ESTIMATING THE SUSPENDED SEDIMENT CONCENTRATION IN THE UPPER PARANÁ RIVER USING LANDSAT 5 DATA: DATA RETRIEVAL ON A LARGE TEMPORAL SCALE AND ANALYSIS OF THE EFFECTS OF DAMMING

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Abstract

The suspended sediment concentration SSC of the Upper Paraná River (Brazil) was strongly affected by the Porto Primavera Dam, but assessing the effects of the dam is complicated by the absence of a series of continuous SSC data. This paper aims to produce satellite estimates of SSC for the Upper Paraná River to partially address the temporal gaps in the existing SSC database and to evaluate the effects of the dam on this variable. For this aim, a total of 164 Landsat TM-5 images were processed: 29 for model generation, supported by SSC data from *in situ* gauging stations, and 135 for SSC retrieval. By using surface reflectance values, three models were obtained: (A) for water dominated by inorganic particles, (B) for clear waters (mixed spectral response of inorganic particles and phytoplankton) and (C) for very clear water conditions. The mean and variance of the SSC was 24.2 and 15.82 mg/l, respectively, before the construction of the Porto Primavera dam and 4.91 and 3.7 mg/l, respectively, after the completion of the dam. Additionally, the Porto Primavera dam modified the seasonal SSC pattern of the Upper Paraná River.

Key words: Suspended sediments. Alto Paraná River. Landsat 5. Surface reflectance.

Resumo

Estimativa da concentração de sedimentos em suspensão no alto rio Paraná a partir de dados LANDSAT 5: recuperação de dados de larga escala temporal e análise dos efeitos de barramento

A concentração de sedimentos em suspensão (CSS) do Alto Rio Paraná foi fortemente afetada pela barragem de Porto Primavera, mas a avaliação de seus efeitos é dificultada pela falta de uma série contínua de dados de CSS. Este trabalho apresenta estimativas de CSS para o Alto Rio Paraná a partir de imagens orbitais para preencher as lacunas temporais da base de dados coletada em campo e então avalia os efeitos da barragem nesta variável. Para tal, um total de 164 imagens Landsat TM-5 foram processadas: 29 para geração de modelos, feitos com base em dados adquiridos em campo e 135 imagens para aplicação dos modelos. A partir do uso de reflectância da superfície, três modelos foram obtidos: (A) águas dominadas por partículas inorgânicas, (B) águas claras (resposta espectral mista entre partículas inorgânicas e fitoplâncton) e (C) águas muito límpidas. A média e variância da CSS foi, respectivamente, 24,2 e 15,82 mg/l, anteriormente à construção da barragem e 4,91 e 3,7 mg/l após sua conclusão. Além dos valores totais, a barragem de Porto Primavera modificou o padrão sazonal do Alto Rio Paraná.

Palavras-chave: Suspended sediments. Upper Paraná River. Landsat 5. Surface reflectance.

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INTRODUCTION

An important problem in studies of suspended sediment transport by rivers is the lack of a suspended sediment concentration (SSC) database that enables the correct identification of temporal and spatial variations. Long-term tendencies and annual patterns cannot be detected by an inappropriate strategy of data collection with low sampling frequency.

Satellite remote sensing is an interesting alternative to traditional field campaigns for SSC monitoring. The synoptic and multitemporal view of the earth provided by remote sensing enables highly detailed monitoring of aquatic systems. Analytical models have been developed and successfully applied in the retrieval of water quality parameters, but such models require the acquisition of the optical parameters of the water, spectra field samples and/or orbital images with suitable spectral and radiometric resolutions, such as MERIS data (DOERFFER; SCHILLER, 2007; GITELSON et al., 2008; ZHANG et al., 2008; LE et al., 2011). Such requirements exclude a large temporal series of multispectral and free data, such as the products of Landsat satellite series.

Using Landsat data, many empirical models have been developed since the 1980s (KHORRAM, 1985; RITCHIE et al., 1987; RITCHIE; COOPER, (1988, 1991) ARANUVACHAPUN; WALLING, 1988; WANG et al., 2009; MONTANHER et al., 2014). Such studies use statistical adjustments between an *in situ* SSC database and the reflectance or radiance from near-concurrent orbital data. However, most of the empirical models are suitable only for application to the specific date and place of the image used for the calibration (RITCHIE; SHIEBE, 2000). As a result, few studies have taken the next step and applied these models to estimate the SSC in other times or places (RITCHIE; SHIEBE, 2000). Therefore, the ability to monitor SSC from multispectral images is still barely explored. Furthermore, most of the models were developed using coastal, estuarine, lagoon, lake and reservoir environments; river studies are more unusual and involve fewer images (WANG et al., 2009).

The Paraná River is the third longest South American river, running from its headwaters in the central and southeastern regions of Brazil to its mouth in the city of Buenos Aires, Argentina, where, together with the Uruguay River, it compounds the La Plata River (ORFEO; STEVAUX, 2002; STEVAUX et al., 2009) The Brazilian portion of the Paraná River Basin has the largest hydroelectric potential in operation in South America (STEVAUX et al., 2009). The river reach between the Porto Primavera dam and the Itaipu reservoir is the last section of the Upper Paraná River (UPR) that is free of damming (SOUZA FILHO et al., 2004). This reach is strongly affected by the dams built upstream, where many changes have occurred in the physical environment (SOUZA FILHO et al., 2004), including a decrease in the SSC. This decrease was observed in field collections, but there were large gaps between sampling periods in that database (STEVAUX et al., 2009). Large gaps also exist in the data provided by the ANA (Agência Nacional de Águas – National Agency of Waters) for this river.

