Exploring the relationship between Landsat-8/OLI remote sensing reflectance and optically active components in the surface water at the UHE Maua/PR.

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Abstract. *The quality and quantity of water available for both economic growth and life sustainability is one of the major challenges for the sustainable development in the 21st century. This challenge requires research focused on the monitoring of time changes in water properties in several spatial scales. Satellite remote sensing has been applied as an alternative for providing information on optically active components, which act as indicators of water quality. Satellite remote sensing performance, however, varies from one aquatic system to another depending on several factors, such as size, depth, optical properties. This study, therefore, aims to explore the viability of applying remote sensing for monitoring the UHE Mauá reservoir, located in Paraná State. For that, an experiment was carried out to obtain water samples at 24 random samples distributed into the reservoir. Those samples were analyzed in laboratory and optically active components, namely, total suspended solids (TSS) and chlorophyll-a (Chl-a) concentration determined. Surface remote sensing reflectance provided by Landsat/OLI images almost concurrently to satellite overpass was computed for each sample in order to assess the best set of spectral bands and band combinations for estimating the concentrations of TSS and Chl-a. Results indicate that Chl-a was the optically active component spanning the widest range of variability in the Mauá reservoir and having the highest potential to be estimated using remote sensing OLI band 3 (green) explained more than 70 % in chlorophyll-a concentration.*

1. Introduction

Hydroelectrical reservoirs can be thought as an aquatic system with transient properties between rivers and lakes depending on the interplay between catchment basin geomorphology, hydrological regime and water withdraw demand. Roughly, reservoirs have a river-like zone at the entrance of the main river, a lotic zone near the dam, and a transition zone between them [Tundisi, J.G. and Matsumura-Tundisi, T. 2003]. Reservoirs water properties depend on the sources of pollution within the catchment basin, in which main sources of pollution are urban and industrial effluents and fertilizers from agriculture [Martinelli and Filoso 2008].

A new generation of satellites, including Landsat/OLI, with improved radiometric resolution and signal-to-noise ratio (SNR) has opened the opportunity for the development of remote sensing products such as total suspended solid and chlorophyll-a concentration which can be used into water quality models [Dorji and Fearns 2017; Dornhofer et al 2016; Sander de Carvalho et al. 2015; Palmer et al 2015]. Several studies have also reported successful application of satellite images for assessing gold mining impacts on water silting of Tapajós River tributaries [Lobo, et al. 2016]. There has been a great deal of scientific and methodological advances in the impact of the optically active components (OAC) on the water and on the measurements of inherent optical properties and on their implications for the application of satellite images in water studies [Verpoorte 2014; Hambright 2014; Giardino et al. 2014; Olmanson, et al. 2013; Roessler, et al. 2013; McCullough et al. 2012; Nas et al. 2008; Simis et al. 2005].

Both, chlorophyll-a (Chl-a) and total suspended solids (TSS) concentration in the water are biological and physical parameters currently in use to assess water quality. Chlorophyll-a concentration usually is used as proxy of phytoplankton abundance, since it is a photosynthesizer pigment common to all species [Reynolds 1984]. Chl-a absorption bands in 438 nm and 676 nm are responsible for changes in water color, causing an increase in the green reflectance as the pigment concentration giving similar boundary conditions of the aquatic system [Weaver and Wrigley 1994]. TSS concentration is defined as a set of suspended particles smaller than 45 μm, being generally dominated by inorganic matter, which is responsible for a monotonic increase in the reflectance with the increase in concentration [Mobley 1994]. Another peculiar aspect of the TSS spectral reflectance is the continuous shift of the reflectance towards longer wavelengths as the concentration increases [Curran and Novo 1988].

This research contributes towards transforming satellite images in operational tools for monitoring the water quality of the UHE Mauá reservoir. For that, the authors carried out an experiment at the reservoir in order to assess the relationship between remote sensing reflectance (Rrs) measured with Landsat/ OLI images and the concentrations of TSS and Chl-a, through the analysis of correlation and linear regression. This exploratory analysis is the first step towards assessing the viability of using those images for controlling Mauá reservoir water quality.

