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Cyanobacteria detection in Guarapiranga Reservoir (São Paulo State, Brazil) using Landsat TM and ETM$^+$ images

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ABSTRACT

Algae bloom is one of the major consequences of the eutrophication of aquatic systems, including algae capable of producing toxic substances. Among these are several species of cyanobacteria, also known as blue-green algae, that have the capacity to adapt themselves to changes in the water column. Thus, the horizontal distribution of cyanobacteria harmful algae blooms (CHABs) is essential, not only to the environment, but also for public health. The use of remote sensing techniques for mapping CHABs has been explored by means of bio-optical modeling of phycocyanin (PC), a unique inland waters cyanobacteria pigment. However, due to the small number of sensors with a spectral band of the PC absorption feature, it is difficult to develop semi-analytical models. This study evaluated the use of an empirical model to identify CHABs using TM and ETM$^+$ sensors aboard Landsat 5 and 7 satellites. Five images were acquired for applying the model. Besides the images, data was also collected in the Guarapiranga Reservoir, in São Paulo Metropolitan Region, regarding the cyanobacteria cell count (cells/mL), which was used as an indicator of CHABs biomass. When model values were analyzed excluding calibration factors for temperate lakes, they showed a medium correlation (R^2=0.81, p=0.036), while when the factors were included the model showed a high correlation (R^2=0.96, p=0.003) to the cyanobacteria cell count. The empirical model analyzed proved useful as an important tool for policy makers, since it provided information regarding the horizontal distribution of CHABs which could not be acquired from traditional monitoring techniques.

Keywords: phytoplankton, water quality, environmental health, satellite imagery.

Detecção de cianobactérias no reservatório de Guarapiranga (Estado de São Paulo, Brasil) utilizando imagens Landsat TM e ETM$^+$

RESUMO

A eutrofização em sistemas aquáticos possui como uma de suas consequências as florações de algas, entre elas as algas com a capacidade de produzir toxinas. Dentre elas, algumas espécies de cianobactérias, também conhecidas como algas azul-esverdeadas, se destacam devido ao seu poder de adaptação na coluna da água. Dessa forma, a distribuição horizontal de suas florações é essencial, não apenas para o meio ambiente, mas também para a saúde pública. A utilização do sensoriamento remoto para o mapeamento dessas florações tem sido explorada por meio da modelagem bio-óptica da ficocianina, um pigmento único das cianobactérias de águas interiores. Entretanto, o baixo número de sensores com a banda espectral da absorção da ficociana dificulta o desenvolvimento de modelos semi-analíticos. O trabalho avaliou a utilização de um modelo empírico para a identificação qualitativa de florações de cianobactérias utilizando os sensores TM e ETM$^+$ a bordo dos satélites Landsat 5 e 7. Cinco imagens foram adquiridas para a aplicação do modelo. Além das imagens foram utilizados dados coletados no reservatório de Guarapiranga, na região metropolitana de São Paulo, da contagem de cianobactéria (cel/mL), que foi utilizada como indicador de biomassa de cianobactéria. A análise dos valores do modelo sem a utilização dos fatores de calibração proposta para um lago temperado teve uma média correlação (R^2=0.81, p=0.036) já com a utilização dos mesmos fatores de calibração houve uma alta correlação com os valores da contagem de cianobactérias (R^2=0.96, p=0.003). O modelo empírico analisado mostrou-se capaz de ser utilizado como uma importante ferramenta para os tomadores de decisão, uma vez que fornece uma informação da distribuição horizontal das florações, que não pode ser obtida por meio das técnicas tradicionais de monitoramento.

Palavras chaves: fitoplancton, qualidade da água, saúde ambiental, imagens de satélite.

1. INTRODUCTION

River damming is a well-known process in the neo-tropical regions mainly due to its electricity generating potential, but also for its other uses such as leisure, navigation, fisheries and water supply (Tundisi et al., 2008). Unfortunately, damming usually causes ecological damage due to the changes in the natural state of the environment. Thus, this manmade aquatic system has its own hydrodynamic structure, which not only affects its water column's vertical and horizontal processes, but also its water quality (Tundisi et al., 2004) and biota distribution. However, changes in the water column structure are not the only factors responsible for the environmental impacts on the aquatic system. Other anthropogenic factors, such as the introduction of exotic species, watershed land cover and wastewater input also contribute to the degradation of the aquatic environment (Agostinho et al., 2008). Moreover, because of the irresponsible uses of water, mainly in urbanized regions, issues such as deforestation, loss of green areas, increased toxicity, accelerated eutrophication and changes in biodiversity lead to the deterioration of water quality (Straskraba and Tundisi, 1999). All of these problems are consequences of the lack of an adequate system of water governance, which negatively impacts the environment and human health (Tundisi, 2008).

Accelerated eutrophication of aquatic systems occurs because of the water's enrichment with vegetation nutrients (mainly nitrogen and phosphorus) and other pollutants (Mudroch, 1999). This process has been noticed worldwide and has been a concern for environmental and public health managers as well as for policy makers because it is very widespread, especially in regions that are rapidly urbaning. For Azevedo et al. (2002), water bodies located in regions where waste water treatment does not keep pace with the speed of urban growth are more vulnerable to eutrophication. The occurrence of algae blooms are one of the main problems associated with this process, to include Harmful Algae Blooms (HABs) (Mudroch, 1999), which are a serious issue because of their capacity to produce toxins (Chorus and Bartram, 1999),

