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Dynamics of limnological parameters in reservoirs: A case study in South Brazil using remote sensing and meteorological data

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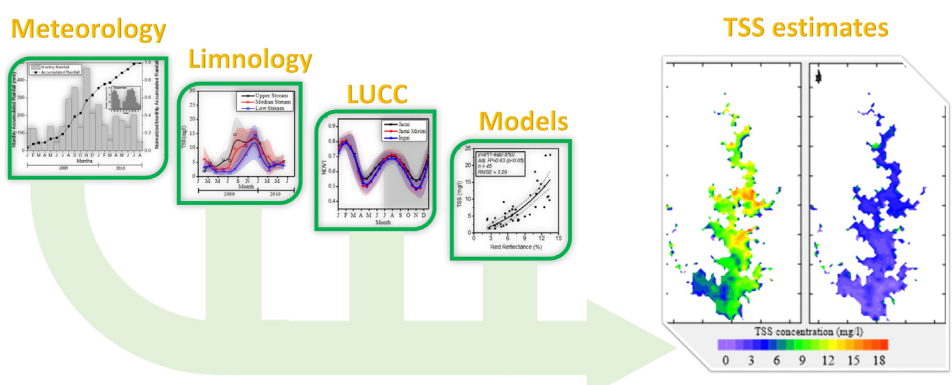
HIGHLIGHTS

- We studied reservoir OAC dynamics and relations with rainfall/temperature/land use.
- TSS/Chlorophyll-*a* were scaled up from field to satellite using exponential models.
- A decrease in TSS and chlorophyll-*a* was observed from upper to lower streams.
- Rainfall was more important than land use as a driver of OAC variability.
- Correction for BRDF was essential when using MODIS single-band regression models.

GRAPHICAL ABSTRACT



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ABSTRACT

Reservoirs are important in Brazil for the production of hydroelectric power and human water consumption. The objective was to evaluate the variability of total suspended solids (TSS) and chlorophyll-*a* as well as the rainfall/temperature and land use impacts on these optically active constituents (OAC). The study area is the Passo Real reservoir in south Brazil. The methodology was divided in four steps. First, we used wavelet to detect anomalous periods of rainfall and temperature (2002–2014). Second, we carried out 12 field campaigns to obtain *in situ* measurements for limnological characterization (2009–2010). The third step was the analysis of Moderate Resolution Imaging Spectroradiometer (MODIS)/Terra and Aqua satellites data corrected and non-corrected for bidirectional effects. Finally, we evaluated potential drivers of OAC changes over time using cross-correlation analysis. The results showed a decrease in the TSS and chlorophyll-*a* concentrations from the upper to the lower streams of the reservoir. The exponential regression between the MODIS red reflectance and TSS had an adjusted r^2 of 0.63. It decreased to 0.53 for the relationship between the green reflectance and chlorophyll-*a*. MODIS data corrected for bidirectional effects provided better OAC estimates than non-corrected data. The validation of MODIS TSS and chlorophyll-*a* estimates using a separate set of measurements showed a RMSE of 2.98 mg/l and 2.33 μg/l, respectively. MODIS estimates indicated a gradual transition in OAC from the upper to the lower streams in

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agreement with the patterns observed using field limnological data. The analysis of land use (greenness) showed two well-defined crop cycles per year. The highest seasonal concentrations of TSS and chlorophyll-*a* were observed in December and the lowest concentrations in April. Despite the interrelationships between both factors, our cross-correlation analysis indicated that the great concentrations of TSS and chlorophyll-*a* were primarily controlled by rainfall and secondarily by land use.

1. Introduction

The pressure on freshwater bodies increases with the predicted scenarios of extreme events due to climate change (Srinivasan et al., 2015; Solomon et al., 2007). Changes in terrestrial ecosystems due to droughts and floods affect the quality of the waters for human consumption and food production (Wang et al., 2004; Hestir et al., 2015). In addition, reservoirs play an important role on greenhouse gases (Tranvik et al., 2009; Fearnside and Pueyo, 2012; Raymond et al., 2013). The importance of the sustainable use of these reservoirs is more evident nowadays. For example, Brazil has experienced recently a severe drought that affected the water consumption of its largest city (São Paulo) as well as the generation of hydroelectric power in other parts of the country. Knowledge on the dynamics of waters of the reservoirs contributes for their sustainable use (Wang et al., 2004).

Among the several water parameters, the total suspended solids (TSS) and chlorophyll-*a* are widely used for water quality characterization. These parameters are inherent optical properties that are related to the spectral response of the water in the visible and near infrared regions (Kirk, 1994; Gitelson et al., 2007; Dall'Olmo et al., 2005; Jiang et al., 2015). TSS estimates from the space are critical to understand the sediment transportation, erosion, and deposition (Tyler et al., 2006; Latrubesse, 2012). Chlorophyll-*a* estimates can be used as a proxy for phytoplankton biomass in aquatic ecosystems (Giardino et al., 2001; Zhang et al., 2011).

