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UNIVERSIDADE ESTADUAL PAULISTA "JÚLIO DE MESQUITA FILHO"
CAMPUS DE PRESIDENTE PRUDENTE
FACULDADE DE CIÊNCIAS E TECNOLOGIA
Programa de Pós-Graduação em Ciências Cartográficas

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A SEMIANALYTICAL ALGORITHM TO RETRIEVE THE SUSPENDED PARTICULATE MATTER IN A CASCADE RESERVOIR SYSTEM WITH WIDELY DIFFERING OPTICAL PROPERTIES

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Thesis presented to the Department of Cartography of the Faculty of Science and Technology of São Paulo State University as part of the requirements for obtaining the PhD degree in Cartographic Sciences.

Advisor: Prof. Dr. Enner Alcântara

PRESIDENTE PRUDENTE
2019

B523s

Bernardo, Nariane Marselhe Ribeiro

A semianalytical algorithm to retrieve the suspended particulate matter in a cascade reservoir system with widely differing optical properties / Nariane Marselhe Ribeiro Bernardo. -- Presidente Prudente, 2019

148 f.

Tese (doutorado) - Universidade Estadual Paulista (Unesp), Faculdade de Ciências e Tecnologia, Presidente Prudente

Orientador: Enner Herênio Alcântara

1. bio-ótica. 2. águas interiores. 3. qualidade da água. 4. sensoriamento remoto. I. Título.

unesp UNIVERSIDADE ESTADUAL PAULISTA

Câmpus de Presidente Prudente

CERTIFICADO DE APROVAÇÃO

TÍTULO DA TESE: A semianalytical algorithm to retrieve the suspended particulate matter in a cascade reservoir system with widely differing optical properties

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ORIENTADOR: ENNER HERENIO DE ALCÂNTARA

Aprovada como parte das exigências para obtenção do Título de Doutora em CIÊNCIAS CARTOGRÁFICAS, área: Aquisição, Análise e Representação de Informações Espaciais pela Comissão Examinadora:

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VIDEOCONFERÊNCIA

Presidente Prudente, 03 de setembro de 2019

To God

To my Grandparents, Florinda e Joaquim, Luiz e Maria Hilda

To my parents, Nadir e Mário Bernardo

To my husband, Alisson do Carmo

To our daughter, Cecília Bernardo do Carmo

AGRADECIMENTOS

Dou início aos agradecimentos, primeiramente expressando em palavras minha gratidão à Deus por permitir que pudesse realizar todas as etapas do trabalho de forma segura. Foi graças à Sua proteção que concluímos os trabalhos de campo mesmo em tantas dificuldades. Gratidão por todas as oportunidades, aprendizados e bênçãos recebidas ao longo desta jornada.

Aos meus pais, Nadir Ribeiro Bernardo e Mário Luiz Bernardo, por todo o amor e incentivo. Obrigada por serem exemplos de amor, respeito, dedicação e caráter. Obrigada por me ensinarem a nunca desistir e a aprender com os erros. Obrigada por proporcionarem todas as condições possíveis para que eu finalizasse meus estudos de forma plena e com dedicação total.

Agradeço ao meu esposo, Alisson Fernando Coelho do Carmo, por todo o amor, apoio e otimismo. Obrigada pela ajuda em trabalhos de campo, processamento de dados e por sempre deixar minha vida mais leve, enxergando as belezas das coisas simples e o melhor lado de todas as situações.

Gratidão ao meu orientador Enner Herênio Alcântara, por todos os ensinamentos na vida profissional e pessoal, por toda a disponibilidade, prontidão e eficiência na execução dos trabalhos, pela busca por aportes financeiros para desenvolvimento de tarefas e por acreditar sempre no nosso trabalho.

À Unesp, pela disponibilidade da estrutura física para desenvolvimento deste trabalho, bem como aos professores do PPGCC - em especial aos professores Dr. Nilton Imai e Dra. Maria de Lourdes Galo. Agradeço também ao professor Dr. Arcilan, participante da banca examinadora, sempre contribuindo com sugestões primorosas para o trabalho.