Cyanobacteria (or cyanophyta) is one of the most common phylum that occurs during algae blooms. Due to its color, it is also known as "blue-green algae". Many of the cyanobateria species are potentially toxic and thus are often present in HABs (Carmichael, 2001). Therefore, the cyanobacteria HABs (CHABs) contribute to aesthetic problems, impairs recreational use and has been responsible for the development of foul tastes and odors in water supplies (Bartram et al., 1999). In addition to these impacts, freshwater CHABs have been receiving increased attention due to their ability to produce toxins in aquatic systems used by humans (Falconer and Humpage, 2006). These toxins, also known as cyanotoxins, have been studied because of well-described and published incidents of animal poisoning. The first academic report of animal poisoning and death by CHABs was found in Francis (1878). Human poisoning attributed to CHABs toxins has been reported in Australia and the UK. It occurred after ingestion of contaminated drinking water and individual exposure to toxins by swimming and canoeing (Chorus and Bartram, 1999). Nevertheless, it is difficult to confirm human deaths by oral consumption of cyanotoxins, since food and water suppliers avoid testing for their presence. However, the first documented human deaths from a type of cyanotoxin called “hepatotoxin” occurred following intravenous exposure in a dialysis clinic in the city of Caruaru, Brazil, in 1996 (Carmichael et al., 2001). This outbreak was reported worldwide, drawing the attention of the media and public health authorities. Since this incident, monitoring of CHABs has become an important task for environmental and health managers.

However, the monitoring of CHABs is difficult since they vary in space and time. Traditional monitoring methods are based on water sampling and laboratory analysis and have been used to quantify cyanobacteria. Nevertheless, its spatial and temporal resolutions are often insufficient to monitor cyanobacteria biomass, especially during bloom conditions (Agha et al., 2012). Further, they are expensive, time consuming and the characteristics of their spatial and temporal heterogeneity are inadequate for monitoring large study areas (Gons, 1999). Remote sensing techniques are capable of overcoming these limitations (Prado et al., 2007). Gons (1999) observed that the use of remote sensing techniques was a time saving, cost-effective, and scientifically rewarding alternative. Accordingly, diverse studies have been using remote sensing to identify and quantify CHABs in inland waters. Initially remote sensing studies of CHABs used chlorophyll-*a* (chl-*a*) as an estimator of CHABs biomass (Reinart and Kutser, 2006). Recent studies have been using a unique pigment of cyanobacteria in inland water, the phycocyanin (PC), to estimate CHABs biomass through remote sensing techniques (Dekker, 1993; Schalles and Yacobi, 2000; Simis et al., 2005; 2007; Ruiz-Verdú et al., 2008).

São Paulo Metropolitan Region (RMSP) is one of the most important financial, commercial and industrial centers in Brazil. The rapid urbanization and population growth in the last 50 years has exceeded the provision of adequate sanitation (Beyruth, 2000). The consequence of this has been an accelerated eutrophication process, mainly in urban reservoirs, which affects the quality of their water. One of the main water supply reservoirs in RMSP is the Guarapiranga Reservoir that usually becomes infested with at least 48 different species of cyanobacteria (Sant'anna et al., 2007). This study explored the use of remote sensing techniques in order to identify and spatialize the CHABs in the Guarapiranga Reservoir. An empirical algorithm presented by Vincent et al. (2004) was applied in order to identify CHABs, which was validated by a cyanobacteria cell count from this tropical urban reservoir.

1.1. Remote sensing of water quality

Remote sensing of water quality is conducted optically, which enables the spatiotemporally comprehensive assessment of water quality parameters. Absorption, scattering and attenuation properties of a water body are thereby determined through the analysis of datasets of the visible domain of the solar reflective spectrum. Such optical properties allow the estimation of primary production, turbidity, eutrophication, particulate and dissolved carbon contents, or the assessment of currents and algae blooms (IOCCG, 2008).

Due to the dependence on optical properties of water, aquatic systems have been classified in a bipartite scheme: case 1 and case 2 (Gordon and Morel, 1983). Case 1 refers to waters whose optical properties are dominated by phytoplankton and associated organic substances which co-vary to phytoplankton. Case 2 waters, on the other hand, may consist of a variety of independently mixed constituents, and have been called “optically complex” (Sun et al., 2009). Thus, for remote sensing purposes, the generic water constituent types are replaced by the three optically functional types: chl-*a*, non algal particles (NAP) and colored dissolved organic matter (CDOM).

One of the first studies of hydrologic optics on ocean waters was conducted by Gordon et al. (1975), and its importance has been enhanced since it became the first bio-optical ocean model. The study utilized a Monte Carlo simulation of the radiative transfer equation to relate the apparent optical properties (AOPs) to the inherent optical properties (IOPs) in oceanic waters containing optically active components (OAC), molecular water and chl-*a*. For inland waters, the first bio-optical model that related the AOPs to its IOPs was developed for Lake Ontario, Canada also using a Monte Carlo simulation of the radiative transfer equation and non-linear multivariate optimization analyses (Bukata et al., 1979).

Since these two studies, the development of empirical and semi-empirical bio-optical models to extract biological activity from remotely sensed data has been proposed. Some models were developed to retrieve PC concentrations. Ogashawara et al. (2013) evaluated the performance of a semi-empirical algorithms to estimate PC such as: baseline algorithm (DE93) (Dekker, 1993), a single reflectance band ratio algorithm (SC00) (Schalles and Yacobi, 2000), a nested semi-empirical band ratio algorithm (SI05) (Simis et al., 2005), a new single reflectance band ratio algorithm (MI09) (Mishra et al., 2009) and a three band algorithm (HU10) (Hunter et al., 2010). Thus, most of the research has been exploiting the PC absorption feature between 615 and 630 nm to develop empirical and semi-analytical models to detect presence of CHABs in water bodies. Nevertheless, few orbital sensors have a spectral band located at 620 nm to be used in the bio-optical models. Thus, Vincent et al. (2004) proposed an empirical algorithm using Landsat TM and ETM$^+$ spectral bands to estimate PC concentration with an accuracy of 26%.

