samples were collected on two dates, coincident with Landsat passages, and when different tide conditions were present at the Bay. TM Bands 1, 2, 3, 4, and 6, band ratios 1/3 and 2/3, and principal component analysis of TM Bands 1-4 were compared with in situ *measurements and laboratory analysis of water samples. Some water quality parameters were very well correlated with the digital remotely sensed data, especially during high tide: for instance, iron and manganese concentrations in total suspended solids; salinity and Secchi depth; temperature and Secchi depth; temperature and total suspended solids; total suspended solids and Bands 4 and 6; Secchi depth and Bands 4 and 6; temperature and Band 6. Lower correlation coefficients, although also significant, were found for the low tide condition. No correlation was found with chlorophyll-a concentrations. TM data were shown to be adequate to analyze temperature, Secchi depth, total suspended solids, and iron and manganese contents in the total suspended solids for the polluted estuary area studied.*

INTRODUCTION

Guanabara Bay, Rio de Janeiro, Brazil (Fig. 1), is a heavily polluted estuary. It has a surface area of about 400 km^2 and contains two large harbors (Rio de Janeiro and Niterói) of intense traffic with nearly 3000 ships per year and 15 oil terminals. It receives polluted effluents from 24 subbasins with about 6000 industries and 7,000,000 inhabitants. About 75% of the organic wastes originate from urban sewage and 25% from industries. Heavy metals and toxic compounds also abound in the effluents (Lacerda, 1983; FEEMA, 1984).

The quality of the water in the Bay is poorly understood. Due to its large spatial and temporal variability, caused by the circulation patterns and differences between the waters of each subbasin,

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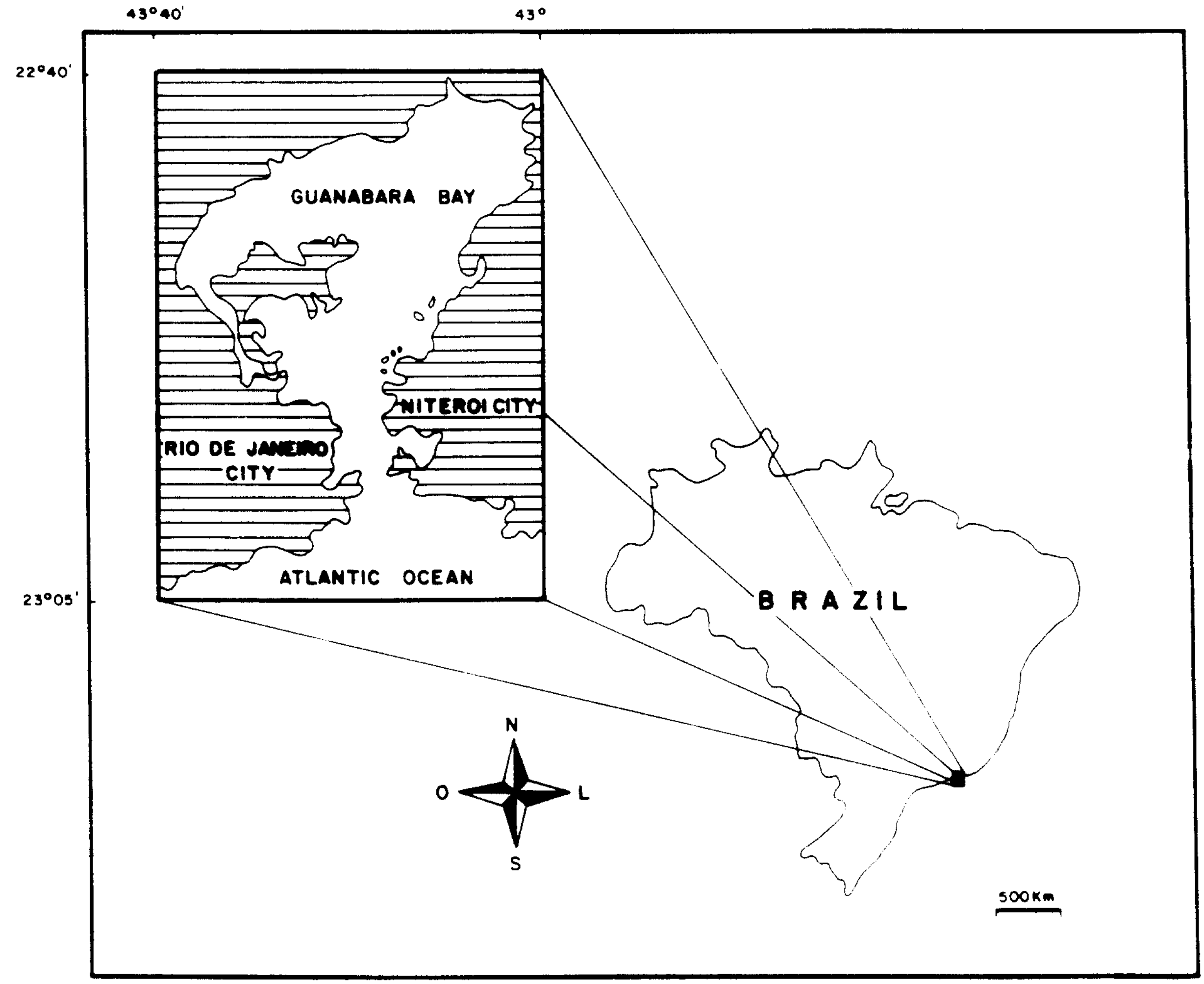

Figure 1. Study area.

a great number of sampling points is necessary for adequate monitoring. However, this monitoring has not been always possible, and for some years there are no data. Existing data indicate critical levels of pollution. Several water quality parameters measured in the tributary rivers, like dissolved oxygen, organic nitrogen, phosphorous, and coliforms, have exceeded standards of critical levels for up to 100% of the cases in many sampling points (FEEMA, 1984).