2. Study Area

The study area - UHE Mauá/PR Reservoir (Figure 1), is located on the Tibagi River basin, upstream of Salto Maua and belongs to the Telêmaco Borba and Ortigueira municipalities, Paraná State. It is a relatively new reservoir which started operating in December, 2012. Tibagi basin land cover was originally composed of different forest types but much of that has been changed to a mixture of extensive pastures with larger or smaller remnants of forest and forest regrowth [Lactec 2009]. Basin natural setting and human impact on the vegetation is a key aspect in the state of degradation of the remaining forest and of the soil organic matter, mainly in the floodplains. The current catchment basin setting is highly threatening to the water quality of the Mauá reservoir which receives and processes the basin output.

Londrina city meets 100 % of this urban population water supply system relying on two systems, one of them, the Tibagi River which contributes to the UHE Mauá with a total of 4.500 m³/h of total [PMSB 2008]. It is the largest center surrounded by a cluster of industrialized cities which responds for more than 50 % of the domestic and industrial waste. In addition to that, agricultural land uses respond for high volumes of pesticides and fertilizers representing an important source of non-point pollution to the reservoir mainly in areas of soybean and Pinus [Pereira and Scroccaro 2010].

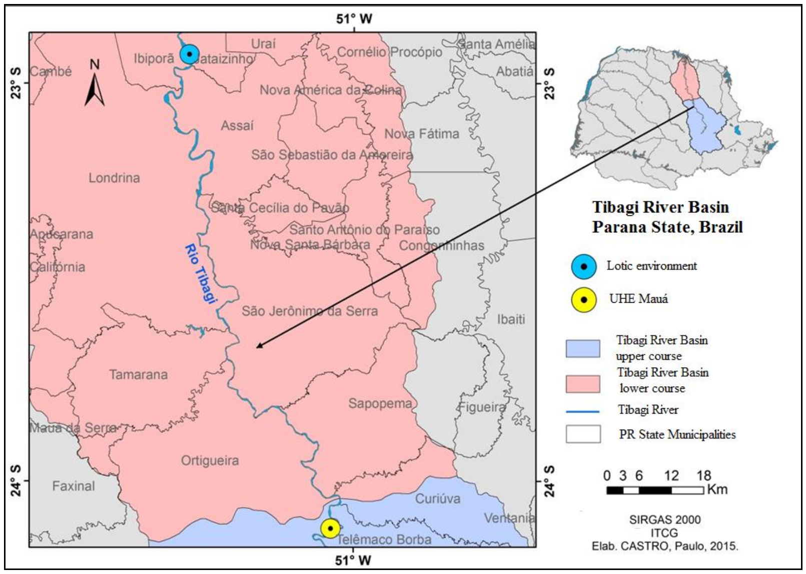

Figure 1. Study area

3. Data acquisition and methods

3.1 Ground data acquisition

Ground data acquisition at Mauá/PR was carried out in July, 9th, 2016, during the dry season, at Secchi Depth (m). In this study, the authors focused only on Chl-a, TSS and Turbidity. Data on weather condition, sampling time, GPS location at each sampling station were also acquired.

The authors adopted a systematic sampling design for convenience (not probabilistic). The reservoir was first stratified into regions according to the rates of time changes in water spectra assessed with OLI images acquired in the previous year. The number of sample stations decreased from the areas with high spectral variability in time to areas characterized by small spectral variability in time [Thompson 2002; Pereira 2015; 2008]. The sampling strata were established as concentric 500 m bands relative to the reservoir central area [Castro 2017]. A total of 24 sampling stations was distributed in the UHE Mauá reservoir (Figure 2). Data collection was carried out between 9:00 am and 14:00 pm with clear skies and weak winds. Data acquisition in each sampling site lasted in average 5 minutes.