Aos amigos do PPGCC, e em especial àqueles que são uma família para mim durante o doutorado e fazem parte do nosso grupo de pesquisa (SERTIE) - Fernanda Watanabe, Luiz Henrique Rotta, Thanan Rodrigues, Carol Campos, Bruno Fagah, Gabi Takahashi. Ainda agradeço pelos momentos de descontração e desabafos com os amigos feitos durante a pós-graduação Dani Arana, Tayná e Mariana Campos, bem como com as meninas que zelavam da integridade da nossa sala de permanência, Cidinha e Zilda, sempre nos presenteando com um bom dia acolhedor mesmo quando estávamos desanimados

À agência de fomento pela bolsa concedida no período dedicado à realização da tese. O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Código de Financiamento 001.

Agradecimentos também à Fundação de Amparo à pesquisa do Estado de São Paulo – FAPESP, pelo financiamento dos projetos **nº 2012/19821-1, 2015/21586-9, 2015/18525-8 and 2019/00259-0**, e ao Conselho Nacional de Tecnologia e Desenvolvimento (CNPq) pelos projetos dos processos n°**472131/2012-5** e n°**482605/2013-8**.

RESUMO

O Material Particulado em Suspensão (MPS) é o principal componente em sistemas aquáticos. Elevadas concentrações de MPS implicam na atenuação da luz, e ocasionam alterações das taxas fotossintéticas. Além disso, a presença de MPS no sistema aquático pode aumentar os níveis de turbidez, absorver poluentes e podem ser considerados como um indicativo de descargas de escoamento superficial. Portanto, monitorar as concentrações de MPS é essencial para a gerar informações técnicas que subsidiem o correto manejo dos recursos aquáticos, prevenindo colapsos hidrológicos. O sensoriamento remoto se mostra como uma eficiente ferramenta para monitorar e mapear MPS quando comparada às técnicas tradicionais de monitoramento, como as medidas in situ. Entretanto, diante de uma grande e complexa variabilidade de componentes óticos, desenvolver modelos de MPS por meio do sinal registrado em sensores remotos é um desafio. Diversos modelos foram desenvolvidos para reservatórios, lagos e lagoas específicos. Atualmente, não há um único modelo capaz de estimar MPS em reservatórios brasileiros em cascata. Com o objetivo de estimar as concentrações de MPS de forma acurada, o objetivo desta tese foi desenvolver um modelo semi-analítico capaz de estimar valores de coeficiente de atenuação, K_d, por meio do uso dos coeficientes de absorção e espalhamento e, consequentemente, utilizar os valores de K_d para estimar as concentrações de MPS. A adoção desta estratégica se baseou na atenuação da luz ao longo da coluna da água, causada pela presença de MPS. Inicialmente, as características óticas dos reservatórios foram investigadas. Foi observado que cada reservatório apresenta um componente oticamente ativo (COA) dominante, como em Barra Bonita, o primeiro reservatório da cascata, dominado pela fração orgânica do MPS, enquanto que Nova Avanhandava, o ultimo reservatório da cascata, a fração inorgânica de MPS é dominante. Além disso, Bariri e Ibitinga, reservatórios localizados próximos à Barra Bonita, apresentaram elevadas contribuições de material orgânico dissolvido colorido (CDOM). Todas estas características implicam em diferentes propriedades bio-ópticas. Sequencialmente, a qualidade da reflectância de sensoriamento remoto (R_{sr}) foi avaliada por meio da comparação de quatro métodos, publicados na literatura, para remoção do efeito especular. Para validação dos resultados, o resultado das simulações obtidas via Hydrolight® foi utilizado como dado de referência. Os resultados demonstraram que o uso de um fator hiperespectral que compense a componente especular foi a melhor abordagem para calcular os dados de R_{sr}, reduzindo aproximadamente 30% dos erros quando comparados às outras abordagens, as quais consideraram apenas a velocidade do vento como causa do efeito especular. Por fim, modelos empíricos e semi-analíticos foram desenvolvidos, sendo que os modelos semi-analíticos apresentaram um resultado mais satisfatório para as estimativas das concentrações de MPS do que os modelos empíricos. O modelo desenvolvido na presente tese, QAA_{TRCS}, resultou em erros médios menores que 30%, enquanto que os modelos empíricos retornaram erros de até 80%. Em vista do grande intervalo de concentrações de COAs e da variabilidade ótica observada no reservatórios em cascata, o QAA_{TRCS} foi capaz de estimar de forma acurada as concentrações de MPS.