Such a situation, therefore, presents a potential for orbital remote sensing, which, as a complementary tool, can provide synoptic multispectral analysis at relatively low costs and in short time (Klemas and Hardisky, 1983). Since the launching of MSS / Landsat and CZCS / NIMBUS in the '70s, many empirical studies have related water quality parameters and remote sensing data. For example, Klemas et al. (1974) related spectral responses of MSS Band 5 with total suspended solids (TSS) and water circulation patterns. Saitoh et al. (1979) and Muralikrishna (1983) also used the ratio of MSS Bands 4 and 5 to estimate total suspended solids. Tassan (1981), working with CZCS, used the difference between radiance in the 590 nm and 680 nm bands to determine sediment concentrations, and the difference between the 520 nm and 550 nm bands to determine total chlorophyll concentration.

The remote sensing literature also shows a strong disparity between tests to identify the most appropriate bands or combinations of bands to study the same water quality parameters for different places, and at the same places with different satellite overpasses (Braga, 1990). This suggests the need for more field data acquired simultaneously with satellite imagery to assess the actual potential of orbital remote sensing in water quality studies.

In this work, the objective was to identify physical, chemical, and biological water quality parameters that could be detected in remotely sensed Landsat-5 TM digital images for a polluted tropical estuary, to assess its water quality conditions.

MATERIALS AND METHODS

Water samples were obtained for up to 37 stations (Fig. 2) on six dates coinciding with Landsat-5 TM overpasses. Landsat-5 has a sun-synchronous equatorial crossing around 09:45 a.m. local time. Due to cloud cover and satellite recording problems, only two dates were selected for analysis, viz., 9 September 1986 and 11 August 1987. Henceforth these dates will be referred as 9 Sep. and 11 Aug., respectively. On the first date, 12 stations were sampled inside the Bay, and for the second date, 21 stations were sampled inside the Bay and 15 outside. The Landsat Thematic Mapper (TM) digital images were recorded with full 30 m spatial resolution by the Brazilian Space Research Institute for path 217 / row 76, quadrant north, centered on about 23°50′ lat. S and 43°10′ long. W. The region covered corresponds to that of the Guanabara Bay area, Rio de Janeiro State, Brazil (Fig. 1), and the bands recorded were 1 (450–520 nm), 2 (520–600 nm), 3 (630–690 nm), 4 (760–900 nm), 5 (1550–1750 nm), and 6 (10,450–12,500 nm, 120 m resolution). No clouds were detected over the areas where field data were obtained simultaneously with the TM overpasses, except for three of the sampling points on the 9 Sep. image.

The TM images were processed in sectors of 512 × 512 pixels in a GE Image-100 multispectral digital analyzer (GE, 1975). Programs used were RATIO to calculate band ratios, and PRINCO (principal component analysis) to improve separability between water spectral classes. Also used in all images were FILTRATION (MD5FIL) to reduce noise, and CONTRAST STRETCHING to enhance image display of the filtered raw images and of the rationed and PRINCO images. The digital processing algorithms are described in INPE (1985). The following products were used in the analysis: TM Bands 1 (TM1), 2 (TM2), 3 (TM3), 4 (TM4), 5 (TM5), and 6 (TM6); ratios of Band 1 / Band 3 (TM1 / 3) and Band 2 / Band 3 (TM2 / 3); resulting Bands 1 (PC1) and 2 (PC2) from PRINCO applied to raw Bands TM1, TM2, TM3, and TM4.

To minimize geographical lack of precision in the location of the sampling points in the images and to obtain a more homogeneous representation of the region, the average of 16 pixels in a square window (120 m × 120 m) centered over the most probable location of the sampling points was used. Since Band 6 has a spatial resolution of 120 m, this procedure was not adopted for this band; instead, the nearest pixel to the sampling site or the average of two nearest neighbor pixels was used. The sampling points were located on a 1:50,000 Brazilian Navy nautical chart, guided by the geometry of visual landmarks observed during sampling collection. The same technique was also used in the digital images by drawing two straight crossing lines between reference points, with the sampling points located at the intersection of the lines.

Water samples were obtained sequentially at depths up to 50 cm using a motor boat during about 5 h of sampling. The following two parameters were measured *in situ*: 1) surface temperature (T) in a shadowed place using a mercury thermometer with 0.1°C divisions, and 2) Secchi depth (SC) with a 20 cm diameter Secchi disk. For laboratory analysis, samples were collected at each site in 0.5-L plastic bottles, which were previously cleaned with diluted nitric acid and deionized water. Immediately before filling the bottles, they were washed with local water in the sampling point (SP). Two bottles were filled at each site, and all samples were taken for laboratory analysis within a few hours after collection. At the laboratory, salinity (SA) was measured with a Shibuia 5.1 Model light refractometer, accurate to 0.5%. Next, the pairs of bottles were stored in a freezer for replicate analysis of total suspended solids (TSS) and iron and manganese contents in the TSS (Fe and Mn, respectively). TSS was separated using a 0.45 μm Millipore filter weighed before and after filtration and following 4 h of drying in an oven at 70°C (Lacerda, 1983). For Fe and Mn analysis, the replicated filters were digested with 5 mL concentrated nitric acid (HNO_3) in Teflon "bombs" at 100°C for 2 h. The extracts were filtered through 0.45 μm Millipore filters. Fe and Mn concentrations were analyzed in a Baird 3400 atomic absorption spectrophotometer, accurate to 0.1 μg / g. Details of the standard techniques used in this study are in Pestana (1989).