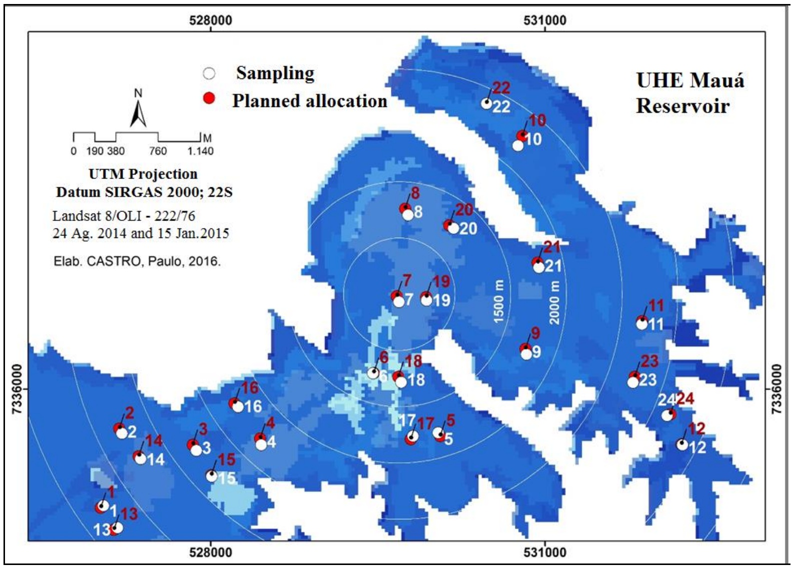

Figure 2. Sampling design and sampling station distribution

Logistical constraints prevented *in situ* data collection concurrently to satellite data acquisition. Therefore, Landsat/OLI images were acquired quasi-simultaneously to ground data, on July, 12th, 2016, with a delay of 3 days in relation to ground data acquisition. During the ground mission, Van Dorn bottle stopped working causing water samples at some of the stations to be collected at 30 cm.

Water samples were preserved and immediately taken to the laboratory for component determination. Turbidity was measured on site. Table 1 summarizes the methods and equipment used for water samples processing.

Table 1. Method and equipment used for determination of Mauá Reservoir limnological properties in the present study.

VARIABLE	REF. APHA, AWWA, WEF (2012)	METHOD	EQUIPMENT(MODEL/TRADE NAME)
Chlorophyll-*a* **(µg L^{-1})**	10200 H	Spectrofotometer with extraction in acetone 90%	Spectrofotometer: Macherey– Nagel – MN Nanocolor vis 919150
Solids **(mg L^{-1})**	2540 B, C, D e E	Gravimetric determination	Membranes 1,2 Mufla 550º C: FORNITEC 1940 Stove 103º C: LUFERCO
Temperature (°C)	2550 B	Electronic Thermometer	Hach HQ 30d
Turbidity **(NTU)**	2130 B	Nefolometric Method	Hach 2100Q

3.2 Remote sensing data processing

Landsat/OLI images were acquired at [https://earthexplorer.usgs.gov] as orthorectified surface reflectance (Table 2).

Table 2. Landsat/OLI data

BANDS	WAVELENGTH RANGES (nm)
1	430 – 450
2	450 – 510
3	530 – 590
4	640 – 690
5	850 – 880
6	1,570 – 1,650
7	2,110 – 2,290

The 24 ground sampling stations were located on the images using their UTM coordinates. The samples were examined with the aid of color composites to assess image quality regarding adjacent effects derived from cloud cover scattering, cloud shadow, among others.

After this careful screening, three samples were discarded (stations 1, 2 and 13) due to poor image quality around the stations. The remote sensing reflectance (Rrs) of the average of 3 x 3 pixels around the sample station was acquired and submitted to an exploratory analysis described in the next section.

3.3 Exploratory Analysis

The exploratory analysis consisted of plotting all *in situ* variables against the Rrs in diagnostic bands and combination of bands recommended in the literature [Gitelson et al., 1986; Mittenzwey and Gitelson, 1988; Mittenzwey et al., 1992; Gitelson, 1992; Gitelson, 1993; Dekker 1993; Dekker and Peters, 1993; Kirk 1994; Gitelson et al., 1995; Rundquist 1996; Schalles and Yacobi, 2000]. Chl-a concentration, for instance, was plotted against the reflectance at the band corresponding to the scatter by phytoplankton cells in the visible spectra, the green region (B3). TSS and Turbidity were plotted against the red and near-infrared bands (B4 e B5). The exploratory analysis allowed to distinguish the existence of at least two optically distinct water masses in the reservoir during the dry season.