The present report aims to produce satellite estimates of the SSC for the UPR (Figure 1), filling in some of the temporal gaps in the existing SSC database. Based on empirical models developed from a large set of field collections and concurrent Landsat 5 and TM sensor (TM-5) images, we applied the obtained equations to 135 images that recorded the Paraná River in a temporal interval from 1984 to 2011. The results were evaluated with two initial questions: (1) Can the effects of more recent damming (the Porto Primavera dam in 1998) and the seasonal pattern of the SSC in the UPR be observed through remote sensing estimates? (2) Is the quantity of the data produced greater than that in the existing SSC database? If the answers to these two questions are positive, the use of orbital estimates in this study area is warranted.

MATERIALS AND METHODS

All downloaded SSC data from the gauging stations of the Paraná River basin are available from the ANA webpage (www.ana.gov.br). Both the images used for the empirical model generation and those used for the SSC retrieval at UPR were downloaded for free from the INPE (Instituto Nacional de Pesquisas Espaciais – National Institute of Spatial Research) catalog webpage, www.dgi.inpe.br/CDSR. The band files were downloaded separately, with each consisting of a Geotiff and XML file.

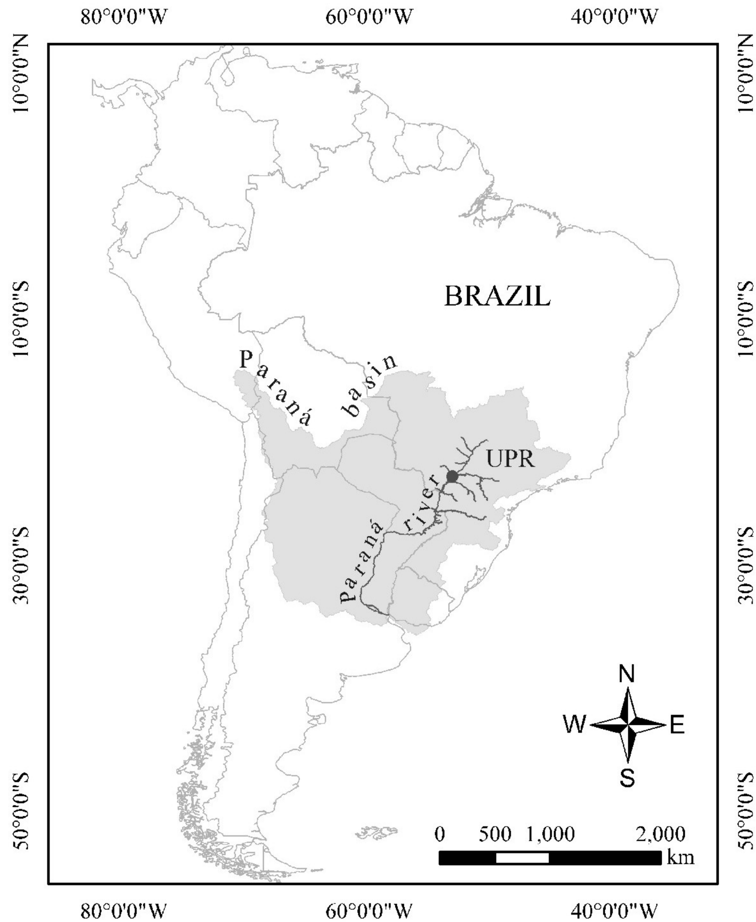

Figure 1 - Map of the Paraná River Basin. The cicle indicates the study area, in the Upper Paraná River (UPR) region

There are no concurrent ANA *in situ* data and TM-5 images in the UPR. Therefore, data from tributaries near the study area, mainly in Paraná State (southern Brazil), were used. Data from thirteen gauging stations, distributed in four rivers, were used (Figure 2). For this reason, a field validation was performed in the Paraná River to produce an adjustment factor for this location. This adjustment was necessary to enable the application of the models developed on other rivers to the study area. Only stations located along sections of the rivers with cross-sections wider than 100 m were used due to the spatial limitation of the TM5 sensor.