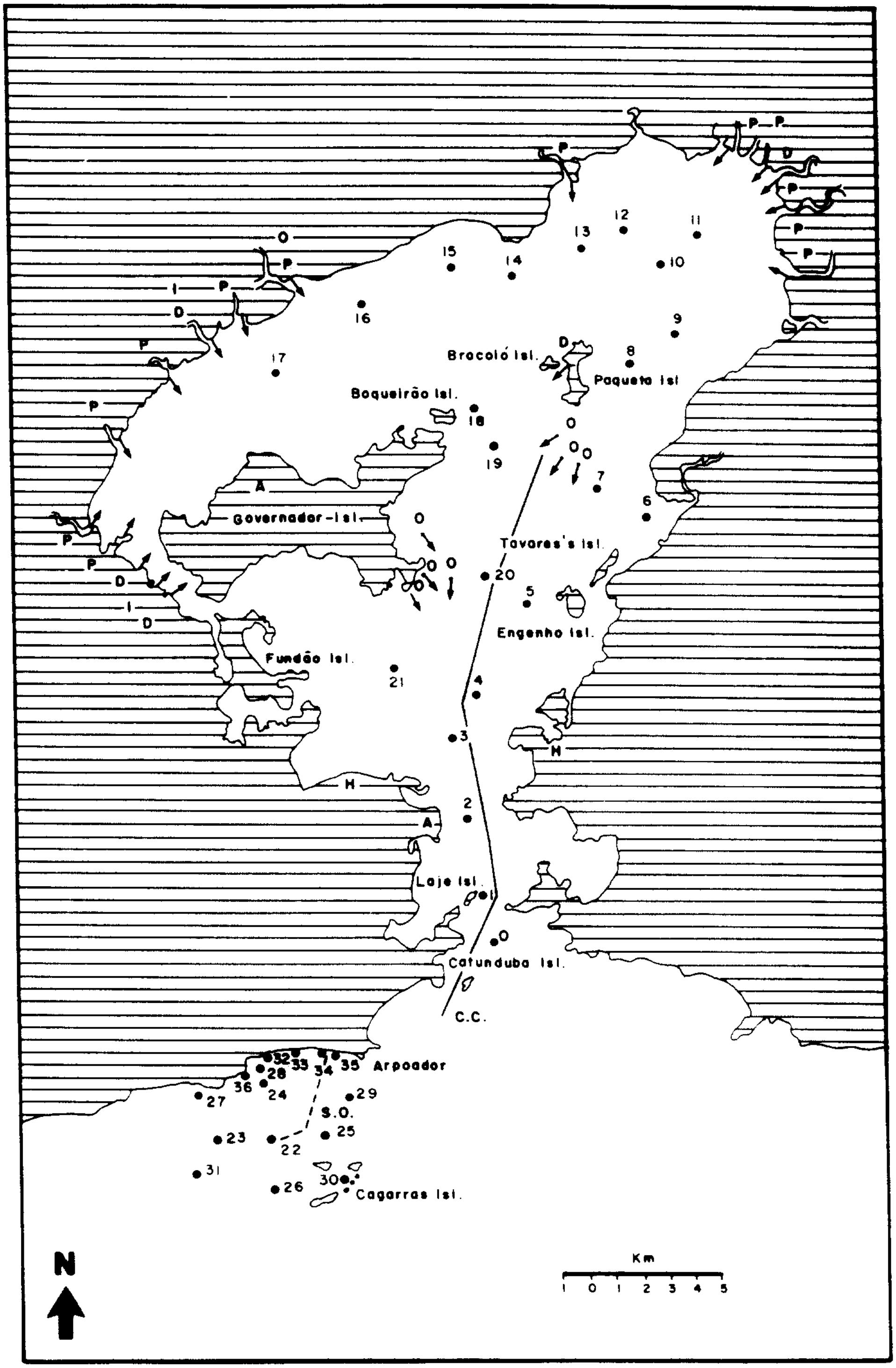

Figure 2. Sampling stations: (P) polluted river; (D) domestic sewage; (I) industrial sewage; (O) oil pollution; (H) harbor; (A) airport; (C.C.) central channel; (S.O.) Ipanema sewage outlet.

The chlorophyll concentration (CH) analysis was made only for 11 Aug. when two additional bottles were collected at each site for this purpose. Analysis was started as soon as the samples arrived at the laboratory, following the procedure of Strickland and Parsons (1972).

The statistical analysis of the water quality parameters and the digital image data (regression analysis, correlation) were performed using BASIS (Burroughs, 1976). The confidence level considered was 95%, and, therefore, according to Bowker and Lieberman (1959), the minimum of

Table 1. Water Sampling Data Obtained on 9 September 1986[a]

SP	*SC* (*m*)	*T* (°*C*)	*SA* (‰)	*Fe* ($mg\ g^{-1}$)	*Mn* ($mg\ g^{-1}$)	*TSS* ($mg\ L^{-1}$)
03	2.50	23.5	32.0	6.57	0.52	18.10
04	2.30	23.6	32.0	7.40	0.67	17.50
05	1.50	23.7	29.0	17.87	1.40	9.80
07	1.60	23.8	28.0	5.82	1.06	16.60
08	1.50	24.8	27.3	6.50	0.65	20.20
11	0.80	26.6	17.5	10.82	1.28	19.50
15	0.60	28.2	27.5	3.35	0.32	38.10
16	0.80	26.6	25.5	11.16	0.98	26.10
17	0.75	26.3	25.0	11.47	0.82	42.60
19	2.00	24.3	27.5	5.77	0.82	21.00
20	2.20	24.1	29.5	4.29	0.48	20.10
21	2.00	24.3	30.5	4.88	0.50	17.40
MIN	0.60	23.5	17.5	3.35	0.32	9.80
MAX	2.50	28.2	32.0	17.87	1.40	42.60
AVG	1.55	24.98	27.61	7.99	0.79	22.25
STD	0.67	1.54	3.89	4.12	0.34	9.29
N	12	12	12	12	12	12