3.4 Correlation Analysis

Based on the exploratory analysis, sample stations were divided into distinct water masses and then submitted to linear correlation analyses between the limnological variables and the Rrs. Before selecting the best set of OLI bands and combination of bands as input to empirical models, the authors set a threshold such that coefficient of explanation, $R^2 \geq 0,70$ and p - value $\leq 0,01$.

4. Results

In situ data (Table 3) indicates that Chl-a was the optically active component spanning the widest range of variability in the Mauá reservoir, with the maximum concentration reaching around 5 times the minimum, being responsible for the optically distinct water masses.

Table 3. Limnological variable statistics

Limnological Variables	Mean	Median	Maximum	Minimum	Standard Deviation	Coefficient of Variation
Chorophyll-a (µg/L)	9,68	7,09	20,91	3,89	5,62	58,0%
TSS (mg/L)	1,74	1,80	2,50	0,10	0,55	31,6%
Turbidity (NTU)	6,80	6,84	7,25	5,99	0,35	5,1%
Secchi (m)	1,05	1,05	1,20	0,80	0,10	9,5%

It was observed in exploratory and correlation analyses the occurrence of two distinct patterns, the first named cluster 1 where the increased concentration of chlorophyll-a corresponds to a discrete increase in reflectance in the green; and a second pattern, cluster 2 where water reflectance increases as the concentration of chlorophyll-a decreases. Such distinct patterns suggest that there are water bodies with distinct optical behavior. A new exploratory analysis was carried out for samples in each cluster and the possible outliers excluded from the analyses (6 points). Therefore, the subsequent analyses were carried out for each cluster independently free from spurious measurements.

Despite the limited number of samples remaining for analyses (cluster 1, n = 5 and cluster 2, n = 10) there was a reasonable increase in R^2 value for cluster 2 (R^2= 0,73). For cluster 1, however, these steps did not work out. Table 4 shows the limnological variables concentration for cluster 2 and Figure 3 presents the dispersion pattern of B3 reflectance in relation to chlorophyll-a concentration. Figure 3 results suggests that B3 has potential for monitoring chlorophyll-a variability in the Mauá reservoir since changes in reflectance explains more than 70% of the variability in chlorophyll-a concentration (that is to say, that chlorophyll-a concentration variation causes a decrease in B3 reflectance) ($R^2 \geq 0{,}70$ and $p - \text{value} \leq 0{,}01$).

Table 4. Sample points, *cluster* 2, n = 10

Sample Points	Secchi (m)	Turbidity (NTU)	TSS (mg/L)	Chlorophyll-a (µg/L)	Temperature (°C)	Collection time	Sky conditions	Wind Wave
3	1,05	7,24	1,90	6,12	20,6	12:40	Sun	weak / without wave
10	1,10	6,57	1,70	10,65	18,3	13:44	Sun	weak / without wave
11	1,00	6,70	1,40	7,14	19,9	14:03	Sun	weak / without wave
12	1,05	6,83	1,90	4,75	19,9	12:55	Sun	weak / without wave
14	1,10	7,08	1,90	7,10	19,5	12:49	Sun	weak / without wave
19	1,10	7,07	2,50	12,83	18,7	10:59	Sun	weak / without wave
20	1,05	6,66	1,30	14,07	18	10:20	Sun	weak / without wave
22	1,20	6,63	1,70	10,73	18,8	09:36	Sun	weak / without wave
23	1,20	6,23	1,60	4,53	20,3	13:52	Sun	weak / without wave
24	1,20	6,62	0,10	3,89	20,1	13:59	Sun	weak / without wave

Table 4 shows that the points belonging to cluster 2 have similar limnological characteristics, specially in relation to the optical data.