Palavras-chave: bio-ótica; águas interiores; qualidade da água; OLI/Landsat-8; sensoriamento remoto.

ABSCTRACT

Suspended particulate matter (SPM) is the main component presented within aquatic system. High levels of SPM concentration attenuate the light affecting the photosynthesis rates. Besides, can increase turbidity levels, absorb pollutions and is an indicative of runoff discharges. Therefore, monitoring SPM concentrations is essential to provide reliable information for a correct water management to prevent hydrological collapse. Remote sensing emerges as an efficient tool to map and monitor SPM when compared to traditional techniques, such as in situ measurements. Nevertheless, considering a widely range of optical components, modeling the remote sensing signal in terms of SPM is a challenge. Several models were developed for specific reservoirs, lakes or ponds. Up to our knowledge, there is not a single model capable to retrieve SPM in Brazilian linked reservoirs in a cascade system. In order to accurately estimate SPM, the aim of the thesis was developed a semianalytical model capable to estimate K_d via absorption and backscattering coefficients, and then, use K_d to derive SPM. This approach was adopted because SPM directly contributes to the light attenuation within the water column. Firstly, optical features were investigated. It was found that each reservoir presented a specific optical active component (OAC) dominance, such as Barra Bonita, the first reservoir in cascade is dominated by organic SPM, while Nova Avanhandava, the last reservoir in cascade is dominated by inorganic SPM. Besides, Bariri and Ibitinga reservoirs located nearest Barra Bonita, demonstrated high levels of CDOM contribution. All these characteristics imply in changes of bio-optical properties. In sequence, the quality of remote sensing reflectance (R_{rs}) was calculated by comparing four methods published in literature, and using as reference for validation, the simulated dataset via Hydrolight®. The results demonstrated that use a hyperspectral factor to compensate the specular component is the best approach to compute suitable R_{rs}, reducing 30% of errors when compared to approaches that use wind speed as the only factor of glint effect. Then, empirical and semianalytical models were developed, and the semianalytical model provided more satisfactory results of SPM estimations than empirical model. Our developed semianalytical model, called QAA_{TRCS}, retrieved errors for SPM estimates lower than 30% on average, while the empirical model reaches errors near 80%. Considering the widely range OACs concentration and the optical properties variability, QAA_{TRCS} was capable to provide reliable SPM estimates.

Keywords: bio-optics; inland water; water quality; OLI/Landsat-8; proximal remote sensing.

LIST OF FIGURES

LIST OF TABLES

CONTENT

CHAPTER 1: INTRODUCTION

1.1 RESEARCH CONTEXT

Earth's system observation has been used along last decades for aquatic system monitoring in a sustainable manner, providing a synoptic view of Earth's dynamics (Kirk 2011, Muow et al., 2015). The mark of using remote sensing signal starts at 1978, with the launch of first satellite for water applications – Coastal Zone Color Scanner (CZCS, see Table 1.1 and 1.2 for descriptions of symbols and acronyms, respectively) for ocean systems. In inland waters, the investigations initialize later, in the last decade of 1980s (Giardino et al 2018). Currently, the technical improvements in remote sensors have been produced better datasets with upgraded of spatial, temporal, spectral, and radiometric resolutions, aiming to provide reliable information for monitoring different sizes of aquatic systems (Lobo et al., 2015; Giardino et al., 2018).

The accessibility of restrict areas, a broader coverage of study areas, and higher frequency rates of dataset production, are the main strengths when compared to the traditional monitoring techniques, as in situ sampling (Muow et al., 2015, Palmer et al., 2015). Besides, remotely sensed monitoring is mostly safe-cost, considering the quantity of remote sensing datasets that are freely available for download, or even better, can be processed in cloud such as the Google Earth Engine platform (Hansen et al., 2018). More robust and easier access of datasets, improvements of processing capacities, evolution of assessments techniques, along with the expansion of knowledge in hydrological optics theory resulting in a bunch of features to efficiently monitor, predict and technically support the water management decisions for sustainable water uses.

Water quality monitoring using remotely sensed datasets that are capable to register and reproduce, by graphs or images, the interaction of electromagnetic energy and the optical active components (OACs) within the aquatic systems. The main OACs are summarizing by water, phytoplankton (characterized as chlorophyll-a, Chl-*a*), colored dissolved organic matter (CDOM) and suspended particulate matter (SPM). All of them interact with the incident energy by absorbing or scattering the light (Morel and Prieur, 1977).