[a] SP = sampling point; SC = Secchi depth; *T* = temperature; SA = salinity; Fe = iron concentration in the TSS; Mn = manganese concentration in the TSS; TSS = total suspended solids.

the correlation coefficients (*r*) for the number of observations available (*n*) is: 0.58 for $n = 12$; 0.55 for $n = 13$; 0.39 for $n = 26$; 0.38 for $n = 27$; and 0.32 for $n = 36$ and $n = 37$.

Whenever the correlation coefficient (*r*) between any of the water quality parameters and SC was smaller than the minimum statistically significant, but greater than 0.3, another parameter corresponding to its rationing in relation to SC was also used in the statistical analysis. This procedure is valid since the Secchi disk measurements are related to the depth of penetration of the light in the water, and assets an indirect evaluation of turbidity. The degree of turbidity in the water interferes with light penetration and determines different layers of water imaged at each sampling point. The rationing procedure normalizes the measurements, making them relative to equal depths in the water.

RESULTS AND DISCUSSION

Water Samples

The water quality data and some descriptive statistics for the images acquired on 11 Aug. and 9 Sep. are presented in Tables 1 and 2, respectively, for all sampling points.

Temperatures were in the low 20s (°C) for most samples, as expected for this latitude and time of year. Higher values (up to 28°C) were found in the shallowest region of the Bay, characterized by poor tide circulation.

Secchi depths, on both dates, were in the range found for eutrophic estuarine waters, varying according to tide height and proximity to outlets of domestic and industrial sewage and to drainage channels.

Salinity had values in the 15–33‰ range on both dates. Within the vicinity of the sewage line outlet, the salinity was 20–30‰ for 11 Aug. and about 35‰ on 10 September 1986. The 10 September 1986 date of sampling only at the sewage outlet did not coincide with the 9 Sep. image because of logistic problems. However, tide conditions (Table 3) were similar for these two days, and no variations in the flow pattern were observed. The salinity values are within results expected in estuarine regions (Durum, 1971).

Total suspended solids (TSS) concentrations also showed a strong relation to the proximity of fresh water discharges in the Bay. The minimum, of about 9 mg/L, occurred at SP 5, which is located in the middle of the central channel and further away from dumping sites than the other points. The maximum, about 40 mg/L, was measured at SP 17, located in the shallowest region of the Bay and near an area of effluent discharge.

Usual concentrations of the metals studied in sea water are about 2×10^{-7} mg/g for manganese, and about 2×10^{-6} mg/g for iron (Henderson, 1982); for soils these values are about 0.76 mg/g

Table 2. Water Sampling Data Obtained on 11 August 1987

SP	SC (m)	T (°C)	SA (‰)	Fe (mg g⁻¹)	Mn (mg g⁻¹)	TSS (mg L⁻¹)	CH[a] (mg L⁻¹ × 10⁻³)
00	4.20	22.2	32.5	8.23	0.48	11.2	6.58
01	3.50	22.2	32.5	4.30	0.48	14.7	8.13
02	3.20	22.5	25.0	7.72	0.82	10.2	12.00
03	2.60	22.3	31.0	17.71	2.29	11.3	13.34
04	2.30	22.3	25.0	5.76	0.89	9.0	14.99
05	1.45	22.6	33.0	4.17	0.83	14.2	27.18
06	0.50	23.0	30.0	10.99	1.10	18.7	39.09
07	1.45	23.0	23.0	5.05	1.53	10.3	23.44
08	1.30	23.2	22.5	7.86	2.53	15.6	
09	0.55	24.2	23.0	7.27	1.27	17.7	44.26
10	0.35	23.5	15.0	13.30	1.44	28.7	
11	0.50	24.6	19.0	14.27	1.45	19.6	31.76
12	1.00	25.1	17.5	6.30	1.44	14.0	
13	0.90	24.8	28.0	4.39	1.92	13.1	9.91
14	1.10	25.2	30.0	9.69	0.83	16.8	
15	1.05	24.9	25.0	2.57	0.51	19.4	
16	0.25	24.8	24.0	2.56	0.65	31.7	90.00
17	0.30	25.0	30.0	8.27	0.72	37.0	
18	2.65	23.5	25.0	1.87	0.45	10.9	
19	2.50	23.1	29.0	4.57	1.05	10.7	
20	1.45	23.7	25.0	8.27	0.81	18.1	
21	3.20	22.7					15.85
22		22.0	26.0	2.97	0.13	17.7	
23		22.0	26.0	1.10	0.07	5.3	
24		22.0	26.0	0.58	0.10	7.7	
25		22.0	20.0	1.63	0.05	13.9	
26		22.0	21.0	0.89	0.06	13.5	
27	6.00	21.5	32.5	4.73	0.06	11.7	
28	4.00	21.5	20.0	1.64	0.07	5.9	
29	5.00	21.5	30.0	1.49	0.04	14.0	
30	6.00	22.0	18.0	0.55	0.08	17.2	
31	7.00	22.0	22.5	0.67	0.03	8.1	
32		21.5	20.0	2.03	0.06	11.8	
33		21.5	27.5	0.47	0.04	13.3	
34		21.5	22.5	1.39	0.06	9.7	
35		21.5	22.5	3.31	0.40	5.7	
36		21.5	20.0	5.17	0.16	10.0	
MIN	0.25	21.5	15.0	0.47	0.03	9.0	6.58
MAX	7.00	25.2	33.0	17.71	2.53	37.0	90.00
AVG	2.38	22.8	25.0	5.10	0.69	19.2	25.89
STD	1.94	1.24	4.76	4.23	0.68	7.22	22.69
N	27	37	36	36	36	36	13