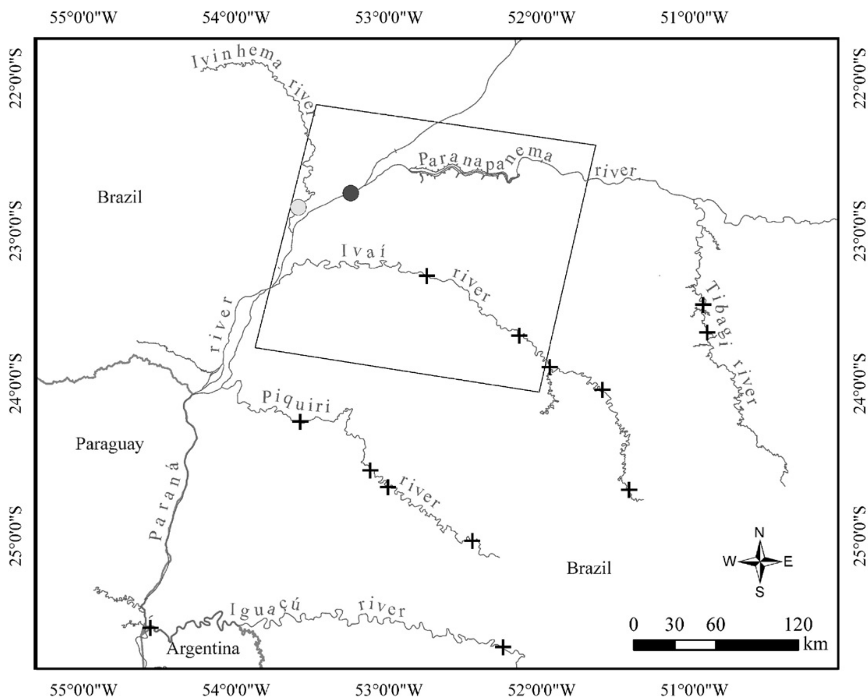

Figure 2 - Detailed map of the study area. Gauging stations are represented by black crosses. The cicles indicate the sampling places of SSC in 20/06/2011. Black: Paraná river; gray: Ivinhema river. The black line indicates the location of the path of orbit/point 223/76

Image processing: physical conversions and atmospheric correction

The methods described herein are valid for both image sets (that used in the model generation and that used for the SSC retrieval). The original digital number (DN) was converted for spectral radiance at the sensor $L_{(PISSILÃO)}$ (eq. 1) and then to the top-of-atmosphere (ρ_{TOA}) reflectance (eq. 2), (MARKHAM; BARKER, 1986; CHANDER et al., 2009).

$$L_{\lambda} = G_{rescale} \times DN + B_{rescale} \tag{1}$$

$$\rho_{TOA} = \frac{\pi \times L_{\lambda} \times d^2}{ESUN_{\lambda} \times \cos\theta_s} \tag{2}$$

where

$G_{rescale}$ = Band-specific rescaling gain factor [(*W* /($m^2 sr\mu$)/ *DN*]

$B_{rescale}$ = Band-specific rescaling bias factor [*W* /($m^2 sr\mu m$)]

d = Earth-sun distance [astronomical units]

$ESUN_{(\lambda)}$ = Mean exoatmospheric solar irradiance [*W* /($m^2 \mu m$)]

(θ_s =Solar zenith angle [degrees]

A total of 164 images were processed, including 29 for the model generation (four were not used) and 135 for the SSC retrieval. The 25 images used in the models development include several paths (Table 1). All the 135 images used for SSC retrieval are from the path of orbit/point 223/76 (Figure 2).

River	Date	Orbit	Point
Iguaçú	30/09/1999	224	78
Iguaçú	19/08/2003	221	78
Piquiri	28/07/1990	223	77
Piquiri	14/09/1996	223	77
Piquiri	17/09/1997	223	77
Piquiri	02/05/1999	223	77
Piquiri	24/08/2000	223	77
Piquiri	07/03/2008	223	77
Piquiri	02/09/2009	223	77
Ivaí	08/09/1988	223	76
Ivaí	17/09/1997	223	76
Ivaí	25/09/2000	223	76
Ivaí	22/04/2007	223	76
Ivaí	18/11/2008	223	76
Ivaí	05/06/1985	222	77
Ivaí	07/07/1985	222	77
Ivaí	06/08/1996	222	77
Ivaí	24/07/1997	222	77
Ivaí	13/05/2000	222	77
Ivaí	30/03/2007	222	77
Tibagi	03/08/1989	222	76
Tibagi	20/09/1989	222	76
Tibagi	25/06/1998	222	76
Tibagi	17/07/1991	221	77
Tibagi	14/04/1992	221	77

Table 1 - Description of the images used for models development

Due to the large quantity of data, the X-6SCorr (semi-automatic conversion of the digital numbers of the orbital images to BRF based on the XML metadata and 6S code) was used for image processing. This recently developed, free Brazilian software (MONTANHER; PAULO, 2014), performs conversions from the DN to the apparent and surface bidirectional reflectance factors semi-automatically. Most of the parameters required for the DN-to-surface BRF conversion are automatically recognized from the XML file, with only the atmospheric parameters being provided manually.

Three atmospheric parameters are necessary in the 6S computation: atmospheric model, aerosol model and optical depth (VERMOTE et al., 1997). The aerosol model was assumed to be constant in the study area (continental model). This region is not strongly influenced by biomass burning, urban areas, desert dust or maritime aerosols. The continental model is composed of 70% dust-like components, 29% water-soluble components and 1% soot components (INTERNATIONAL RADIATION COMMISION, 1983). The predominance of dust-like and secondarily water-soluble components is consistent with a regional pattern in which agricultural activity is the main source of troposphere aerosols, emitting soot to the atmosphere mainly during the dry season (July–September). This greater quantity of optical matter in the atmosphere during the dry season influences the extinction coefficient of light. Therefore, a second approximation was adopted for the optical depth: the values were coded according to the mean values for each month. The AERONET database of nearest locales and visibility values of the meteorological stations were used to estimate these mean values.

A third approximation was used for the atmospheric model definition. Due to the mean latitude (23°37’S) of the study area, the atmospheric model varies with the time of year. For the winter months (June–August), the middle-latitude summer model was adopted. For other periods of the year, the tropical model was adopted.

The adopted approach of atmospheric correction is not entirely accurate, because the actual atmospheric conditions in the moment of image acquisition can be different from the approximate parameters. However, other options such as the MODIS atmosphere products are available only from the most recent decade.

Statistical relationship (two initial models)

The surface reflectance values of the visible and near-infrared TM bands of 29 images were compared with the SSC field data (Figure 3).

