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Three-dimensional modeling of inland waters optical properties from aerial hyperspectral images.

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À Deus,

Aos familiares e amigos,

em especial meus pais João e Rozangela

e aos meus avós Manoel e Izabel,

à minha esposa Nariane,

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"O sol se levanta, o sol se põe e se apressa para voltar a seu lugar, onde renasce. O vento gira para o sul e dobra para o norte; passando ao redor de todas as coisas, ele prossegue e volta aos seus rodeios. Todos os rios correm para o mar, e o mar contudo não transborda; para o lugar de onde saíram voltam os rios, no seu percurso. Todas as coisas são difíceis e não se pode explicá-las com palavras. A vista não se cansa de ver, nem o ouvido se farta de ouvir."

(Eclesiastes, 1:5-8)

RESUMO

A aquisição de dados por meio da combinação de Sensoriamento Remoto e amostragens in-situ permite que várias fontes de dados sejam integradas para a análise e observação de características do alvo de interesse e pode exigir métodos computacionais para apoiar o processamento, exploração e análise de dados. A necessidade de integrar dados de diferentes fontes é destacada em estudos de ambientes dinâmicos e complexos que se alteram frequentemente, como os reservatórios hidrelétricos. Os reservatórios são ecossistemas artificiais, que influenciam diretamente nas características regionais, principalmente devido ao seu uso múltiplo uso. As interações da energia eletromagnética com os componentes opticamente ativos ocorrem ao longo de toda a coluna d'água, de modo que o comportamento do campo de luz reflete as mudanças aplicadas ao longo da zona eufótica. No entanto, as grandezas registradas nas imagens são usados de acordo com o plano e limitadas ao respectivo ponto ou área da superfície. A calibração de modelos bio-ópticos, considerando apenas os dados de amostragem da superfície, pode não fornecer resultados totalmente eficazes, porque a radiação eletromagnética interage com os componentes localizados ao longo da coluna de água e, consequentemente, a resposta capturada pelos sensores não representa apenas o valor associado à superfície. Este trabalho propõe uma investigação sobre a influência da distribuição vertical das propriedades ópticas ao longo da coluna d'água, a fim de contemplar registros sobre a interação em diferentes níveis de profundidade, além da própria disposição espacial, configurando-se como um ambiente genuinamente tridimensional. Para isso, dados coletados por sensores espectrais in-situ e por câmera hiperespectral embarcada em uma plataforma aérea foram usados para construir o modelo. Por fim, espera-se que o produto final desta investigação, composto pelo modelo tridimensional ajustado a partir de relações semi-analíticas e empíricas, possa ser uma contribuição inédita para a área de Sensoriamento Remoto e permitir identificar relações ao longo do volume de água que pode fornecer subsídios para a melhoria de modelos bio-ópticos e derivação de outros estudos relacionados à propriedades ópticas em diferentes profundidades.

Palavras-chave: Modelo bio-óptico tridimensional. Propriedades ópticas. Distribuição vertical da luz. Águas Interiores.

ABSTRACT

The acquisition of data using Remote Sensing and in-situ sampling allows several data sources to be integrated for the analysis and observations of environmental characteristics and may require computational methods to support the data processing, exploration and analysis. The need to integrate data from different sources is highlighted in studies of dynamic and complex environments that frequently change, such as hydroelectric reservoirs. Reservoirs are artificial ecosystems, which influence directly the regional characteristics, mainly because of their multipurpose use. The interactions of the electromagnetic energy with the optically active components occur along the entire water column, so that the behavior of the light field reflects the changes applied along the entire euphotic zone. However, the values taken from images are used accordingly to a plane and associated with the respective point or area of surface. The calibration of bio-optical models considering only the surface sampling data can not deliver fully effective results because the electromagnetic radiation interacts with the components located along the water column and the response captured by the sensors does not only represent the value associated with the surface. Considering this scenario, this work proposes an investigation on the influence of the vertical distribution of the optical properties along the water column, in order to contemplate records about the interaction in different levels of depth, besides the spatial disposition itself, being configured as a genuinely three-dimensional environment. For that, data collected by in situ spectral sensors and by hyperspectral camera in an aerial platform are used to construct the model. Finally, it is expected that the final product of this investigation, composed of the three-dimensional model adjusted from semi-analytical and empirical relations, may be an unprecedented contribution to the Remote Sensing area, and allow to identify relations along the water body volume which may assist as subsidies for the improvement of bio-optical models and derivation from other related studies about depth-related optical properties.