[a] CH = Total chlorophyll concentration; for other abbreviations, see footnote to Table 4.

and 32.0 mg/g, respectively (Ure and Benow, 1982, cited by Salomons et al., 1988). In the Rhine river subrecent sediments, manganese, and iron concentrations were about 0.96 mg/g and 32.3 mg/g, respectively (Forstner and Muller, 1974, cited by Salomons et al., 1988). The ranges found for Guanabara Bay, 0.3–1.4 mg/g TSS on 9 Sep. and 0.03–2.5 mg/g TSS on 11 Aug. for manganese and 3.4–17.9 mg/g TSS on 9 Sep. and 1.9–17.7 mg/g TSS on 11 Aug. for iron, are closer to typical concentrations in soils. This suggests a major contribution from drainage systems in the region carrying eroded soils and rocks. Accordingly, Tables 1 and 2 and Figure 2 show that higher manganese and iron levels were found along the central waters of the Bay channel (SP 5, SP 11, SP 15, and SP 17), where the outflow of drainage water takes place. The range of concentrations for Fe and Mn was higher on 11 Aug.

Chlorophyll data for 11 Aug. (refer to Table 2) varied from 6.5×10^{-3} mg/L to 44×10^{-3} mg/L. At SP 16, where an algae bloom was visually

Table 3. Tide Variations at Rio de Janeiro, Brazil

Date	Time (LST)	Height (m)	Date	Time (LST)	Height (m)
08 / Sep. / 86	05:14	1.2	10 / Aug. / 87	03:00	1.3
	12:41	0.6		09:56	0.0
	17:16	1.0		15.46	1.2
	21:46	0.5		21:50	0.4
09 / Sep. / 86	06:05	1.1	11 / Aug. / 87	03:32	1.3
	10:21	0.8		10:25	0.0
	14:19	0.7		16:09	1.2
	17:51	0.9		22:05	0.4
	22:02	0.6			
			12 / Aug. / 87	04:02	1.3
10 / Sep. / 86	00:07	0.7		10:52	0.2
	02:33	0.6		16:29	1.1
	07:16	1.0		22:18	0.4
	12:01	0.9			
	22:14	0.7			

observed, chlorophyll concentration reached 90×10^{-3} mg/L. On two other dates in the same year (Braga, 1988), chlorophyll also showed wide variations, making it difficult to characterize this eutrophic environment. Similar results in estuarine waters were also reported elsewhere in the world (Ketchum, 1967) in association with nutrient availability variations.

TM Images

The TM images that were spatially filtered and enhanced were the best for visual detection of water circulation patterns. Since these images were further used in the multispectral analysis, a test was made to compare the relationship between pixels in the raw and filtered images. The results are presented in Table 4. The very high correlation coefficients indicate that this processing produced little effect in terms of pixel cross-characterization.

The TM Band 4 image was tested to distinguish land features from water, after the work of Freden and Gordon (1982). TM Band 5, however, presented higher separability for these classes, allowing the best possible location of the sampling sites in relation to landmarks. This resulted from the homogeneous count level of about 1 in the 0–255 level scale, found for all water surfaces. For the same reason, TM Band 5 did not provide information related to the water quality parameters measured and was not used in the statistical tests.

The average digital values for the 16-pixel squares around the sampling sites in Bands TM1, TM2, TM3, and TM4 and in the band combinations, or the nearest-neighbor pixel value in Band TM6, are presented in Tables 5 and 6.

The digital data from the 9 Sep. image (refer to Table 5) presented lower standard deviations in all TM bands and band combinations in relation to the standard deviations obtained on 11 Aug. (refer to Table 6). On 9 Sep. the minimum values are associated with SPs 3 and 4, in the south part of the Bay, whereas the maximum values occurred at SPs 11 and 15, in the north part of the Bay. The minimum and maximum values occurred in the same areas of the Bay, in all TM bands. The only exception occurred for TM1 where the site of minimum radiance (SP 15) was found at the most northern part of the Bay. For the band combinations, the minimum values were found at the northern part of the Bay, whereas the maximum values occurred at the south.

On 11 Aug. (Table 6), only the maximum radiance values of the TM bands kept a regular pattern of occurrence, all at SP 17. This situation may be explained by a random pattern of water

Table 4. Correlation Coefficients (r) between Raw and Processed Images of 9 September 1986 on TM Bands 1, 2, 3, 4, and 6

Band	1	2	3	4	6
r	0.98	0.97	0.99	0.97	0.99

Table 5. Digital Data from the Landsat / TM on 9 September 1986[a]