The absorption and scattering processes can be defined as the coefficients that characterize the inherent optical properties (IOPs) of the water column. Because of these interactions, the

IOPs can be considered as proportional to the concentration and types of OACs within the water column (Kirk, 2011). The aquatic systems also can be described accordingly to the apparent optical properties (AOPs), such as the remote sensing reflectance (R_{rs}) and vertical coefficient of light attenuation (K_d). The AOPs are influenced by the presence of OACs, but also are directly affected to the variation of the incident light field (Preisendorfer 1961, Kirk, 2011).

Among the OACs, the major component of inland water sytems is the SPM, which plays an important role in hydrophysical functioning and internal cycles (Lymburner et al., 2016). Due to its capability to absorb and scatter the light, the SPM is responsible to increase the levels of turbidity, attenuate and reduce the underwater light field, absorb the pollution components, and affect the photosynthesis process that compromises the benthonic life (Billota and Brazier, 2008). Therefore, understanding the SPM dynamics that are responsible to affect the availability of energy inside the aquatic system is essential to guarantee better conditions for the underwater life, besides providing the sustainability of the water resources for now and future uses.

In inland waters, in contrast of ocean systems, presented a higher complexity of OACs due to the widely variation composition and concentrations ranges. Because of the runoff from catchments and anthropogenic activities, inland waters are commonly characterized as highly turbid environments (Zhang et al., 2009). Consequently, a widely OACs variability implies in more complex optical system (Lee et al., 2002) and great efforts are required to establish a bio-optical models capable to produce accurately SPM estimates (Muow et al., 2018; Palmer et al., 2015; Giardino et al., 2018).

Besides the optical complexity challenge, the radiometric signal resulted from aquatic and light interactions cross the atmosphere to reach the sensors. Throughout the atmospheric optical path, the atmospheric components directly attenuate the signal, and almost 90% of registered information is derived from atmospheric influence (Bernardo et al., 2016), also affecting the accuracy of SPM estimates. Beyond aforementioned challenges, other drawbacks that might be considered are the viewing geometry set and the environmental conditions during the field measurements, such as the cloud coverage, time acquisition, wind speed and platform stability, in this case, the boat stability. Viewing geometry is an important factor into the field site measurements due to the glint effects (Mobley 1999), while the field conditions can introduce errors to compute R_{rs}, the most relevant variable to establish an accurate bio-optical modeling (Lee et al., 2010). Therefore, the present thesis aims to deal with these challenges that decrease the performance of SPM retrieval model, and presenting the key solutions found to provide the most accurately SPM estimates over a widely range of OACs within aquatic systems.

Table 1.1 List of acronyms.

Acronym	Description
AOPs	Apparent Optical Properties
IOPs	Inherent Optical Properties
BB	Barra Bonita Hydroelectric Reservoir
BAR	Bariri Hydroelectric Reservoir
IBI	Ibitinga Hydroelectric Reservoir
NAV	Nova Avanhandava Hydroelectric Reservoir
CDOM	Colored dissolved organic matter
CZCS	Coastal Zone Color Scanner
Chl-*a*	Chlorophyll-a
QAA	Quasi analytical algorithm
NAP	Non-algae particles
OAC	Optical active components
PIM	Suspended Particulate Inorganic Matter
POM	Suspended Particulate Organic Matter
SPM	Suspended Particulate Matter
TRCS	Tietê River Cascade System

Table 1.2 List of symbols

Symbol	Parameter	Unit
Γ	Geometrical light factor	-
R_{rs}	Remote sensing reflectance above water surface	sr^{-1}
r_{rs}	Remote sensing reflectance below water surface	sr^{-1}
Y	Spectral power of particle backscattering coefficient	-
S	Spectral slope for non-algae particles (S_{nap}) or CDOM (S_{cdom})	nm^{-1}
SPM	SPM = PIM + POM	$mg.L^{-1}$
$E_d(\lambda)$	Spectral downwelling irradiance below the water surface	$W.m^{-2}. nm^{-1}$
$E_s(\lambda)$	Spectral downwelling irradiance incident onto the water surface	$W.m^{-2}. nm^{-1}$
$L_t(\lambda)$	Spectral total radiance above water surface	$W.m^{-2}.sr^{-1}.nm^{-1}$
$L_{sky}(\lambda)$	Spectral incident sky radiance	$W.m^{-2}.sr^{-1}.nm^{-1}$
$K_d(\lambda)$	Downwelling diffuse attenuation coefficient	m^{-1}
$a(\lambda)$, $a_t(\lambda)$	Spectral total absorption coefficient ($a(\lambda) = a_{cdom}(\lambda) + a_p(\lambda) + a_w(\lambda)$)	m^{-1}
$a_{cdom}(\lambda)$	Spectral absorption coefficient of CDOM	m^{-1}