Keywords: Three-dimensional bio-optical model. Optical Properties. Vertical distribution of light. Inland Water.

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CHAPTER 1

INTRODUCTION

Brazil has a set of energy power plants producing over 151.6 million kilowatts, which more than 61% is generated from hydro-power managed by the 219 hydroelectric plants built in the country (ANEEL, 2019). The greatest energy potentials come from hydroelectric built on accumulation reservoirs, in which the river is dammed and a large area is flooded. The impacts from these artificial systems result in changes in regional hydrology, flooding of riparian forests, interference in physical and chemical processes, expansion of river geometry, an increase of material discharge, aggressive implantation of a lentic system, a change in the reproduction cycle of species, among other factors that cause the gradual eutrophication of the system.

The reservoirs changes the physical, chemical and biological characteristics of water bodies, whose magnitude of impacts is directly related to the size of the reservoir and the technology adopted. Elseways, reservoirs have positive aspects, which can produce socioeconomic benefits, such as: energy generation; water for consumption; recreational and sports activities; flood control; irrigation; economic development; jobs and navigation (KORNIJóW, 2009; TUNDISI; MATSUMURA-TUNDISI; TUNDISI, 2008). The effects and impacts are cumulative in reservoirs arranged sequentially in cascade systems on the same river (NOGUEIRA et al., 2006).

The Paranapanema River is the second river in Brazil with the largest number of cascading reservoirs, comprising eleven hydroelectric plants installed. One characteristic of the Paranapanema River is the integration with large tributaries, such as the Tibagi River. The confluence region between the Tibagi and Paranapanema rivers is part of the lake of the Capivara reservoir.

Large tributaries act as important contributors to nutrient availability, changing the effects of eutrophication of the dammed regions (LANSAC-TÔHA et al., 2004). Despite the impacts attributed to anthropogenic intervention on the natural flow of the river, large tributaries are essential for maintaining the changed environment and mitigating the consequences of damming. The tributaries may have lotic or semi-lotic features and preserve some original features of the system (HOFFMANN; ORSI; SHIBATTA, 2005; ORSI et al., 2002; AGOSTINHO; PELICICE; GOMES, 2008; BENNEMANN et al., 2006).

Monitoring and control complex environments which can be characterized by secondary circulation, flux separation, and vertical layer segmentation (KENWORTHY; RHOADS, 1995), requires studies that consider data from sampling in transects and in vertical profile with different depths. Constant and periodic data acquisition are essential for effective management of dynamic ecosystems that frequently change. Remote sensing techniques based on images produced by orbital sensors and photographs generated by other aerial imaging devices have been consolidated as important resources to obtain data about the characteristics of targets of interest with various temporal, spectral and spatial resolution. Hyperspectral sensors can be useful to analysis of water bodies with complex mixtures, such as found in tropical inland water. The remote sensors offer an alternative to the analysis, which, integrated with local sampling methodologies (in situ), represents an important tool for environmental monitoring, with benefits related to the temporal (higher frequency) and spatial (larger area) resolution of the analyzes with no impact on the execution cost.

Remote sensing products represent the interaction of electromagnetic energy with the optically active constituents (OAC) of the target and elements present on atmosphere. The electromagnetic wave interacts with the targets from the path in the water column to the depth of the light field can react (euphotic zone), which is directly dependent on the specfic wavelength (MCCLUNEY, 1974). The images represent the characteristics of the composition of the water column, according to the associated electromagnetic spectrum. However, the values from the orbital images are usually processed under a plane and associated with the respective point or area of the surface, because they are usually adjusted from surface samplings. Different interactions along the water column can not be decomposed and segmented precisely in depth using only the response of the remote sensors.

Since the energy recorded by the sensors interacts with the components along the water column, and the vertical variation and depth of light penetration directly depends on the wavelength, the response captured by the sensors does not represent only the value associated with the surface, and the calibration of bio-optical models considering only surface sampling data may not agree fully effective results. Therefore, it is still necessary to understand the process of interaction of light within the water column.

The use of surface-based sampling method for calibration and validation of bio-optical models highlights the main concern of this work: Is it possible to estimate the behavior of optical properties at different depths from remote sensing images?