This initial data visualization shows a behavior consistent with that described in previous studies. There is an increase in the R^2 value from the blue to red bands. This phenomenon is related to the fact that the point of saturation is wavelength-dependent, with the relation saturating at lower SSCs, for shorter wavelength (RITCHIE; SHIEBE, 2000). These authors also found in a literature review that as the range of the suspended sediment increases to 200 mg/l or more, a curvilinear relationship is established between the SSC and reflectance.

However, as observed in Figure 3, there aren’t appropriate statistical relationships to apply the resulting equations for estimating the SSC in other images. Thus, the data were divided into two groups with similar optical properties (Figure 4).

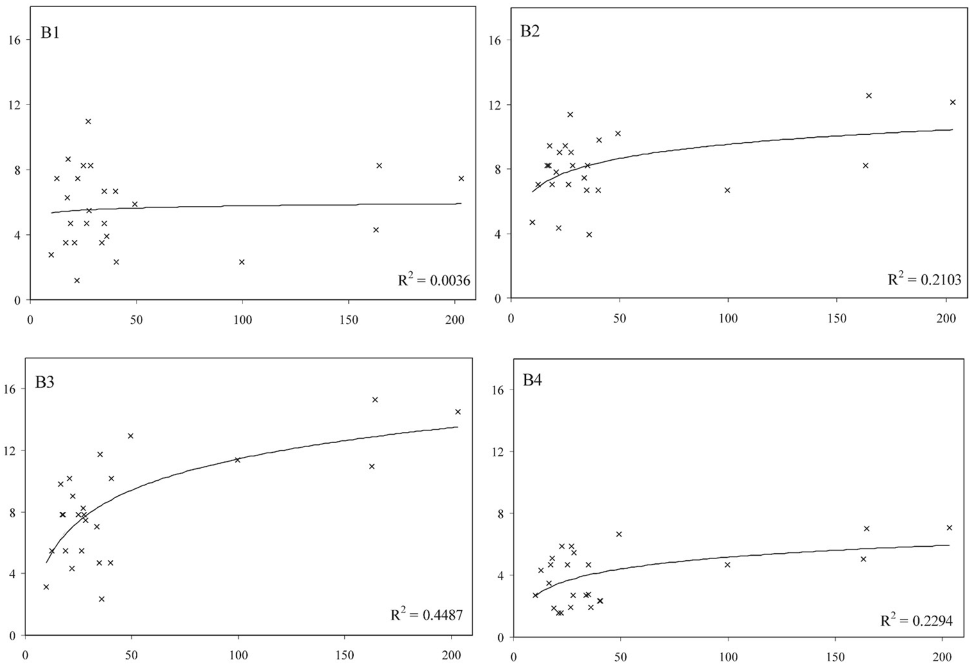

Figure 3 - Relationship between the SSC and surface reflectance in the TM-5 bands. The X axis is the SSC in mg/l, and the Y axis is the surface reflectance (0 – 100%)

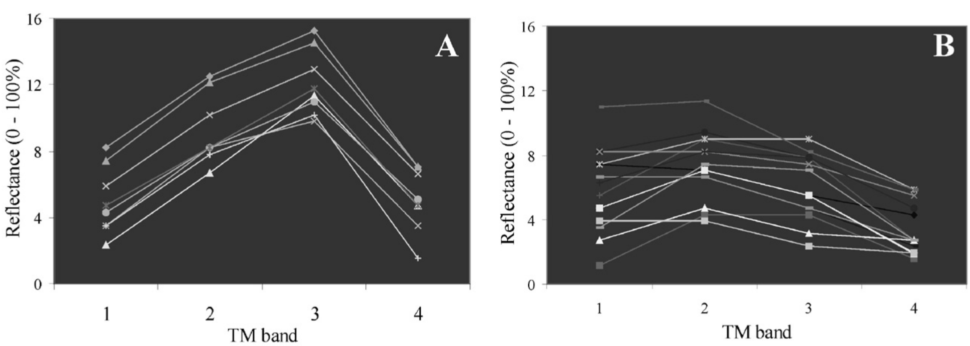

Figure 4 - Reflectance in the TM-5 bands of two water groups: (A) dominated by inorganic particles, (B) a mixture of inorganic particles and phytoplankton

These two groups are very different with respect to their spectral forms and ranges of reflectance. A series of statistical tests was performed with these new data groups. For the group of inorganic particles, the red band provided an improved adjustment (Figure 5.A). For the second group, a band ratio using bands 2, 3 and 4 provided a suitable result (Figure 5.B). The second group has a greater number of points, with a smaller R², than the first group. However, the second group deals with a smaller SSC range.

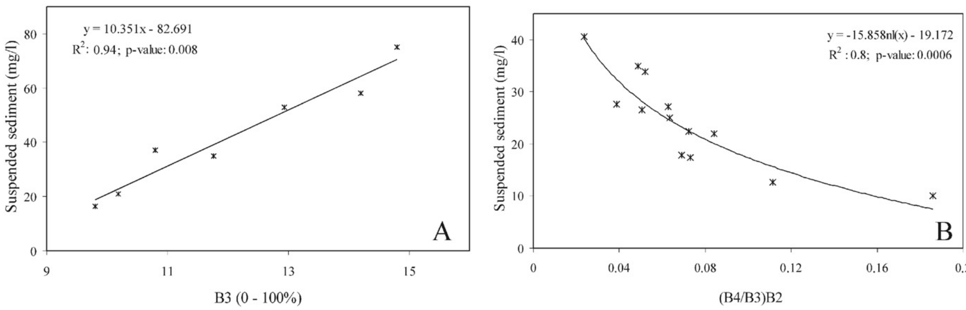

Figure 5 - Statistical relationship between the SSC and reflectance of the water group dominated by inorganic particles (A) and the water group with a mixture of inorganic particles and phytoplankton (B)

Validation (a third model)

The actual clear water condition of the Paraná River is very different from the waters sampled in the tributaries, which generated the SSC database used in the models. For this reason, a filing study was performed to collect SSC data in the current clear water conditions of the Paraná River (after the Porto Primavera damming). Samples from the Paraná River (clear water) and Ivinhema River (turbid water) were collected on June 20, 2011, concurrently with the Landsat 5 path of orbit/point 223/076. The water samples were collected from the surface and the concentrations were obtained by filtration in a Millipore filter system (pore size = 0.45 μm). A comparison of field collections and orbital estimates is presented in Table 2.