2. MATERIAL AND METHODS

2.1. Study site

The study was conducted in the RMSP during 2009. The climatologic data were collected by the meteorological station of the Institute of Astronomy, Geophysics and Atmospheric Sciences at the University of São Paulo (IAG/USP) located in the “Parque das Fontes do Ipiranga”, Southern Region, Água Funda, São Paulo – SP. Geographically, the meteorological station area corresponds to latitude 23° 39'S and longitude 46° 37'W. To the south are the reservoirs of Billings and Guarapiranga, which are responsible for supplying water to the RMSP. According to Morais et al. (2010), the maximum depths of each reservoir are 25 and 13 m, respectively, and are thus considered to be shallow reservoirs.

All of the analysis was conducted at Guarapiranga Reservoir (Figure 1), with an area of 33km^2 and an estimated volume of $194 \cdot 10^6$ m^3. It is located in the city of São Paulo, in an area that belongs to the Companhia de Saneamento Básico do Estado de São Paulo (SABESP, 2012), which is responsible for drinking water treatment and distribution in the RMSP. The study site is in a tropical climate characterized by a wet summer and a cold and dry winter; the average air temperature is 20°C with a annual precipitation of 1355 mm

(EMBRAPA, 2014).This reservoir is used to supply drinking water for a population of approximately 6 million people (Mierzwa et al., 2012). Although it is important to the water supply of RMSP, water quality is monitored at only three sample points (Figure 1) no more than three times a week by traditional methods, which is insufficient to reveal the horizontal distribution of CHABs.

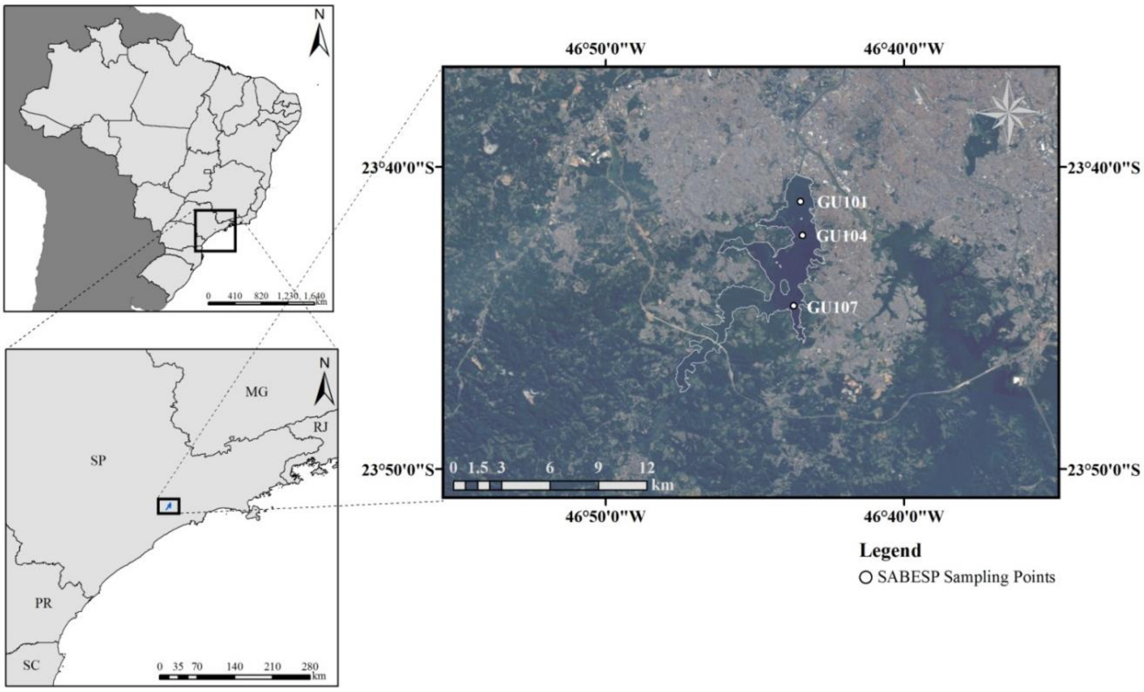

Figure 1. Guarapiranga Reservoir location in São Paulo State.

2.2. Remote Sensing Data

The remote sensing data used in this research were multi-temporal datasets from Landsat 5 and Landsat 7 (USGS, 2006a; 2006b; 2006c) satellites. We used cloud-free images acquired between January 2009 and June 2011 (Table 1). The Landsat Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper Plus (ETM^+) datasets have a 30 meter spatial resolution in their multispectral bands that cover portions ranging from blue to mid-infrared regions of the electromagnetic spectrum.

The Landsat data were acquired from United States Geological Service (USGS) online database. The images used in this study cover an area measuring 180 km x 170 km and their position is defined by the Worldwide Reference System (WRS) of path (ground track parallel) and row (latitude parallel) coordinates (276/076) (Arvidson et al., 2006).

Table 1. Remote Sensing data used (satellite, sensor system, date, and year).

Satellite	Sensor	Year	Date
Landsat 7	ETM^+	2009	March 6th
Landsat 5	TM	2010	April 18th
Landsat 5	TM	2010	August 24th
Landsat 5	TM	2011	April 21st
Landsat 5	TM	2011	May 23rd

2.3. Limnological Data

Water samples were collected three times a week by SABESP to calculate cyanobacteria density. The samples were taken from the surface at three different locations (Figure 1) in Guarapiranga Reservoir: water entrance (GU 101), middle of the reservoir (GU 104), and the entrance of the Parelheiros River (GU 107). The period analyzed was from January 1st, 2009 to May 31st, 2011.