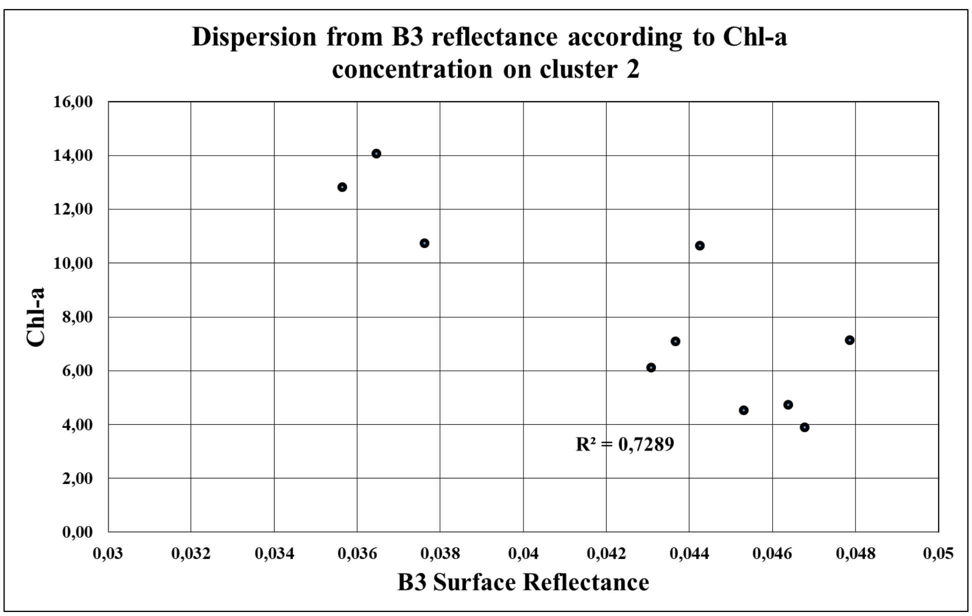

Figure 3. Dispersion from Band 3/OLI Reflectance according to Chlorophyll-a concentration, *cluster* 2, n = 10

Pearson linear correlation analysis results for cluster 2 for all OLI bands (table 5) show that despite the limited number of samples and the delay between ground data and image acquisitions, all OLI bands are highly correlated with chlorophyll-a concentration, but only bands 3 and 4 meet authors requirements.

Table 5. Linear Correlation Analysis between Bands/OLI and data collected *in situ* - Pearson Correlation and *p-value*

Bands	Chl-a
B1	-0,794 0,006
B2	-0,806 0,005
B3	*-0,854* 0,002
B4	-0,845 0,002
B6	-0,763 0,010

Pearson linear correlation analysis (Table 6) shows that band combinations did not outperformed the use of Band 3. Despite de limited number of samples, all the correlations are significant (p-value < 0,01), but the proportion of variance 'explained' by any model based on those bands would not meet authors requirement ($R^2 \geq 0,70$).

Table 6. Linear Correlation Analysis between /OLI bands combination and in situ Chl-a (Pearson Correlation and *p-value) – Cluster 2*

Bands Combinations	Chl-a
B3/B4	0,801 0,005
B5/B4	-0,768 0,009
B4/B3	-0,797 0,006
(B3-B4)/(B3+B4)	0,799 0,006
(B3-B5)/(B3+B5)	0,770 0,009
B4/B2	0,840 0,002
B2/B3	-0,798 0,006

5. Discussions

Despite the experimental limitations due to the limited number of samples, problems with the Van Dorn bottle and delay between in situ data collection and OLI image acquisition, the results show that the green reflectance (B3) can be used to monitor chlorophyll-a concentration in the UHE Mauá Reservoir. It is important, however, to highlight that more experiments are needed in order to cover a wider range of chlorophyll-a concentration and also the information on the vertical distribution of chlorophyll-a concentration in the water column as pointed out by Barbosa et al. 2016.

It is important to highlight, however, that B3 performance might be an artifact of the explanatory analyses used to split the clusters. This aspect should be investigated further in the next steps of this research as well.

6. Conclusions

The exploratory and linear correlation analyses indicated that Landsat/OLI band 3 can be applied to estimate chlorophyll-a concentration in the Mauá reservoir. Due to the small sample size, however, it is highly recommended that more experiments be carried out in different seasons and using different sampling designs before satellite images can be used operationally. The exploratory analyses proved to be quite useful to identify the existence of optically distinct water masses in the Mauá Reservoir, which should be taken into account in the monitoring of this reservoir.

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