SP	TM1	TM2	TM3	TM4	TM6	TM2/3	TM1/3	PCB1	PCB2
03	58.00	46.00	32.00	06.00	141.50	143.13	174.81	128.88	127.30
04	58.00	43.00	31.75	06.00	143.00	141.25	132.21	129.63	127.81
05	57.63	46.00	32.00	07.75	147.00	139.81	171.69	129.13	127.00
07	56.00	46.00	35.00	09.50	143.00	136.50	163.13	128.63	126.06
08	57.25	46.00	32.19	09.25	146.50	140.88	170.19	129.13	126.69
11	70.88	60.50	51.00	13.00	150.25	112.81	115.81	118.81	127.19
15	55.25	46.00	35.00	19.00	166.00	136.25	160.94	128.25	124.88
16	63.81	48.00	39.88	13.75	150.75	123.63	147.25	125.19	126.69
17	70.50	52.81	43.75	18.63	153.00	120.66	142.00	122.19	128.38
19	58.38	46.00	33.06	09.00	143.50	139.81	170.88	128.31	127.38
20	58.00	46.00	32.00	06.25	145.00	137.50	170.75	128.94	127.19
21	57.88	46.13	35.00	10.38	147.00	135.00	163.44	128.25	126.44
MIN	55.25	43.00	31.75	06.00	141.50	112.81	115.81	118.81	124.88
MAX	70.88	60.50	51.00	19.00	166.00	143.13	174.81	129.63	128.38
AVG	60.13	47.70	36.05	10.71	148.04	133.94	156.93	127.11	126.92
STD	5.11	4.62	5.97	4.53	6.66	9.58	18.62	3.36	0.89
N	12	12	12	12	12	12	12	12	12

[a] SP = Sampling point; TM1 = data on TM Band 1; TM2 = data on TM Band 2; TM3 = data on TM Band 3; TM4 = data on TM Band 4; TM6 = data on TM Band 6; TM1/3 = data on TM band ratio 1/3; TM2/3 = data on TM band ratio 2/3; PCB1 = data on principal comp. Band 1; PCB2 = data on principal comp. Band 2.

quality in the Bay caused by a deep low tide on this date, which will be discussed further.

Statistical Analysis

Water quality data obtained at different dates from those of the images were not used in the statistical analysis. Correlations between water quality parameters were initially investigated for the pairs of variables with coefficients of correlation statistically significant. These correlations are presented in Table 7.

The positive correlations between SC and SA, SC and TSS, and *T* and TSS, and the negative correlations between SC and *T* and between *T* and SA, for 9 Sep., suggest that marine conditions were present in the Bay, because seawater usually presents high correlation between these same four parameters. In fact, as shown in Table 3, the tide levels were high and had hardly varied between this and the previous date, thus making it difficult for the fresh water to drain from the tributary subbasins and other discharge sites.

Fe and Mn were well correlated on the two dates (Table 7). Both elements abound in nature, having similar geochemical behavior and common sources in rocks and soils.

Results in Table 7 for 11 Aug. characterize opposite conditions in the Bay in relation to the first date. No correlations were found relating SA, SC, *T*, and TSS, except for the negative correlation between SC and TSS. This single correlation value cannot characterize any particular condition, since it is expected that greater TSS concentrations will produce greater turbidity in the water. Instead, Fe and Mn were correlated with *T* ($r = 0.41$ and $r = 0.55$, respectively). Again, the tide levels in Table 3 explain these results, showing an extreme condition of tide level variation. Fresh water strongly predominated in the Bay causing no relationships between *T* and TSS or SA, as would be expected in sea water. Nonetheless, since sea water is denser and flows below fresh water, the sampling collection (up to 50 cm depth) was done in the layer of higher fresh water content. The correlations between Fe and *T* and between Mn and *T*, although statistically significant, are very low, and are explained as a result of transport of these elements by fresh water.

Next, correlations were found between water quality parameters and TM data, including the data resulting from the rationing procedure described in the methodology (refer to Table 8 for the statistically significant results).

On 9 Sep., the correlation coefficient between SC and Fe was -0.33 and between Fe and Mn, 0.31. According to the methodology adopted, these coefficients indicate a possible relation between SC and Fe and Mn. Thus, ratios of Fe / SC and Mn / SC were calculated and used in the

