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ABSTRACT

This paper reports preliminary results from the research project developed to model the relationship between TM/Landsat data and limnological variables in the Barra Bonita reservoir, located in São Paulo State. Multispectral Landsat-5 data recorded on July 4, 1989 were acquired in the TM bands 1, 2, 3 and 4. These data were digitally processed and converted into apparent reflectance values. Secchi depth, temperature, total suspended solid concentration, total chlorophyll pigment concentration, and nutrient concentration were determined concurrently with TM/Landsat-5 overpass. TM/Landsat bands were geometrically corrected and the average of a 3 by 3 pixel window in each band for each sample station was related to field data using stepwise regression techniques. Stepwise techniques were also applied to field variables to identify how optically active parameters were influenced by nutrients. The adjusted coefficient of determination (r^2) for the relationship between TM bands and Secchi depth was 0.73 and the regression model included bands TM1 and TM3. The stepwise regression using Secchi depth as dependent variable was run against all the remaining limnological variables to identify which of them would be vicariously represented by the remote sensing model. The coefficient of determination for the Secchi model was 0.77 with the following limnological independent variables in the equation: total phosphorus , total nitrogen , total suspended solids and total chlorophyll pigment concentration.

1.0 INTRODUCTION

Water quality monitoring is vital since water is a natural resource under extreme pressure nowadays. The conventional techniques for assessing water quality are expensive, time consuming, and spatially limited. Most of the information derived

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from the water is based upon a few samples collected without taken into account the spatial variability in the aquatic system. Remotely sensed data can be integrated to those derived from traditional techniques so as to improve their spatial significance. The application of remote sensing data to water quality assessment is not operational as far as continental aquatic systems are concerned. The presence of many different optically active components on continental waters makes it difficulty to relate water color to a single component. The application of remote sensed data to water quality assessment is based upon the hypothesis that by estimating the optically active variables through remotely sensed data, one will be getting information about the system as a whole. This hypothesis is based on the following assumptions: a- the processes in the water surface can represent most of the processes which occur in the whole euphotic zone; b- the lost of in-depth information is balanced by the gain of spatial information from the aquatic system under study.

2.0 THEORETICAL BACKGROUND

The water spectral radiance is a function of the water spectral reflectance, which depends on the ratio between the scattering and absorption coefficients of the water and its dissolved and suspended optically active components (Kirk, 1986). According to Bricaud and Sathyendranath (1981), these substances can be classified into a)photosynthetic pigments; b)dissolved organic matter; and c)organic and inorganic suspended solids. The variation of their concentrations, sizes and types in the water body produces different spectral responses. More recent works have mentioned that zooplancton may also affec the water spectral response (Balch et al., 1989)

The maximum reflectance of pure water takes place in the blue region of the electromagnetic spectrum. The presence of chlorophyll pigment produces an attenuation of the light backscattering in this region and enhances the water reflectance in the green region (Clarke and Ewing, 1974). The study of inland waters with remote sensing techniques is specially complicated by the high variability in space and time of the water components. Many limnological parameters not optically active are indirectly related to the active ones, and their study may be very useful. In this case, phosphorus and nitrogen compounds are the most important to be considered. Correlation analysis performed between nutrients and TM bands resulted in statistically significant coefficients for the same spectral regions correlated to chlorophyll concentration (Novo et al., 1991). This is probably related to the algae growing dependence on those nutrients. Another essential aspect to be considered is the depth of the euphotic layer which is very well represented by the Secchi depth measurements. This limnological parameter is dependent upon water turbidity, and so it evaluates the global effect of the substances optically active which define the spectral behaviour of the water body.

The presence of chlorophyll in the water has been detected through multispectral images obtained by orbital remote sensors, and its spectral behaviour has been utilized in the development of algorithms to estimate different pigment concentrations. Through empirical procedures, many authors have related MSS bands or band combinations to waters trophic state. (Welby et al., 1979 and Nielsen et al., 1983). The advent of TM images, with better spectral and spatial resolution than MSS/Landsat images, increased the researches in that subject (Schiebe et al., 1984; Braga, 1988, Tassan, 1988, Novo et al.,1991).

3.0 METHODOLOGY

3.1 STUDY SITE

Barra Bonita Dam is located at 22° 29'S and 48°34'W in the Tietê river. The reservoir covers an area of approximately 300 km^2 in the central region of the São Paulo State. It belongs to the Tietê river basin which has approximately 32,300km^2 and drains a large variety of litologies ranging from basalts to sandstones and migmatites. The following aspects were taken into account to select Barra Bonita reservoir as test site: a- it is an old reservoir which presents a spatial and temporal gradient of trophic states ranging from hipereutrophic to mesotrophic conditions; b- it has been subjected to intensive limnological studies during the last two decades having a large amount of ancillary data to help image interpretation; c-its catchment basin is heavily urbanized; d- Tiete river, the major reservoir's tributary is also an important source of nutrients and sediment derived from both industrial and domestic efluents and agriculture.