The analysis of cyanobacteria density uses the processes described by the Technical Note L5.303 (CETESB, 2005). The samples were preserved with Lugol's iodine and the cell count for cyanobacteria strains was conducted using a Whipple grid eyepiece with a Sedgwick-Rafter chamber. The first one was used as an auxiliary tool in order to limit the area for cell counting. The chamber was used to place the sample and it was also used to determine the area used for determining the counting factor (Equation 1):

$$F = \frac{A}{a} \tag{1}$$

where:

F = counting factor;

A = chamber's area; and

a = analyzed area (Whipple grid)

The counting factor was used to calculate the volume of cyanobacteria by multiplying it by the number of cells found in the Whipple grid area. This operation gave the number of cells in 1 cm³ of sample preserved with Lugol's iodine

2.4. Radiometric Transformation

LANDSAT 7 ETM$^+$ and LANDSAT 5 TM data were processed using the ENVI 4.8 image processing software from ITT Solutions. Each image was processed using the mask of Guarapiranga Reservoir. The images were converted in spectral radiance according to Equation 2 (Chander et al., 2009).

$$L_\lambda = \left(\frac{LMAX_\lambda - LMIN_\lambda}{Q_{calmax} - Q_{calmin}}\right)(Q_{cal} - Q_{calmin}) + LMIN_\lambda \tag{2}$$

where:

$L\lambda$ = Spectral radiance from each band [W/(m² sr µm)];

Q_{cal} = Pixel value after atmospheric correction [Digital Number (DN)];

Q_{calmin}= Minimum value of the pixel to be calibrated [ND];

Q_{calmax} = Maximum value of the pixel to be calibrated [ND]; $LMIN_\lambda$ and

$LMAX_\lambda$ = Spectral radiance parameters for each band [W/(m² sr µm)].

Following the proposed method of Vincent et al. (2004) a dark object subtraction (DOS), proposed by Chavez Jr. (1988), was applied to each band for atmospheric correction. This procedure assumes the existence of dark objects (zero or small surface reflectance) throughout a Landsat TM image. The minimum DN value in the histogram from the entire image is thus attributed to the effect of the atmosphere and is subtracted from all pixels. While the atmospheric correction of satellite water color imagery in sediment-laden and algal bloom waters remains a challenge (Singh and Shanmugan, 2014) due to the inefficiency of present methods to accurately assess aerosol radiances in the near-infrared (NIR) bands and extrapolate these into the visible spectrum, the use of DOS was considered sufficient for our purpose of identifying CHABs.

The spectral radiance detected by the i^{th} spectral band sensor can be approximated by Equation 3 (Vincent et al., 2004):

$$L'_i = (L_i - \beta_i) \tag{3}$$

where:

L'_i = Dark object subtracted radiance [W/(m² sr μm)];

L_i = Spectral radiance from i^{th} band [W/(m² sr μm)];

β_i= minimum value of dark object [DN].

2.5. Bio-optical empirical modeling of phycocyanin

The empirical bio-optical model proposed by Vincent et al. (2004) is based on band ratio among the dark object subtracted radiances from equation 3. The empirical model is then based on 6 band ratios organized according to Equation 4.

$$PC \approx \left[A - \big(B(R31)\big) + \ (C(R41) - \big(D(R43)\big) - \big(E\ (R53)\big) + \big(F(R73)\big) - \ (G(R74))\right] \tag{4}$$

where:

PC = phycocyanin concentration (μg/L);

R_{ij} = spectral ratio among dark object subtracted radiances from band i and

j and A, B, C, D, E, F and G are calibration factors.

To validate the PC estimation from Landsat TM and ETM^+ images, a linear regression analysis between the estimated PC concentration and the cyanobacteria cell count was conducted that should be considered as a proxy for PC concentrations or CHABs biomass. The empirical modeling of PC was used not to quantify the PC concentration in the reservoir, but to identify the main spots of CHABs in Guarapiranga Reservoir. Although it is a qualitative analysis, the horizontal distribution of CHABs can be useful for strategic decisions such as determining the location of water intakes.

3. RESULTS AND DISCUSSION

Figure 2 showed the spectral profile of reflectance at the top of the atmosphere for TM and ETM^+ bands 1, 3 4, 5 and 7, used in this study. Each spectrum corresponds to the pixel over the SABESP' station GU104; colors represent cyanobacteria's cell count as follows: red (23450 cells/ml), orange (5765 cells/ml), yellow (3615 cells/ml), green (2510 cells/ml), and blue (1282 cells/ml).

The five spectra showed the same pattern with a high reflectance in the blue region and an absorption in the others, mainly due to pure water absorption spectra. However, it is interesting to note that the absolute slope between band 1 and band 3 is higher (0.00023) for the spectrum with highest cyanobacteria density and lower (0.00011) for the spectrum with the lowest cyanobacteria density.

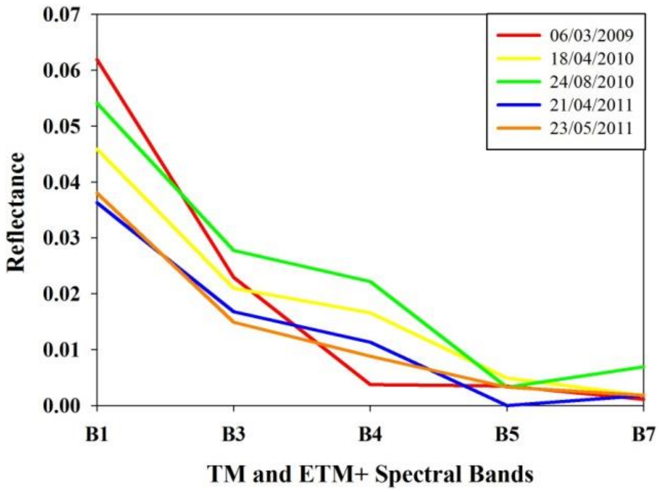

Figure 2. Reflectance spectra of GU104 station for the Landsat data used in this study.

When applying the relationships without the factors proposed by Vincent et al. (2004) (Equation 4) to the series of Landsat images listed above, we notice a medium relation (R^2=0.81, p=0.036) between the empirical algorithm values and cyanobacteria cell count (Figure 3a), which was used as a CHABs indicator as described by Mishra et al. (2009). However, if we applied the factors proposed by Vincent et al. (2004), the relationship between cell count and empirical algorithm values increased to an R^2 of 0.96 (p=0.003). Figure 3b shows the scatter plot of this relationship.