Table 6. Digital Data from the Landsat / TM on 11 August 1987

SP	*TM1*	*TM2*	*TM3*	*TM4*	*TM6*	*TM1/3*	*TM2/3*	*PCB1*	*PCB2*
00	88.25	13.50	53.00	12.00	162.00	171.50	203.75	128.75	128.50
01	92.00	16.00	53.25	16.00	162.00	166.75	199.75	127.25	127.50
02	115.00	27.13	69.00	20.00	162.00	137.00	164.25	121.50	127.00
03	120.00	37.00	76.00	24.00	162.00	157.50	150.25	118.75	125.25
04	112.25	31.00	70.75	24.00	162.00	162.50	151.50	120.75	126.50
05	105.25	27.00	66.50	20.00	162.00	174.00	157.00	122.00	127.50
06	94.50	30.75	69.25	20.00	157.00	144.50	153.00	123.75	124.75
07	96.50	21.00	62.25	18.00	157.00	177.50	164.25	124.75	127.00
08	94.50	21.00	57.75	16.25	152.00	181.00	176.50	128.00	126.50
09	92.50	21.44	59.50	16.00	154.50	174.50	168.00	127.50	126.75
10	95.50	28.00	64.00	16.00	157.00	160.00	165.00	127.00	125.50
11	96.00	34.00	69.00	19.75	157.00	141.50	153.00	125.75	124.75
12	92.25	28.00	62.50	16.00	160.75	158.25	160.50	127.25	125.25
13	95.25	28.00	64.50	16.00	162.00	159.00	157.00	126.50	126.00
14	96.00	21.00	60.25	16.00	164.50	178.00	171.25	128.25	126.75
15	92.00	18.19	59.75	16.00	172.00	196.50	178.00	127.25	127.00
16	104.00	27.00	69.00	20.00	167.00	168.00	154.50	123.50	125.50
17	147.00	48.00	86.25	28.00	179.50	153.00	138.50	109.75	127.00
18	117.00	34.00	67.75	20.00	162.00	169.25	162.50	122.25	126.75
19	119.25	36.19	70.75	20.00	158.25	159.00	150.50		
20	125.75	37.00	76.00	24.00	162.00	162.00	153.00	116.50	127.25
21	128.19	37.00	76.25	24.00	168.00	200.75	152.25	117.50	126.25
22	105.25	18.19	52.00	12.00	147.00	171.75	213.00	125.75	129.50
23	104.00	16.00	48.00	10.00	147.00	186.00		125.00	130.75
24	97.25	16.00	48.75	12.00	147.00	176.25	216.75	127.25	129.75
25	103.50	16.00	52.00	13.00	147.00	176.75	215.00	126.00	129.25
26	104.00	16.00	51.00	16.00	147.00	178.00	215.25	125.25	130.75
27	103.50	16.00	48.75	15.00	147.00	182.25	222.00	126.50	130.50
28	98.25	16.00	48.75	12.00	147.00	176.50	219.50	127.50	129.00
29	108.75	21.00	55.50	16.00	149.00	167.50	211.50	123.75	129.50
30	112.00	16.00	52.00	16.00	147.00	177.25	215.00	124.75	130.00
31	99.25	16.00	52.00	16.00	147.00	169.25	214.25	125.50	129.00
32	104.00	17.25	52.00	19.00	151.00	176.25	220.00	124.75	129.25
33	100.00	16.00	50.50	12.00	147.00	176.50	219.25	127.50	129.00
34	107.00	24.00	52.00	15.50	147.00	172.00	231.75	123.75	129.50
35	111.75	21.00	52.00	15.25	147.00	177.75	223.25	123.75	129.75
36	106.25	20.58	51.75	15.25	147.00	178.00	225.50	124.25	129.50
MIN	88.25	13.50	48.00	10.00	147.00	137.00	138.50	109.75	124.75
MAX	147.00	48.00	86.25	28.00	179.50	200.75	231.75	128.75	130.75
AVG	104.96	24.01	60.28	17.22	156.04	170.11	184.62	124.33	127.78
STD	12.16	8.38	9.86	4.07	8.57	13.34	30.32	3.87	1.81
N	37	37	37	37	37	37	36	36	36

[a] See footnote to Table 2 for key to abbreviations.

Table 7. Significant Correlations *r* for Water Quality Data

09 / Sep. / 86		*11 / Aug. / 87*	
Variables	*r*	*Variables*	*r*
Fe and Mn	0.81	Fe and Mn	0.74
SA and SC	0.74	Fe and T	0.41
SC and TSS	0.63	Mn and T	0.55
T and SC	−0.89	SC and TSS	−0.69
T and TSS	0.78		
T and SA	−0.63		

correlation analysis. On 11 Aug., the correlation between SC and Mn was 0.30, and, therefore, the ratio Mn / SC was also calculated for correlation purposes.

On 9 Sep. (Table 8), TM4 and TM6 were the best bands for the assessment of SC, *T*, and TSS. In addition, the correlation between SC and TM2 / 3 was good ($r = 0.72$). There was not a significant correlation between Mn and Fe and any TM image data. After their rationing in relation

Table 8. Significant Correlations *r* for Water Quality Data and TM Data

09 / Sep. / 86		11 / Aug. / 87	
Variables	*r*	*Variables*	*r*
TSS and TM4	0.86	F3 and TM2	0.57
SC and TM2	-0.58	Fe and TM3	0.62
SC and TM3	-0.69	Fe and TM4	0.48
SC and TM4	-0.89	Fe and TM1/3	-0.57
SC and TM2/3	0.72	Fe and TM2/3	-0.62
SC and PCB1	0.65	Fe and PCB2	-0.71
T and TM6	0.91	Mn and TM2	0.51
Fe/SC and TM1	0.79	Mn and TM3	0.59
Fe/SC and TM2	0.68	Mn and TM4	0.42
Fe/SC and TM3	0.74	Mn and TM1/3	-0.39
F3/SC and TM4	0.59	Mn and TM2/3	-0.73
Fe/SC and TM2/3	-0.79	Mn and PCB2	-0.80
Fe/SC and PCB1	-0.76	SC and TM2/3	0.46
Mn/SC and TM1	0.79	SC and PCB2	0.53
Mn/SC and TM2	0.81	T and TM6	0.73
Mn/SC and TM3	0.86	Fe/SC and PCB2	-0.64
Mn/SC and TM1/3	-0.65	Mn/SC and PCB2	-0.64
Mn/SC and TM2/3	-0.87		
Mn/SC and PCB1	-0.85		

to SC, good correlations were found between these parameters and the TM data, particularly with TM2 / 3 (refer to Table 8).

Due to prevailing fresh water on 11 Aug., there were no significant correlations between any two pairs of the water quality parameters TSS, CH, and SC. However, as shown in Table 8, there were good correlations among Fe, Mn, and TM data and between *T* and TM6. The rationing procedure produced little changes in the degree of correlation between the variables, and even reduced the correlation indices in some cases. Chlorophyll data at this date were not significantly correlated with TM data.

Finally, a stepwise multiple regression analysis was carried out to identify how much the measured water quality variables could explain the TM data variability. The default values were those of the BASIS software (Burroughs, 1976).