3.2 DATA ACQUISITION

The data used in this study were acquired during the winter of 1989, from July to September and include both limnological variables and TM/Landsat-5 multispectral images. During this period two Landsat overpasses were sucessfully acquired with near zero percent of cloud cover. This study focus specially data acquired during the Landsat overpass on July 4, 1989. Limnological data were collected for three more dates: July 20, August 21, and September 22. Thirty stations were selected by inspecting historical TM/Landsat images (Novo and Tundisi, 1990). The time difference between satellite overpass and water sampling was kept within three hours. After plotting the stations on 1:50,000 topographic sheets, they were referred to geographical features easily identified on the ground. Water quality reference data consisted of surface measurement (0.50cm) of the following limnological variables: temperature (TEMP); Secchi depth (SEC); Nitrite (NO2); Nitrate (NO3); Ammonia (NH4); Total nitrogen (NTOT), Silicate (SIO2); Orthophosphate (PO4); Total phosphorus (PTOT); Total suspended solids (TSS); TSS inorganic matter (MI); TSS organic matter (MO); Total chlorophyll pigment concentration (CLTOT). The samples were filtered and fixed immediately after the collection and sent to the Applied Ecology and Water Resources Center (CRHEA, São Paulo University) to be chemically and biologically analysed according to methods described in Calijuri(1988).

3.3 DIGITAL PROCESSING

Digital TM/Landsat data in the visible and near-infrared bands (TM1 to TM4) were converted to the apparent reflectance (Markham and Barker, 1986) resulting in the bands TM1R, TM2R, TM3R and TM4R, respectively . These bands were registered to the Universal Transverse Mercator (UTM) reference system. The sample site locations were then converted to their corresponding row/column position in the geometrically corrected image. A 3 by 3 pixel window corresponding to each sampling station was used to average digital number (DN) of reflectance data for the four TM/Landsat bands so as to reduce location errors. For striping removal a recursive median filter was applied to the digital reflectance image (Godoy Jr. and Novo,1989).

3.4 DATA ANALYSIS

The satellite reflectance and surface reference data were analysed using the Statigraphics statistical package. Simple correlation and stepwise regression techniques were applied to explore the relationships between the spectral data and the limnological data. Simple correlation was used to assess the relationships between pairs of limnological variables along the winter. It was also applied to determine the relationship between the limnological variables and remotely sensed data (TM1R, TM2R, TM3R, TM4R) for July 4, 1989. A 95% confidence interval was used to assess correlation significance between variables. The stepwise regression technique allows the selection of the best set of independent variables to estimate a given variable. Essentially, this method computes a sequence of regression equations, at each step adding or deleting an independent variable. The criterium for inclusion or exclusion of an independent variable is based on the reduction of the sum of square error, coefficient of partial correlation and F statistics. Stepwise regression was run in three different ways: 1- between the limnological data assuming the optically active as dependent variables; 2- between the optically active limnological variables and TM data assuming the later as independent variables; 3- between the optically active limnological variables and TM data assuming the later as dependent variables to identify the water components which are explaining the changes in water color in this data set.

4.0 RESULTS

Correlation coefficients between the ground data varied widely from one to the other date. Table 1 lists the pairs of variables significantly correlated and the respective coefficients for every dates.

Table 1. Correlation Coefficients of Significantly Correlated Limnological Variables

LIMNOLOGICAL VARIABLES	JUL 4	JUL 20	AUG 21	SEP 22
NO3 and NTOT	0.73	0.86	0.95	0.57
NO3 and SEC	-0.48	-0.66	-0.73	-0.62
SIO3 and PDIS	0.63	0.62	0.56	0.54
PO4 and PDIS	0.75	0.77	0.88	0.89
NTOT and SEC	-0.46	-0.67	-0.59	-0.52
TSS and MI	0.94	0.98	0.97	0.92
TSS and MO	0.55	0.72	0.66	0.70
TSS and SEC	-0.55	-0.87	-0.88	-0.81
MI and SEC	-0.60	-0.87	-0.89	-0.79

The results on Table 1 show that the total nitrogen is highly and positively correlated to nitrate from July to September, while the remaining forms of nitrogen are not consistently correlated to total nitrogen in the whole winter. The high correlation means that in the whole winter the inputs of NO3 are spatially constant. There is a spatial interdependence between NTOT and NO3. In fact the NO3 represents around 50% of the NTOT for every sample station and date, while the remaining nitrogen forms are important only for some reservoir compartments. Results presented in Novo and Braga (1991) show that high concentrations of NO4 are spatially restricted to the Tietê and Piracicaba upper reaches. NO4 contributes significantly to the NTOT only in those areas . The ranges of variation of NTOT are between 400 microgram and 3,500 micrograms per liter, while both NO4 and NO2 concentrations are below 400 micrograms per liter during the whole winter, reaching values as small as 1 microgram per liter.