Table 2 - Estimated data and collected data of the suspended sediment concentrations

River	SSC in laboratory (actual)	SSC of TM-5 (estimated)
Paraná	8.6	20
Paraná	8.3	20
Paraná	5.2	19.5
Paraná	5.6	18
Paraná	7.5	22
Paraná	6.6	22
Ivinhema	15.4	16.4
Ivinhema	15.8	14.2

Using the data presented in Table 2 and presuming the *in situ* collects as "actual data", an average adjustment factor (A_{djs}) for the two rivers was calculated by the equation:

$$A_{djs} = \frac{actual}{estimated} \quad (3)$$

The mean adjustment factor for the Ivinhema River was 1.02 which shows a robust relation between *in situ* and estimated values. However, the mean factor for the Paraná River was highly substantial: 0.35. In other words, the model for clearer water wasn't fully suitable for the current conditions of the very clear water of the Paraná River. This finding can be understood when we evaluate the spectral responses of these two rivers (Figure 6).

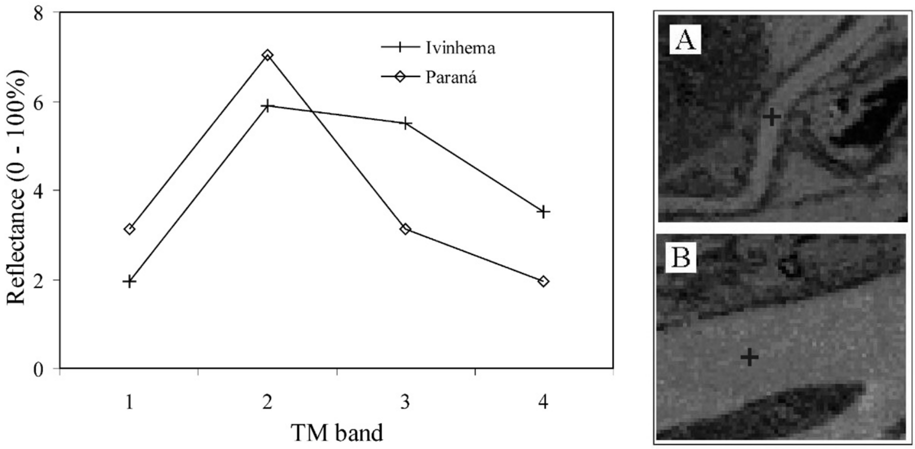

Figure 6 - Spectral response of: (A) Ivinhema River and (B) Paraná River (natural composition), for the image of 20/06/2011. The black crosses indicate the place of spectral sampling

The estimate in the Ivinhema River was suitable because its spectral form is similar to the spectral samples used in the model generation (Figure 4.B). Therefore, when the band ratio was applied, the estimate was effective. In contrast, the Paraná River spectra were different from all reflectance samples. The green band had a pronounced peak, whereas the red band was smaller than the reference group. This difference was likely caused by a higher quantity of phytoplankton and smaller quantity of SSC. This pronounced green peak changed the band ratio, resulting in an overestimation of the SSC. Thus, in these very clear waters with a pronounced green peak, the adjustment factor of 0.35 was adopted, resulting in a third model.

Model application

After image processing, the spectrum of each 9 x 9 pixel set of each image was collected in the central part of the UPR, outside of the influence of the tributaries (Figure 7).

After spectra extraction of the images, the river waters were classified into one of three water types: 1 – water dominated by inorganic particles, 2 – clear water, 3 – very clear water with a low SSC. The spectral angle mapper (SAM) was employed in this step. The reference spectra for types 1 and 2 were defined by an average reflectance value of the spectra presented in Figure 4. For the very clear water type (3), the spectra obtained in the image from 20/06/2011 were used together with six other images from 2005-2006 and four images from 2000. Data collected *in situ* (ROCHA, 2001; HAYAKAWA, 2007), demonstrate extremely low SSCs in these periods (ranging from 0.5 to 4 mg/l).