Results from the stepwise analysis (Tables 9 and 10) indicated that the water quality parameters measured in this research, although significantly different in the two cases examined, explain most of the variability in TM images. The residual variability of the TM images could be due to other factors not considered, such as dissolved organic matter concentration (yellow substances) and atmospheric variability. Even the time lag between TM imaging and sample collection, which in the utmost case reached almost 6 h, could have influenced the degree of correlations. However, the sampling points that influenced the correlations most were not those obtained too long after the satellite overpass. The last sampling sites visited in the Bay were SP 19, SP 20, and SP 21 but the highest variances were found at SP 11, SP 15, and SP 17 (refer to Fig. 2), located in the shallowest and most polluted areas of the Bay.

The highest coefficient of determination, on the two dates, occurred with PCB2 as the independent variable, and included all the water quality parameters used in the stepwise analysis in the final models. It means that this band was the most representative of these water quality parameters together, if compared with the other bands used in this research.

The water quality parameters (independent variables) included in the final models selected for each TM band (dependent variables) are listed according to the step they were included in the model (refer to Tables 9 and 10). It is noticeable that the stepwise results for 9 Sep. show the inclusion of SC in the first step for all TM bands,

Table 9. Stepwise Regression Results for 9 September 1986 Data

Dependent Variable	*Variables in Model in Order of Inclusion*	*Coefficient of Determination (r^2)*
TM1	SC, Fe, TSS, Mn	0.74
TM2	SC, Mn, TSS, Fe	0.69
TM3	SC, Mn, TSS, Fe	0.77
TM4	SC, TSS	0.97
TM1/3	SC, Mn, TSS, Fe	0.53
TM2/3	SC, Mn, TSS, Fe	0.79
PCB1	SC, Mn, TSS, Fe	0.75
PCB2	Fe, SC, TSS, Mn	0.86

Table 10. Stepwise Regression Results for 11 August 1987 Data

Dependent Variable	*Variables in Model in Order of Inclusion*	*Coefficient of Determination (r^2)*
TM1	Fe, TSS, CH, SC, Mn	0.63
TM2	Mn, Fe, SC, TSS, CH	0.76
TM3	Mn, CH, Fe, TSS	0.71
TM4	Fe, SC, TSS, CH	0.59
TM1/3	Fe, Mn, SC, CH, TSS	0.65
TM2/3	SC, Mn, TSS, CH, Fe	0.84
PCB1	Fe, Mn, CH, TSS, SC	0.61
PCB2	SC, Fe, TSS, Mn	0.89

except PCB2. And the results for 11 Aug. show the inclusion of Fe or Mn in the first step for all TM bands, except TM2 / 3 and PCB2.

Concerning the regression between TSS and TM4, it is important to notice that this linear association differs from previous results in the literature. According to Holier (1978) and Rimmer et al. (1987), the relations between TSS and orbital remotely sensed data should fit a logarithmic curve, which depends mainly on sediment particle size, mineralogy, and color. The above results, therefore, indicate the high uncertainty revealed in remote sensing studies of water quality. Other results of Braga (1990) confirmed this uncertainty. The author analyzed water quality parameters and TM data simultaneously collected at Tucurui Reservoir, Pará State, Brazil, from two different dates 16 days apart in July and August 1989. On the first date, silicate was the only parameter significantly correlated with TM data, but, on the second date, many limnological parameters were correlated.

CONCLUSIONS

The foremost conclusion is that TM / Landsat images detected the variability of water quality patterns determined from ebb and flow conditions in the estuary of Guanabara Bay.

High correlation coefficients were observed between water quality parameters and TM digital data. With high tide (9 September 1986), sea water predominated in the Bay and significant correlations between Secchi depth (SC), total suspended solids (TSS), temperature (T), and salinity (SA) were found. SC, TSS, and T were well correlated with TM data, too. Iron and manganese concentrations in the TSS only correlated significantly with TM data after their rationing in relation to SC. This result is probably related to the dependence between the depth of penetration of the light in the water and the orbital remote detection of these two parameters.

For the low tide condition (11 August 1987), fresh water predominated in the Bay and significant correlations between Fe, Mn, and T were found. SC and TSS were significantly correlated, too. Fe and Mn showed significant correlations with TM data, especially with a principal component resultant Band 2 (PCB2). SC presented significant but low correlations with TM data. T and TM6 were well correlated. SC was not significantly correlated with any TM data. The rationing procedure applied to Fe and Mn data did not increase the correlations between these parameters and TM data. This can be explained by the random distribution of fresh waters originating from different kinds of sources, without a regular pattern between total suspended solids, Secchi depth, salinity, and temperature simultaneously.

The results of the stepwise regression seem to have been influenced by the different characteristics of the two dates analyzed. On 9 Sep., SC showed to be the water quality parameter alone that explained better the variability of all TM bands considered, except PCB2; the marine conditions on this date were expressed by significant and high correlations between SC, TSS, SA, and T. On 11 Aug., Fe and Mn were the water quality parameters that explained better the variability of all TM bands considered, except TM2 / 3 and PCB2; the mixture of different fresh waters on this date was expressed by the absence of correlations between all SC, TSS, SA, and T.

PCB2 concentrated the greatest amount of spectral information related to the water quality conditions at Guanabara Bay, as expressed by the high coefficient of determination between this band and the water quality parameters modeled. The software of principal component analysis, therefore, is recommended in other studies of water quality to verify its potential under different climatological and / or geographical conditions.

Orbital remote sensing can be used to assess water quality parameters in polluted estuaries. Local conditions, including tides, fresh water discharges, and shallow areas with sedimentation, have to be considered in the analysis of the data. Significant variations between different images are also expected. Notwithstanding such limitations, orbital remotely sensed data can and should be used as a complementary tool when field data are scarce, to obtain synoptic views of pollution patterns.

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