Total nitrogen and nitrate are also negatively and lowly correlated to Secchi depth . It means that, during the whole winter, the availability of nitrogen has some spatial relation with water components which control water transparency. The analysis of other significant correlations suggest an indirect relationship of NO3 and NTOT with TSS, which is strongly correlated with SEC in most of the dates.

Dissolved phosphate (PDIS) and PO4 presented high and positive correlation in the whole winter. This correlation would be expected, since the ortophosphate (PO4) is one of the main components of PDIS. Dissolved phosphate is also correlated to the silica (SIO2) during the whole winter indicating that they might have common sources.

The correlations between TSS and MI and TSS and MO are obvious since, TSS is the sum of MI and MO. The correlation between TSS and SEC and TSS and MI were also expected, since the TSS (mainly the inorganic fraction) scatter light and decrease water transparency.

Table 2. Presents the results of the subsequent tests performed with data collected on July 4. These results indicate an inverse correlation between the blue and green reflectance and chlorophyll concentration.

Table 2. Correlation Coefficients Between Optically Active Limnological Variables and Spectral Data

CLTOT	AND	TM1R	r = -0.69
CLTOT	AND	TM2R	r = -0.68
TSS	AND	TM3R	r = 0.42
TSS	AND	TM4R	r = 0.44
MI	AND	TM3R	r = 0.51
MI	AND	TM4R	r = 0.46
SEC	AND	TM1R	r = -0.52
SEC	AND	TM2R	r = -0.64
SEC	AND	TM3R	r = -0.84
SEC	AND	TM4R	r = -0.62

These inverse correlations are similar to those reported by Novo et al., (1991) when analysing data collected on July 17, 1988 in the same aquatic system. The inverse correlation between TM1R and CLTOT is expected since the chlorophyll absorbs blue light. The inverse correlation for TM2R band, however, is not completely understood, since it has been reported elsewhere (Kirk, 1986) an increase in the green reflectance with increasing chlorophyll concentration. It suggests that other optically active parameters have strong influence on TM2R variability. The presence of dissolved organic matter (DOM) associated to the fitoplankton decomposition could explain the decrease in the green reflectance as chlorophyll concentration increases, since the DOM strongly absorbs blue and green light. Unfortunately DOM measurements were not available to confirm this hypothesis.

The highest correlation between TM remotely sensed reflectance and TSS was observed in the infrared region, but the coefficient was very low. TSS concentration on July 4 ranged from about 3 mg/l to 11 mg/l. These low concentrations and variability could explain the poor relationship between spectral data and TSS mainly in the infrared region where water absorption dominates its spectral behavior (Kirk, 1986). When the correlation is run between spectral data and the inorganic fraction of TSS (MI) the coefficient increases and the most sensitive waveband turns out to be the red. Most of the dray inorganic material has an increasing reflectance towards longer wavelengths that explains the sensitivity of the red band to changes in the inorganic matter concentration.

The four TM bands were highly and negatively correlated to Secchi depth. The TM3R in the red region, however, presented the highest value (r=-0.84). It means that 70% of the water reflectance variation was explained by changes in water transparency, which is, in other words, changes in water color or changes in the concentration of the optically active parameters.

The following step was then to analyse if and how Secchi depth and chlorophyll were functionally related to the remaining limnological variables. Table 3 presents the results of the stepwise regression analysis applied to the data. The variables MI and MO were not used in this phase because they are highly correlated to TSS.

Table 3. Stepwise Multiple Regression Analysis Among Ground Truth Data

DEPENDENT VARIABLE	VARIABLES IN MODEL	ADJUSTED COEFFICIENT(r^2)
CLTOT	PO4 PTOT NO3 NTOT	0.32
SEC	CLTOT TSS	0.54
TSS	PO4 PTOT	0.40

The most interesting aspect in Table 3 is that clorophyll and TSS concentration are the selected variables in the model predicting Secchi depth. It means that about 54% of the Secchi depth variability is explained by changes in both clorophyll and TSS concentration. Part of the 46% unexplained variability is probably related to the DOM concentration.

Only 32% of the CLTOT distribution are explained by limnological parameters (PO4, PTOT, NO3 and NTOT). This low spatial relationship between chlorophyll and its growing essential nutrients is probably related to the reservoir operation which is responsible for releasing water from its upper layers. This release increases the flux in the upper layer of the water column producing a displacement of the phytoplankton in relation to its nutrient source.