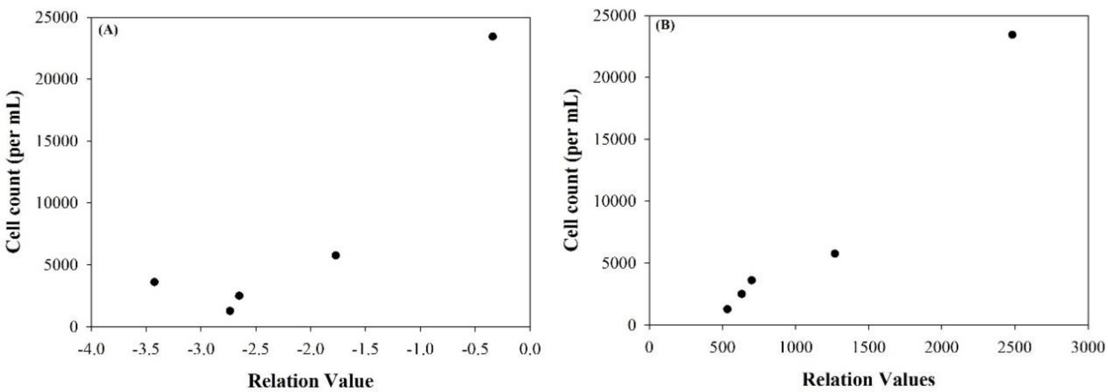

Figure 3. Scatter plot of cyanobacteria cell count and empirical algorithm values (A) without factors; (B) with factors.

According to the analysis of both applications of the empirical algorithm proposed by Vincent et al. (2004), we notice that a CHAB occurred on March 6, 2009. In this image it can be observed an extensive spatial distribution with high values of the empirical algorithm horizontally distributed. Figure 4 shows the Landsat image of March 6, 2009, with the empirical algorithm factors of Vincent et al. (2004) applied. The biological analysis of the cyanobacteria cell count for this day at the same point was 23450 cells per mL. This value is considered high since, according to Brazilian Resolution 357 from the National Environment Council (Brasil, 2005), the maximum cell count of cyanobacteria allowed for a water supply reservoir is 20000 cells per mL.

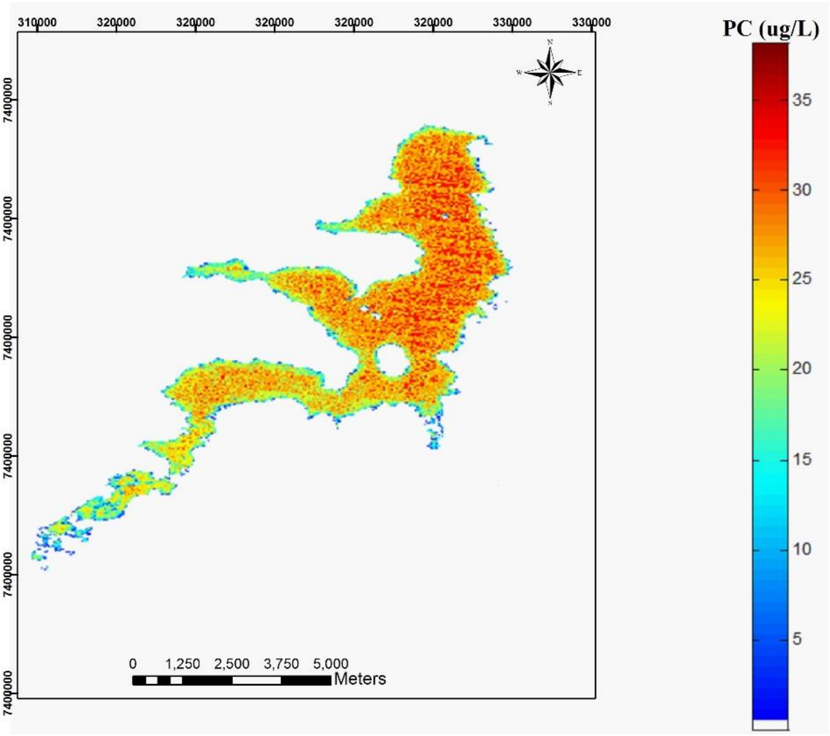

Figure 4. PC quantification from the application of the empirical algorithm in the remote sensing data.

The occurrence of CHAB on this date can be explained by the relationship between phytoplankton succession and meteorological factors over the RMSP (Morais et al., 2010). This relationship is based on a study conducted by Tundisi et al. (2004) stating that in a shallow reservoir the water quality as well as algae blooms are related to mixing and stratification processes in the water column. They also identify that *Microcystis* sp blooms can occur during the stratification process. In a recent study, Tundisi et al. (2010) proposed a model to forecast algae blooms based on the stability of the water column during the passing of cold fronts in tropical shallow reservoirs. Ogashawara et al. (2014) identified that on March 6, 2009 there was a western current acting over the RMSP. According to the authors, this western current occurred after the passing of a Polar Atlantic Front. This sequence of events (cold front passing and western current) was determinant to the occurrence of the cyanobacteria bloom since during this period there was an occurrence of a stratification process in the water column of the Guarapiranga Reservoir. Thus, combining the results presented by Ogashawara et al. (2014) and the information derived from the image used in this study, it is possible to infer the validation of the model proposed by Tundisi et al. (2010), which defined the period of cold front dissipation as the "beginning of a new cycle of stability with the increase of light and nutrients in the stable layer" and suggested that a consequence was the "beginning of cyanobacterial growth".