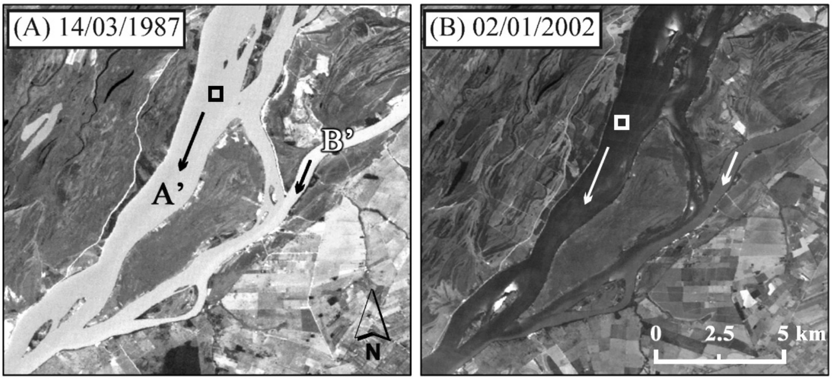

Figure 7 - Sample locations of two images (square). A' is the Paraná River, and B' is the Paranapanema River. The sample location in (B) was displaced because of sand bottom effects. Note that the Paranapanema River is much more influenced by the SSC (natural composition RGB 321)

Evaluation of the Porto Primavera dam on the SSC

The estimated SSC data were divided into two groups: before Porto Primavera damming (67 samples) and after damming (68 samples). The mean and variance of each set were calculated, and Student's t-test was applied. The results were compared with those in the previous literature. The monthly average and standard deviation of SSC of these two sets were used for an assessment of the seasonal dynamics.

RESULTS AND DISCUSSION

Model applications

Figure 8 presents all 135 spectral samples used for the SSC retrieval. Few water spectra indicated an optical domain of inorganic particles, whereas the two other sets were more numerous.

Data quantity

The SSC data from the public domain (ANA) and the SSC data from the UPR published in previous studies were compared with the orbital estimate. *In situ* data (STEVAUX, 1994; ROCHA, 2001; HAYAKAWA, 2007; STEVAUX et al., 2009) are presented in Figure 9 together with the TM-5-derived data using the same axis scales.

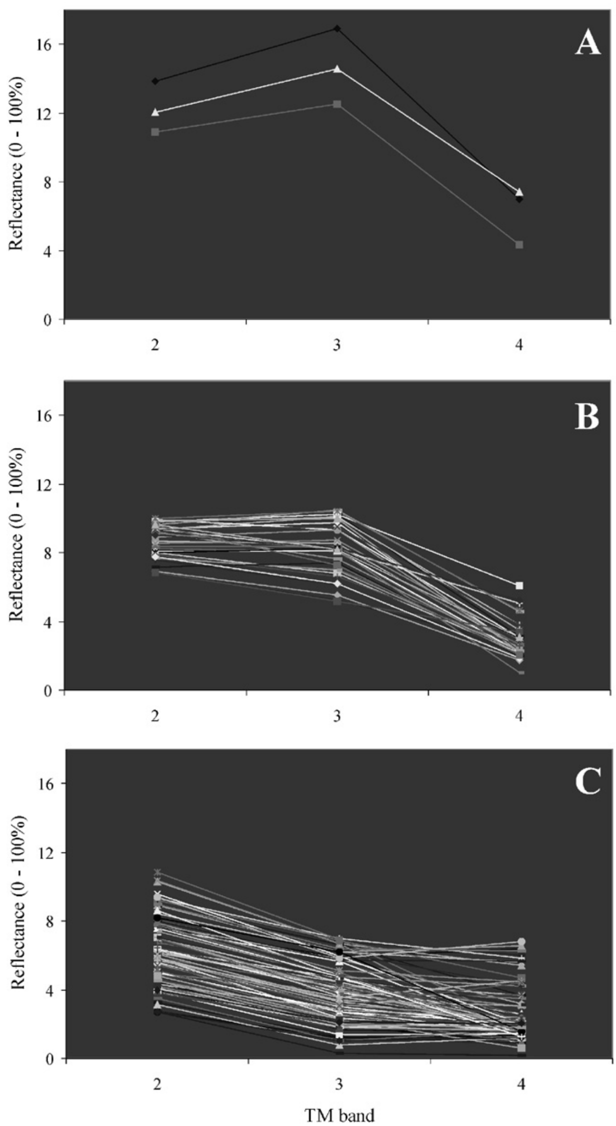

Figure 8 - Spectra from A – water dominated by inorganic particles (three dates), B – clear water (41 dates) and C – very clear water with a low SSC (91 dates). The blue band was omitted for clarity

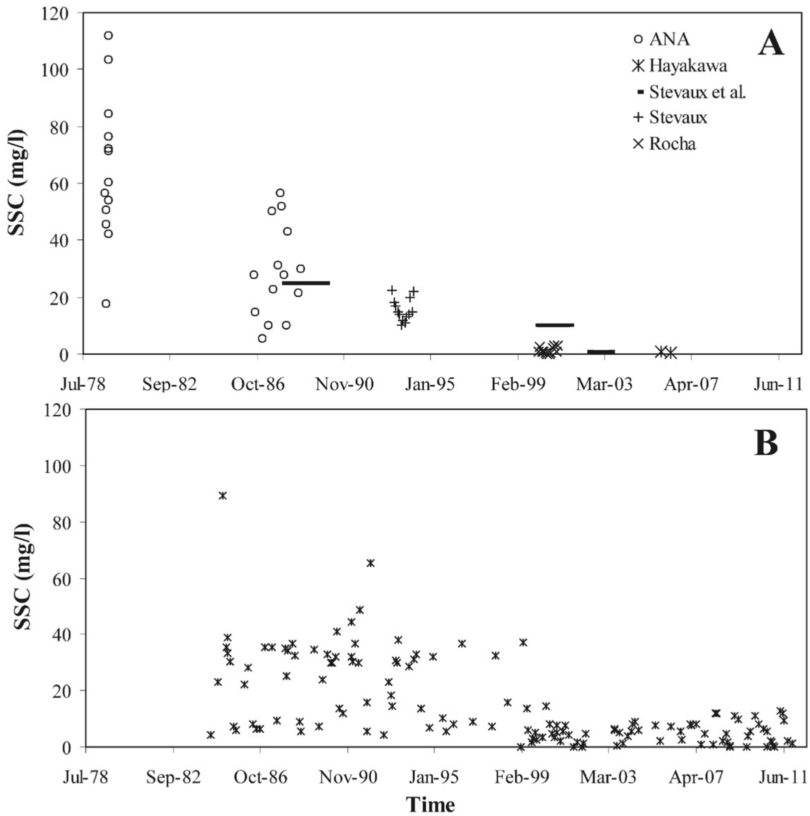

Figure 9 - Comparison between the data acquired from field samples (A) and the TM-5 estimates (B)