Table 4 presents the resulting models from the stepwise regression. The remotely sensed water spectral reflectance TM data were used as independent variables and the optically active limnological variables which were proposed to be modelled were considered the dependent ones. TSS were also included because of their relationship with SEC (Table 3).

Table 4. Stepwise Regression Between Ground Truth Data and TM Data

DEPENDENT VARIABLE	VARIABLES IN MODEL	ADJUSTED COEFFICIENT(r^2)
CLTOT	TM1R	0.48
SEC	TM1R TM3R	0.75
TSS	TM2R TM3R	0.32

The Secchi depth model presented the best result. It includes TM1R and TM3R meaning that changes in the water transparency in July, 4 are explained by changes in blue and red water surface reflectance. It is interesting to observe that SEC variation was related to Chlorophyll and TSS variation (Table 3). As seen in Table 2, CLTOT and TSS were correlated to TM1R and TM2R and TM3R and TM4R respectively. SEC also presented high correlation with all those bands. In the model however, the TM1R and TM3R selected present respectively, the lowest and the highest correlation with Secchi depth. TM1R has the highest correlation with CLTOT and TM3R has the highest correlation with MI. These two bands give complementary information about water components, which individually affect the reflectance in the blue and red regions.

The model for Secchi depth estimation through TM reflectance was:

$$SEC = 0.403583 + 0.192298\ TM1R - 0.26435\ TM3R$$

The standard error of estimate for the model was 0.25 cm, which gives a 10% error for the highest Secchi depth (250cm) measurements found in the reservoir and almost a 40% error in the estimates of the lowest Secchi depths (60cm). So the model will perform quite well in regions of Secchi depth greater than 250 cm.

The models for CLTOT and TSS can not be applied to their estimation since the adjusted r^2 coefficients were very low.

In a final stage, another stepwise regression analysis was performed with TM data as dependent variables and optically active limnological parameters as independent variables to identify which of them were responsible for the variability of each TM spectral band. Table 5 resumes the results obtained in this analysis.

Table 5. Stepwise Regression Between TM/LANDSAT and Ground Truth Data

DEPENDENT VARIABLE	VARIABLES IN MODEL	ADJUSTED COEFFICIENT(r^2)
TM1R	CLTOT SEC	0.54
TM2R	CLTOT SEC	0.59
TM3R	CLTOT SEC MI	0.86
TM4R	CLTOT SEC MI	0.32

These results once more points out to the intricate nature of the optically active limnological variables. As discussed in section 2.0, three variables, namely inorganic suspended solids, chlorophyll pigments and dissolved organic matter, due to their specific absorption and scattering properties determine the water color. The high intercorrelation among those variables makes it difficult to separate the effect of one single parameter on the remotely sensed reflectance. In this study, dissolved organic matter was not measured, but as it affects Secchi depth, at a certain extent, it can be expressed by this variable. It can be seen from Table 5 that all wavebands are affected by more than one optically active component. Chlorophyll concentration and Secchi depth changes, for instance, account for near 60% of the reflectance changes in the blue (TM1R) and green (TM2R) regions of the electromagnetic spectrum. There are, at least, 40% of the reflectance variation which are not explained by changes in chlorophyll concentration. The poor performance of the models for bands TM1R and TM2R can be related to the low Chlorophyll concentration values in July 4. In that occasion the maximum and minimum chlorophyll concentration were around 12 and 3 micrograms per liter, respectively. The remotely sensed reflectance is not sensitive to those small changes in concentration in this case . Changes in surface reflectance and atmosphere can account, at least in part, for the remaining variability. In the red region (less affected by atmospheric effects) changes in the optically active variables accounted for over 80% of the reflectance variation on July,4 In the infrared band the adjusted R^2 coefficient drops to 32%. This poor performance can be related to the low concentration of water components and high water absorption.

5.0 CONCLUSION

Results from this study allowed to identify Secchi depth as the limnological variable to be estimated from the TM Landsat-5 remotely sensed reflectance on July 4, 1989. Secchi depth is related to changes in both TSS and chlorophyll concentrations in this date. The low concentrations of TSS (3 to 11 mg/l) and chlorophyll (3 to 12 micrograms per liter) produced poor modelling results. The remotely sensed reflectance could not be used to estimate their concentration in the system. The presence of those components in the system can be indirectly assessed by the changes in water transparency. The Secchi depth modelling resulted in a model in which reflectances in the blue and red bands account for 75% in changes in that variable. So, by mapping SEC it will be possible to assess the changes in both TSS and CLTOT concentrations in the Barra Bonita reservoir.

Results also indicate that dissolved organic matter measurements are essential to the comprehensive understanding of the water color reflectance. The future tasks of this project will include DOM measurements and band combination approaches to improve the operational application of remotely sensed reflectance to the water management practices.

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