The spatial distribution of CHAB showed that the areas prone to algal bloom occurrence were near the water intake and in the middle of Guarapiranga Reservoir. This region was described as a priority area for water treatment in the second largest water system of RMSP (SABESP, 2012). This area is also important due to its recreational use for aquatic sports; there is therefore a high concentration of marinas and bathing beaches. Thus, the use of the empirical algorithm allowed the identification of priority areas not only for the treatment of water, but also to prevent human contamination. However, it cannot accurately quantify the PC concentration in the reservoir due to the lack of more effective calibration methods suitable for the study area, a fact that justifies the need for more studies on aquatic remote sensing.

Finally, this study is also important due to the launch and operation of the newest Landsat satellite, developed by a cooperative effort called the Landsat Data Continuity Mission (LDCM), also known as Landsat 8 (Irons et al., 2012). In this satellite, there are two Earth observing sensors, the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). A comparison between OLI and ETM^+ is showed on Table 2.

Table 2. OLI and ETM^+ spectral bands.

Bands	OLI spectral bands	ETM + spectral bands
	Band width (μm)	**Band width** (μm)
1	0.433–0.453	-
2	0.450–0.515	0.450–0.515
3	0.525–0.600	0.525–0.605
4	0.630–0.680	0.630–0.690
5	0.845–0.885	0.775–0.900
6	1.560–1.660	1.550–1.750
7	2.100–2.300	-
8	0.500–0.680	2.090–2.350
9	1.360–1.390	-

Nota: Adapted from Irons et al. (2012).

Although OLI and ETM^+ do not have the same spectral bands, the band widths are very similar from which it can be inferred that OLI bands could be used to parameterize an empirical model for the identification of CHABs. The use of OLI is also interesting since USGS has decided to distribute this data free of charge directly from its Internet site. This policy of providing data at no cost has increased the number of studies using satellite images and developing new methods and algorithms.

4. CONCLUSIONS

CHABs have been a concern for human health mainly after the incident at a dialysis clinic in Caruaru City. As a result, studies have continually examined various potential bloom-causing conditions mainly in urban reservoirs due to their importance to the water supply. Guarapiranga Reservoir is an important aquatic system for RMSP not only because of the water supply, but also for energy production, leisure, and the practice of aquatic sports.

Our work employed LANDSAT TM and ETM^+ remote sensing data to qualitatively map CHABs in a freshwater reservoir from space, following the empirical model proposed by Vincent et al. (2004). Although the empirical model was calibrated for a temperate lake, it was able to accurately (R^2=0.96, p=0.003) relate to CHAB's indicators (cyanobacteria cell count values). Cyanobacteria cell count was analyzed for five different dates using *in situ* data from SABESP. The evaluation of this empirical algorithm for tropical turbid waters was an important contribution to tropical inland water remote sensing due to the lack of tropical specific studies and associated algorithm development. This study also contributes to the monitoring of water quality as a tool for quickly identifying regions affected by CHAB.

However, more research is needed to provide calibration methods for tropical waters and for different seasons.

5. REFERENCES

AGHA, R.; CIRÉS, S.; WORMER, L.; DOMÍNGUEZ, J.A.; QUESADA, A. Multi-scale strategies for the monitoring of freshwater cyanobacteria: Reducing the sources of uncertainty. **Water Research**, v. 46, p. 3043 - 3053, 2012. http://dx.doi.org/10.1016/j.watres.2012.03.005

AGOSTINHO, A. A.; PELICICE, F. M.; GOMES, L. C. Dams and the fish fauna of the Neotropical region: impacts and management related to diversity and fisheries. **Brazilian Journal of Biology**, v. 68, n. 4, p. 1119-1132, 2008. http://dx.doi.org/10.1590/S1519-69842008000500019

ARVIDSON, T.; GOWARD, S.; GASCH, J.; WILLIAMS, D. Landsat-7 long-term acquisition plan: development and validation. **Photogrammetric Engineering & Remote Sensing**, v. 72, n. 10, p. 1137–1146, 2006.

AZEVEDO, S. M. F. O.; CARMICHAEL, W. W.; JOCHIMSEN, E. M.; RINEHART, K. L.; LAU, S.; SHAW, G. R. et al. Human intoxication by microcystins during renal dialysis treatment in Caruaru - Brazil. **Toxicology**, n. 181-182, p. 441 - 446, 2002. http://dx.doi.org/10.1016/S0300-483X(02)00491-2

BARTRAM, J.; CARMICHAEL, W.W.; CHORUS, I.; JONES, G.; SKULBERG, O.M. In: CHORUS, I.; BARTRAM, J. (Eds.). **Toxic cyanobacteria in water**: a guide to their public health consequences, monitoring and management. London: UNESCO/WHO/UNEP, 1999. Chap. 1. p.12-24.

BEYRUTH, Z. Periodic disturbances, trophic gradient and phytoplankton characteristics related to cyanobacterial growth in Guarapiranga Reservoir, São Paulo State, Brazil. **Hydrobiologia**, n. 424, p. 51-65, 2000. http://dx.doi.org/10.1023/A:1003944726346

BUKATA, R. P.; JEROME, J. H.; BRUTON, J. E.; JAIN, S. C. Determination of inherent optical properties of Lake Ontario coastal waters. **Applied Optics**, v. 18, n. 23, p. 3926 - 3932, 1979. http://dx.doi.org/10.1364/AO.18.003926

BRASIL. Conselho Nacional do Meio Ambiente - CONAMA. **Resolução nº 357 de 17 março 2005**. Available at: http://www.mma.gov.br/port/conama/res/res05/res35705.pdf>. Access in: 28 Sep. 2012.

CARMICHAEL, W. W. Health effects of toxin-producing cyanobacteria: ‘‘The CyanoHABs’’. **Human and Ecological Risk Assessment**, v. 7, p. 1393-1407, 2001. http://dx.doi.org/10.1080/20018091095087

CARMICHAEL, W. W.; AZEVEDO, S. M. F. O.; AN, J. S.; MOLICA, R. J. R.; JOCHIMSEN, E. M.; LAU, S. et al.Human fatalities from Cyanobacteria: chemical and biological evidence for cyanotoxins. **Environmental Health Perspectives**, v. 109, n. 7, p. 663-668, 2001.