$a_p(\lambda)$	Spectral absorption coefficient of particulate matter ($a_p(\lambda) = a_p(\lambda) + a_{nap}(\lambda)$)	m^{-1}
$a_\varphi(\lambda)$	Spectral absorption coefficient of phytoplankton pigments	m^{-1}
$a_{nap}(\lambda)$	Spectral absorption coefficient of non-algae particles	m^{-1}
$a_w(\lambda)$	Spectral absorption coefficient of water	m^{-1}
$a_{tnw}(\lambda)$,$a_{\text{t-w}}$	Spectral non-water total absorption coefficient	m^{-1}
$b(\lambda)$	Spectral scattering coefficient	m^{-1}
$b_b(\lambda)$	Spectral total backscattering coefficient ($b_b(\lambda)$=$b_{bp}(\lambda)$+ $b_{bw}(\lambda)$)	m^{-1}
$b_{bp}(\lambda)$	Spectral total backscattering coefficient of particulate matter	m^{-1}
$b_{bw}(\lambda)$	Spectral total backscattering coefficient of water	m^{-1}
$u(\lambda)$	Ratio of backscattering coefficient to the sum of absorption and backscattering coefficient ($b_b(\lambda)$/ $b_b(\lambda)$+ $a(\lambda)$)	-
Z	Depth within the water column	m
z_i	Depth for time - i	m
Z_{SD}	Secchi Disk Depth	m
Q	Ratio between	
T	radiance transmittance	
γ	water to air internal reflection coefficient	
λ_0	Reference wavelength	nm

7.2 FUTURE RECOMMENDATIONS

Our findings demonstrated improvements related to the expansion of optical knowledge in linked systems as cascade of reservoirs, quality of R_{rs} calculations, the empirical model and its strengths and limitations, besides to provide a new SA model capable to estimate SPM over a widely range of OACs concentrations. However, some recommendations are also highlighted for future works.

The first recommendation is to test new sensors with similar spatial resolution and high spectral resolution, such as Sentinel-2 that has spectral bands centered at 705 nm, 740 nm and 783 nm with 20 meters at spatial resolution. It might be possible that the red-edge band used as the reference wavelength can improve the SPM estimations in more eutrophic reservoirs, as shown in Watanabe et al. (2016) that developed QAA_{BBHR} using a dataset obtained in Barra Bonita reservoir. Moreover, additional dataset considering the other two reservoirs, Promissão and Três Irmãos, will offer a more robust dataset and can be used to revalidate our model, QAA_{TRCS}.

Another relevant issue is related to the atmospheric correction methods. Besides OLI/Landsat-8 reflectance product presents a good accuracy (Pahlevan et al., 2019), it was noticed that coastal band introduced errors in SPM estimations when we applied the model II (561/(482-443)) to the image. Maybe tests related to new atmospheric correction methods, such as the presented in ACOLITE (Vanhellemont, 2019) can derive more accurately K_d values, and retrieved lowest errors of SPM.

Further studies about profile measurements of absorption and backscattering can be conducted to better understand the dynamic inside the aquatic systems. Additional challenge might be faced regarding to backscattering coefficient, that was not measured just-below the surface. The first measurement was conducted at least in 0.50 depth and some of measurements were affected by the boat instability. Hydrolight simulations can be an alternative to provide reliable optical information in the case of in situ measurement limitations.

Once the QAA_{TRCS} was validated using OLI/Landsa-8 images, it is possible to apply the model to a pre-processed time-series and identify the occurrence of SPM standards along the TRCS. In this case, it will be also possible to identify possible causes or drivers related to high levels of SPM (rainfall, temperature, flow rates, retention time, and so on).

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