The SSC data available from the ANA database are temporally discontinuous and do not show any clear pattern, but they provide the unique information about the SSC conditions during the 1970s. Average data are presented for three periods (STEVAUX et al., 2009), which the data from 1988-1989 were similar to the TM-5 estimate and the ANA database, but the collections from 2000-2001 did not correspond with another *in situ* sampling (ROCHA, 2001). This finding may have been caused by the different sample locations of the studies. Regarding these collections, the TM-5 estimate presented average values that were neither as low as collections presented in Rocha (2001) nor as high as those of Stevaux et al., (2009). In 2002-2003, the values were very low, with the TM-5 estimate resulting in overestimates from 4 to 8 mg/l in the summer months but decreasing the error to 2 mg/l in the winter months.

A year of monthly samples (03/1993 to 03/1994) are presented (STEVAUX, 1994). For these samples, the TM-5 estimate resulted in an average overestimate of 8 mg/l. *In situ* samples were obtained on two dates (November 12, 2005, and May 13, 2006 - HAYAKAWA, 2007), which showed a good correspondence with the TM-5 estimate, with low SSC values that were near 1 mg/l. placement

For the monitoring proposal, in addition to its temporal advantage, the use of TM-5 has the benefit of method stability. Over decades, the *in situ* samples acquired by several people may be treated in the laboratory using different methods and materials, and the sample location may also differ. The influence of the SSC of the Paranapanema River, a large tributary of the Paraná River, was previously reported in the main river (HAYAKAWA, 2007). On other hand, the sample location in the TM-5 images was maintained in an area outside of the tributaries interference (example of Figure 7).

Porto Primavera dam

Effects on total SSC

Figure 10 presents the results of the estimates. Before the construction of the Porto Primavera dam, the mean and variance of the SSC were 24.52 and 15.82 mg/l, respectively. After the completion of the dam, the values decreased to 4.91 and 3.7 mg/l, respectively. The t-test showed that the pre and post-dam data had distinct means and variances (p-value < 0.0001). Figure 11 presents a graphic description of the two data sets.

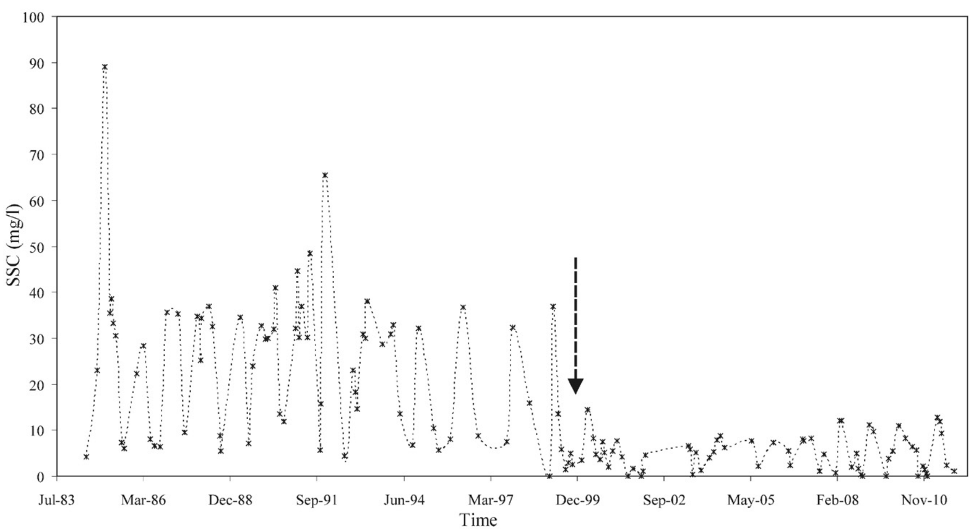

Figure 10 - Temporal series of the SSC estimated from the TM-5 sensor data. The black arrow indicates the date of completion of the Porto Primavera dam

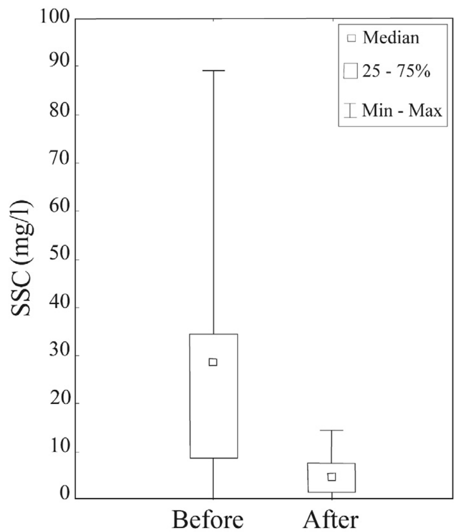

Figure 11 - Graphic description of the data sets before and after the completion of the Porto Primavera dam

The SSC average value of 24.52 mg/l before the construction of the Porto Primavera dam is approximately five times higher than the SSC average value of 4.91 mg/l after its completion, representing an 80% decrease in the SSC. Based on the available SSC data for the Paraná River at its confluence with the Paraguay River (Argentina), was computed the average SSC of 33.3 mg/l from 1990–1999 (AMSLER; DRAGO, 2009), a value 64% lower than the SSC in the 1971–1974 period (DRAGO; AMSLER, 1988). The authors concluded that the large reservoirs built during this period accounted for the decreased sediment load of the Upper Paraná River. As the present research assesses different periods and places, the results are not comparable, but they can be integrated. Herein, we affirm that there was a large decrease in the SSC from the periods 1984-1998 to 1999-2011 under conditions that were already exhibiting a reduction in SSC.