CHANDER, G.; MARKHAN, B. L.; HELDER, D. L. Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM$^+$, and EO-1 ALI sensors. **Remote Sensing of Environment**, v. 113, p. 893 - 903, 2009. http://dx.doi.org/10.1016/j.rse.2009.01.007

CHAVEZ JR., P. S. An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data. **Remote Sensing of Environment**, v. 24, n. 3, p. 459-479, 1988. http://dx.doi.org/10.1016/0034-4257(88)90019-3

CHORUS, I.; BARTRAM, J. (Eds.). **Toxic Cyanobacteria in water**: a guide to their public health consequences, monitoring and management. London: UNESCO/WHO/UNEP, 1999.

COMPANHIA DE SANEAMENTO BÁSICO DO ESTADO DE SÃO PAULO - SABESP. **Complexo metropolitano**. Available at: <http://site.sabesp.com.br/site/interna/ Default.aspx? secaoId=36> Access in: 01 Oct. 2012.

COMPANHIA DE TECNOLOGIA DE SANEAMENTO AMBIENTAL - CETESB. São Paulo. **Norma técnica L5.303**. São Paulo, 2005. Available at: <http://www.cetesb.sp.gov.br/userfiles/file/servicos/normas/pdf/L5303.pdf>. Access in: 26 Sep. 2012.

DEKKER, A. G. **Detection of optical water quality parameters for eutrophic waters by high resolution remote sensing**, 1993. 222p. PhD. (Thesis) - Vrije Universiteit, Amsterdam, 1993.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMPBRAPA. **Banco de dados climáticos do Brasil**. Available in: <http://www.bdclima.cnpm.embrapa.br>. Access in: May 2014.

FALCONER, I. R.; HUMPAGE, A. R. Cyanobacterial (blue-green algal) toxins in water supplies: cylindrospermopsins. **Environmental Toxicology**, v. 21, n. 4, p. 299-304, 2006. http://dx.doi.org/10.1002/tox.20194

FRANCIS, G. Poisonous Australian Lake. **Nature**, v. 18, p. 11-12, 1878. http://dx.doi.org /10.1038/018011d0

GONS, H. J. Optical Teledetection of Chlorophyll-a in turbid inland waters. **Environmental Science & Technology**, v. 33, n. 7, p. 1127-1132, 1999. http://dx.doi.org/10.1021/ es9809657

GORDON, H. R.; BROWN, O. B.; JACOBS, M. M. Computed relationships between the inherent and apparent optical properties of a flat homogeneous ocean. **Applied Optics**, v. 14, n. 2, 1975. http://dx.doi.org/10.1364/AO.14.000417

GORDON, H. R.; MOREL, A.Y. **Remote assessment of ocean color for interpretation of satellite visible imagery**: a review. New York: Springer-Verlag, 1983.

HUNTER, P. D.; TYLER, A. N.; CARVALHO, L.; CODD, G. A.; MABERLY, S. C. Hyperspectral remote sensing of cyanobacterial pigments as indicators for cell populations and toxins in eutrophic lakes. **Remote Sensing of Environment**, v. 114, p. 2705–2718, 2010. http://dx.doi.org/10.1016/j.rse.2010.06.006

INTERNATIONAL OCEAN-COLOUR COORDINATING GROUP - IOCCG. Why ocean colour? The societal benefits of ocean-colour technology. In: PLATT, T.; HOEPFFNER, N.; STUART, V.; BROWN, C. (Eds.). **Reports of the International Ocean-Colour Coordinating Group**, No. 7. Dartmouth: IOCCG, 2008.

IRONS, J. R.; DWYER, J. L.; BARSI, J. A. The next Landsat satellite: the Landsat Data continuity mission. **Remote Sensing of Environment**, v. 122, p. 11 - 21, 2012. http://dx.doi.org/10.1016/j.rse.2011.08.026

MIERZWA, J. C.; SILVA, M. C. C.; VERAS, L. R. V.; SUBTIL, E. L.; RODRIGUES, R.; LI, T.; LANDENBERGER, K. R. Enhancing spiral-wound ultrafiltration performance for direct drinking water treatment through operational procedures improvement: A feasible option for the Sao Paulo Metropolitan Region. **Desalination**, v. 307, p. 68-75, 2012. http://dx.doi.org/10.1016/j.desal.2012.09.006

MISHRA, S.; MISHRA, D. R.; SCHLUCHTER, W. M. A novel algorithm for predicting phycocyanin concentrations in Cyanobacteria: a proximal hyperspectral remote sensing approach. **Remote Sensing**, v.1, p. 758-775, 2009. http://dx.doi.org/10.3390/rs1040758

MORAIS, M. A.; CASTRO, W. A. C.; TUNDISI, J. G. Climatologia de frentes frias sobre a Região Metropolitana de São Paulo (RMSP), e sua influência na limnologia dos reservatórios de abastecimento de água. **Revista Brasileira de Meteorologia**, v.25, n.2, 205-217, 2010.

MUDROCH, A. (Ed.). **Planning and management of lakes and reservoirs, an integrated approach to Eutrophication**. Shiga: UNEP International Environmental Technology Centre, 1999. (Tech. Publ. Ser. 11).

OGASHAWARA, I.; ZAVATTINI, J. A.; TUNDISI, J. G. The climatic rhythm and blooms of Cyanobacteria in a tropical reservoir in São Paulo, Brazil. **Brazilian Journal of Biology**, (in press).