To improve models calibrated with surface data and to bring a new contribution to the area, studies related to the volumetric bio-optic characterization of the water body are necessary to understand the processes present in the water column. For this, it is necessary to use specific tools that allows: (1) the acquisition of real data in different depth, minimizing the errors inserted in the process of estimation of these values; (2) effective methods capable of integrating and processing the collected data; and (3) genuinely three-dimensional data management and processing approaches to enable exploration and analysis in 3D space.

CHAPTER 7

CONCLUSIONS AND FINAL REMARKS

The behavior of the light field below the water surface is a significant challenge in understanding the interaction of electromagnetic energy along the water column. This work presented analysis and contributions to all processes, from data acquisition, processing, integration, transformation and modeling. The topics covered by each chapter, unified in individual papers, were directed to compose the research minimizing the overlapping of the chapters, but highlighting the synergy among the subjects by the serial and gradual integration of each chapter.

The Geosciences area, and several other contexts dependent of a field campaign using different methods of data collection based on sensors. However, integrating data from different sources is not a trivial task since each manufacturer produces specific tools to manipulate the data of the respective sensor. The solution proposed in this work solves the problem of integrating the data of five sensors frequently applied to field work in aquatic environments. The system including data management and automatic information processing was efficient and fundamental for the reporting of this work, and other impact studies of the group. We automated all manual process performed after each field survey using the system for data standardization, automatic processing and quality control.

Remote sensing images of water bodies are often affected by noises and specular reflection. Using images with high spatial resolution, such as that used in this work, amplifies the occurrence of glint because increase the probability of acquired variations from the surface caused by waves. The original images achieved with the field survey had a high noise level, mainly on the border of the images. We evaluated several approaches, and the proposed model based on the multi-scale reference algorithm showed to be more efficient than conventional methods. The proposed algorithm does not produce any new value or data because it searches for the best candidate pixel with the minor influence of noise. However, this approach considers that the overlap between images is sufficient to guarantee the existence of at least one pixel not affected by noise, limiting its applications in previously mosaic images that do not present redundancy in the values of each pixel.

After correct the images and eliminate or reduce noises, the process of radiometric transformation of the digital number values into physically meaning quantities can begin. Images acquired from aerial surveys require field work to support further processing, justifying the application of the empirical line method in this scenario for a local calibration. We evaluated several targets and samples settings for empirical line calibration. The results showed the difficulty in applying this method to recover information about the water body, due to the intense absorption through the water. However, the adaptation of the method to including a sample point measured in water along with another artificial target produced better results.

Finally, after all the processing to integrate and correct of the information sources, in the last chapter we present a proposal for a semi-analytical model to determine the measures of reflectance along the water column from the acquired images. We constructed the model from physical and mathematical relations known in the literature. The proposed model uses the data of the vertical attenuation coefficients of the light, both ascending and descending, to determine the variation of light at any depth and to estimate the optical property. The data of the vertical attenuation coefficients of the light have a great influence on the model, and its precision and accuracy is essential for the good performance of the model. Unexpected values of K_d and K_u will produce uncertain results of the model.

In all the stages of this work, we have an effort to keep the data, algorithms, scripts, and system publicly accessible to the whole community. The discovery and access to the data collected in the field is a current demand, considering the large amount of data collected, observing different attributes, following different methods, using diverse tools and stored in multiple data formats. Given this scenario, methodologies for standardization and definition of the data infrastructure are necessary to promote the interoperability of the data, especially regarding data sharing.

As future possibilities to expand the subjects addressed in this work, we can cite recommendations on:

- Test and validate the models using another set of images acquired in another aquatic system with different characteristics of composition;
- Investigate visual analytics techniques to include on the system to amplify visual and interactive exploration of data from multiple sources;
- Analyze the use of parallel processing on the glint mitigation algorithm to optimize

the execution of large scenes;

- Check the performance of the empirical line using a gradient gray scale of artificial targets to find the one that best fits in this and another dataset;
- Use simulations based on the radiative transfer function, such as Hydrolight, to validate and verify the behavior of the proposed model to estimate depth-related reflectance in an environment with variant composition;
- Verify the application of models to calculate the vertical attenuation coefficients from image to replace the use of spatial interpolation of these values;
- Investigate the relation of the Secchi disk with the optical properties related to each depth. This relationship can represent a factor to be included on the proposed model.

We hope the results obtained and showed in this work can provide subsidies, applicable both to the area of Geosciences and Computer Science, to amplify the investigations and discussions to understand the light field below the water surface mainly to the recovery depth-related information using remote sensing images as an input source.

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