Satellite sensors have been widely used to monitor large water bodies and to allow per-pixel estimates of the OAC (Palmer et al., 2015; Dekker et al., 2002; Park and Latrubesse, 2014; Duan et al., 2014). In the absence of physical models, *in situ* data are essential to build and validate regression models between the OAC concentrations and the spectral response of the waters. Since Brazil is one of the largest countries of the world with thousands of rivers, lakes, and reservoirs, conventional field data collection and associated laboratory analysis are expensive and time-consuming. Therefore, remote sensing is an alternative to complement and optimize these conventional approaches, providing field-calibrated estimates of OAC for large water bodies (Bergamino et al., 2010; Gitelson et al., 2008; Dall'Olmo and Gitelson, 2006; Le et al., 2009). For instance, several procedures have been proposed in the literature to estimate chlorophyll-*a* and TSS in inland waters using orbital sensors (Dall'Olmo and Gitelson, 2006; Chavula et al., 2009; Min et al., 2012; Park and Latrubesse, 2014). Among the available sensors to provide these estimates, the large field-of-view Moderate Resolution Imaging Spectroradiometer (MODIS) is an alternative because it acquires data with a high revisit time of the scene.

Two almost identical MODIS sensors are on board the Terra and Aqua satellites with nearly daily coverage. This is important to increase the chances to obtain cloud-free data in tropical and subtropical regions of Brazil. In addition to provide surface reflectance data, several other products are generated from MODIS such as the normalized difference vegetation index (NDVI) and the nadir-adjusted bi-directional reflectance distribution function (BRDF), both available on a global 16-day basis (Friedl et al., 2000; Xiong et al., 2009; Ju et al., 2010; Sun et al., 2014). MODIS acquires data in 36 bands, covering a spectral range from the visible to the thermal infrared, with a spatial resolution of 250 m (2 bands), 500 m (5 bands) and 1000 m (29 bands) (Barnes et al., 2003; Xiong et al., 2009).

In south Brazil, the largest reservoirs are used for power generation, and new dams have been planned. As the dams cause changes in water characteristics in the upper and lower streams of the reservoirs, an assessment of the water quality over time is required. The dynamics of TSS and chlorophyll-*a* in reservoirs is in great part associated to meteorological attributes such as rainfall and temperature (Brandini and Rebello, 1994; Tundisi et al., 2004; Fragoso et al., 2011). Another important potential factor is land use in the vicinities of the reservoirs (Fritz, 1989; Bramley and Roth, 2002; Ahearn et al., 2005; Liu et al., 2015). Moreover, in reservoirs from south Brazil, temperature variations due to cold fronts affect the limnological parameters by inducing water column stratification and resuspension (Tundisi et al., 2004, 2007; Rolim et al., 2015).

Comprehension of the relationships between land use, precipitation/temperature and OAC of the reservoirs is therefore important to accurately plan and mitigate adverse impacts of climatic variations at local, regional and global scales. Here, the objective is to evaluate the variability of TSS and chlorophyll-*a*, across space and time, in the Passo Real reservoir, located in south Brazil, using MODIS and field data. In addition, the rainfall/temperature and land use impacts on the variability of these water constituents are analyzed. By comparing the MODIS products, the bidirectional effects on OAC estimates using single-band regression models are discussed.

2. Methodology

2.1. Limnological/meteorological data acquisition in the study area

We selected the Passo Real reservoir as study area in south Brazil because it is the largest reservoir of the Rio Grande do Sul state (233 km^2) constructed in 1973 for power generation and water flow regulation (Fig. 1a). The reservoir receives waters from three main watersheds, especially from the Jacuí River (Fig. 1b). Except for the riparian forests, the original vegetation cover (subtropical deciduous forest, mixed ombrophilous forest and grasslands) was replaced by annual crops (*e.g.*, soybean, maize, wheat) and pasture (Wachholz, 2011). The climate type is Cfa (Humid subtropical climate in the Köppen-Geiger classification) with an average annual rainfall of 1737 mm. The precipitation increases from the first to the second semester of each year (CEEE-GT, 2011). The predominant soil type derived from tholeiitic basalts is Red Latosol (Rhodic Acrustox in the Soil Taxonomy; RA). The topography is gently undulating with a mean elevation of 483 m (Wachholz, 2011).

We performed 12 field campaigns covering the period from February 6, 2009 to June 9, 2010 between 10 am and 15 pm. We sampled 25 sites in the major sections of the reservoir (Fig. 1a). A GPS unit was used to locate the 25 sample plots and keep them approximately fixed across campaigns. In each plot, we collected water samples at 10-cm depth for TSS and chlorophyll-*a* determination. In the laboratory, TSS was determined using 600 ml of water and pre-weighted cellulose filters of 45 μm of porosity and 47 mm of diameter. The filters were dry out before and after filtering during 24 h at 50 °C. The TSS was measured by the difference between the first and final weight of the filters as a function of the water volume filtered in mg/l. To obtain the chlorophyll-*a* concentration (μg/l), we used a glass fiber filter and the spectrophotometric methodology without acidification, which is based on