OGASHAWARA, I.; MISHRA, D. R.; MISHRA, S.; CURTARELLI, M. P.; STECH, J. L. A performance review of reflectance based algorithms for predicting Phycocyanin concentrations in inland waters. **Remote Sensing**, v. 5, p . 4774 - 4798, 2013. http://dx.doi.org/10.3390/rs5104774

PRADO, R. B.; NOVO, E. M. L. M.; PEREIRA, M. N. Avaliação da dinâmica do uso e cobertura da terra na bacia hidrográfica de contribuição para o reservatório de Barra Bonita - SP. **Revista Brasileira de Cartografia**, v. 59, n. 2, 2007.

REINART, A.; KUTSER, T. Comparison of different satellite sensors in detecting cyanobacterial bloom events in the Baltic Sea. **Remote Sensing of Environment**, v. 102, p. 74 - 85, 2006. http://dx.doi.org/10.1016/j.rse.2006.02.013

RUIZ-VERDÚ, A.; SIMIS, S. G. H.; HOYOS, C.; GONS, H. J.; PEÑA-MARTÍNEZ, R. An evaluation of algorithms for the remote sensing of cyanobacterial biomass. **Remote Sensing of Environment**, v. 112, p. 3996-4008, 2008. http://dx.doi.org/10.1016/j.rse.2007.11.019

SANT'ANNA, C. L.; MELCHER, S. S.; CARVALHO, M. C.; GEMELGO, M. P.; AZEVEDO, M. T. P. Planktic Cyanobacteria from upper Tietê Basin reservoirs, SP, Brazil. **Revista Brasileira de Botânica**, v. 30, n. 1, p. 1 - 15, 2007. http://dx.doi.org/10.1590/S0100-84042007000100002

SCHALLES, J. F.; YACOBI, Y. Z. Remote detection and seasonal patterns of phycocyanin, carotenoid, and chlorophyll pigments in eutrophic waters. **Archives Hydrobiologica Special Issues on Advanced Limnology**, v. 55, p. 153-168, 2000.

SIMIS, S. G. H.; PETERS, S. W. M.; GONS, H. J. Remote sensing of the cyanobacterial pigment phycocyanin in turbid inland water. **Limnology and Oceanography**, v. 50, p. 237−245, 2005. http://dx.doi.org/10.4319/lo.2005.50.1.0237

SIMIS, S. G. H.; RUIZ-VERDU, A.; DOMINGUEZ, J. A.; PENA-MARTINEZ, R.; PETERS, S. W. M.; GONS, H. J. Influence of phytoplankton pigment composition on remote sensing of cyanobacterial biomass. **Remote Sensing of Environment**, v. 106, p. 414-427, 2007. http://dx.doi.org/10.1016/j.rse.2006.09.008

SINGH, R. K.; SHANMUNGAN, P. A novel method for estimation of aerosol radiance and its extrapolation in the atmospheric correction of satellite data over optically complex oceanic waters. **Remote Sensing of Environment**, v. 142, p. 188-206, 2014. http://dx.doi.org/10.1016/j.rse.2013.12.001

STRASKRABA, M.; TUNDISI, J. G. **Reservoir water quality management**: guidelines of lake management. Kusatsu: International Lake Environmental Committee, 1999. Vol. 9. 227 p.

SUN, D.; Li, Y.; WANG, Q.; GAO, J.; LV, H.; LE, C. et al. Light scattering properties and their relation to the biogeochemical composition of turbid productive waters: a case study of Lake Taihu. **Applied Optics**, v. 48, n. 11, p. 1979-1989, 2009. http://dx.doi.org/10.1364/AO.48.001979

TUNDISI, J. G.; MATSUMURA-TUNDISI, T.; ARANTES JUNIOR, J. D.; TUNDISI, J. E. M.; MANZINI, N. F.; DUCROT, R. The response of Carlos Botelho (Lobo, BROA) Reservoir to the passage of cold fronts as reflected by physical, chemical, and biological variables. **Brazilian Journal of Biology**, v. 64, n. 1, p. 177-186, 2004. http://dx.doi.org/10.1590/S1519-69842004000100020

TUNDISI, J. G. Recursos hídricos no futuro: problemas e soluções. **Estudos Avançados**, v. 22, n. 63, p. 7-16, 2008.

TUNDISI, J. G.; MATSUMURA-TUNDISI, T.; TUNDISI, J. E. M. Reservoirs and human well being: new challenges for evaluating impacts and benefits in the neotropics. **Brazilian Journal of Biology**, v. 68, n. 4, p. 1119-1132, 2008. http://dx.doi.org/10.1590/S1519-69842008000500020

TUNDISI, J. G.; MATSUMURA-TUNDISI, T.; PEREIRA, K. C.; LUZIA, A. P.; PASSERINI, M. D.; CASTRO, W. C. C. et al. Cold fronts and reservoir limnology: an integrated approach towards the ecological dynamics of freshwater ecosystems. **Brazilian Journal of Biology,** v. 70, n. 3 (suppl.), p. 815-824, 2010. http://dx.doi.org/10.1590/S1519-69842010000400012

UNITED STATES. Geological Survey – USGS. **Landsat Project.** 2006a. Available at: <http://landsat.usgs.gov>. Access in: 08 Mar. 2013.

UNITED STATES. Geological Survey – USGS. Earth Resources Observation and Science - EROS. **Landsat Enhanced Thematic Mapper Plus (ETM$^+$).** 2006b. Available at: <http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/ETM>. Access in 08 Mar. 2013.

UNITED STATES. Geological Survey – USGS. Earth Resources Observation and Science - EROS. **Landsat Thematic Mapper (TM).** 2006c. Available at: <http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/TM>. Access in 08 Mar. 2013.

VINCENT, R. K.; QIN, X.; McKAY, R. M. L.; MINER, J.; CZAJKOWSKI, K.; SAVINO, J. et al. Phycocyanin detection from LANDSAT TM data for mapping cyanobacterial blooms in Lake Erie. **Remote Sensing of Environment**, v. 89, p. 381 - 392, 2004. http://dx.doi.org/10.1016/j.rse.2003.10.014