Seasonal pattern

Figure 12 shows the decrease in the SSC due to the presence of the dam, but it also presents the annual distribution of this reduction. The months of October, November and December have a strong relative decrease of the SSC. These data suggest that the Porto Primavera dam influences the temporal dynamics of the SSC, causing a time delay of the SSC transport. This phenomenon has not yet been reported in previous studies, mainly due to the lack of data. Similarly, the ecological effects of this SSC time delay are not known.

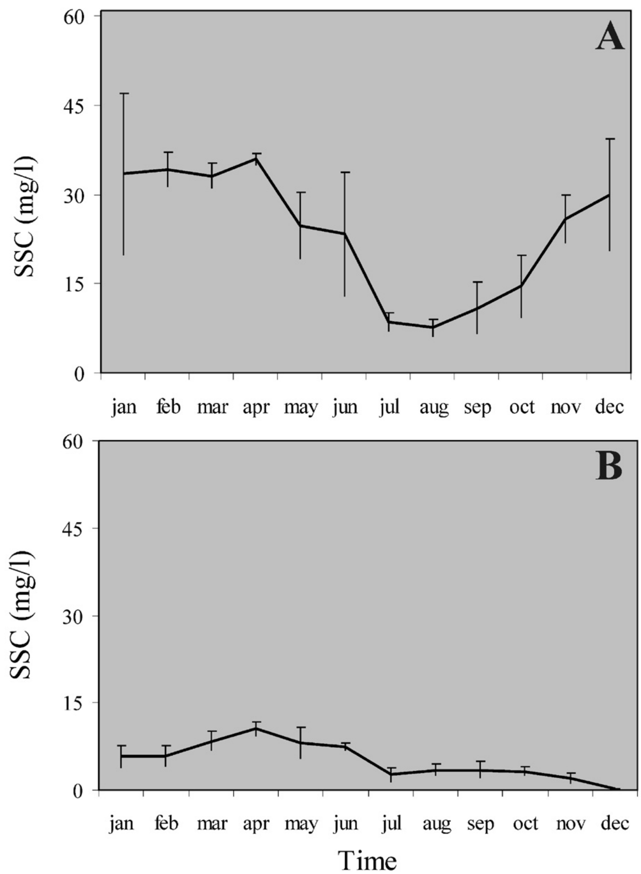

Figure 12 - Monthly average and standard deviation of the SSC for the UPR before (A) and after (B) the completion of the Porto Primavera dam

Atmospheric correction

A generalist atmospheric correction approach was employed in this research, and the atmospheric parameters varied mainly according the annual cycle. However, these parameters were approximated for the study area. Another characteristic that minimizes the influence of the atmosphere in the SSC estimate is the massive use of band ratios (models 2 and 3). Only on three dates, or 2.22% of the water conditions were optically dominated by inorganic particles, which were submitted to the model 1 for SSC estimate. As the model 1 has a direct correlation with reflectance in the red band, the provided estimates are more influenced by atmospheric uncertainty. Models 2 and 3 are based on a three-band ratio ([B4/B3]/B2), which makes them more resistant to precarious atmospheric data, such as the well-known effects of the band ratio in vegetation indices.

CONCLUSIONS

For water optically dominated by inorganic particles, the reflectance in the red band shows a linear relationship that is suitable for estimating the SSC. The single bands of the TM did not show a significant power relationship for clear water, but the band ratio among bands 2, 3 and 4 was appropriate, mainly before the Porto Primavera dam. This band ratio was not suitable for very clear water group, which led to the use of an adjustment factor for estimating the SSC at current very clear water conditions.

Responding to initial questions based on the presented data, we affirm that it was possible to observe the seasonal SSC pattern of the UPR and the effects of the Porto Primavera dam on the decrease in the SSC, through remote sensing estimates. Although the orbital estimation error was higher than that in the traditional laboratory procedure, the quantity of the retrieved SSC data was larger than in the existing SSC database, and their temporal distribution allowed for a better evaluation of the SSC dynamics. Therefore, the use of orbital estimates in this study area should be of interest to the scientific community. The quantity and temporal distribution of orbital-derived data represent great progress in studies investigating the anthropic influences in the UPR. Replicating the materials and methods reported, a large quantity of SSC data can be retrieved for the tributaries of the Paraná River, which are situated in an important agricultural area.

The research reported herein is one of the largest SSC data retrieval using Landsat data for the same location, with a large temporal scale and data quantity. The approach described herein can influence the paradigm of empirical models, which are not able to estimate water quality parameters for images and conditions other than those used for calibration (RITCHIE; SHIEBE, 2000). The method applied herein can be replicated anywhere in the world, but the empirical relationships should be developed considering the specificities of the optical properties of local water bodies.

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