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Analyzing the feasibility of a space-borne sensor (SPOT-6) to estimate the height of submerged aquatic vegetation (SAV) in inland waters

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ABSTRACT

Remote sensing based approaches have been widely used over the years to monitor and manage submerged aquatic vegetation (SAV) or aquatic macrophytes mainly by mapping their spatial distribution and at the most, modeling SAV biomass. Remote sensing based studies to map SAV heights are rare because of the complexities in modeling water column optical proprieties. SAV height is a proxy for biomass and can be used to estimate plant volume when combined with percent cover. The objective of this study was to explore the feasibility of a satellite sensor to estimate the SAV height distribution in an inland reservoir. Also to test different radiative transfer theory based bio-optical models for estimating SAV heights using SPOT-6 data. The satellite-based multispectral data have rarely been used and SPOT-6 data, to the best of our knowledge, have never been used to estimate SAV heights in inland water bodies. In addition to depth and hydroacoustic data, *in situ* hyperspectral radiance and irradiance were measured at different depths to compute remote sensing reflectance (R_{rs}) and the attenuation coefficients (K_d and K_{Lu}). Two models, Palandro et al. (2008) and Dierssen et al. (2003), were used to derive bottom reflectance from both *in situ* and atmospherically corrected SPOT-6 R_{rs}. Bottom reflectance-based vegetation indices (green-red index, slope index, and simple ratio) were used to estimate SAV heights. Validation was performed using echosounder acquired hydroacoustic data. *In situ* model calibration produced an R^2 of 0.7, however, the validation showed a systematic underestimation of SAV heights and high Root Mean Square Error (RMSE); indicating that there is a greater sensitivity in *in situ* models to localized variations in water column optical properties. The model based on SPOT-6 data presented higher accuracy, with R^2 of 0.54 and RMSE of 0.29 m (NRMSE = 15%). Although the models showed a decreased sensitivity for SAVs at depths greater than 5 m with a height of 1.5 m, the finding nonetheless is significant because it proves that re-calibration of existing bottom reflectance models with more field data can enhance the accuracy to be able to periodically map SAV heights and biomass in inland waters. Although the initial results presented in this study are encouraging, further calibration of the model is required across different species, seasons, sites, and turbidity regime in order to test its application potential.

1. Introduction

Excessive growth of submerged aquatic vegetation (SAV) or submerged macrophytes in inland waters can produce negative economic and ecologic impacts. But when managed properly they play several important functions, such as influencing nutrient cycling, maintaining water and sediment chemistry, providing food and shelter for various invertebrates and vertebrates, and changing the spatial structure of the waterscape by increasing habitat complexity (Thomaz et al., 2008). In addition to spreading rapidly around the globe by anthropogenic means such as dispersal via hitchhiking and unauthorized release, some of the invasive SAV species have experienced a range-shift in past few decades spreading to higher latitudes mainly due to a pattern shift in temperature, precipitation, and atmospheric CO_2 triggered by climate change. Inland waters with ecological imbalance can facilitate an uncontrolled growth of SAV, which could be a significant problem especially in developing countries with lax regulations such as Brazilian reservoirs. Negative economic and ecologic impacts caused by excessive SAV will affect navigation, water quality and supply, hydropower, irrigation, fisheries, recreation, human and animal health, and land

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values (Jakubauskas et al., 2002; Rockwell, 2003). SAV will have major effects on the productivity and biogeochemical cycles of the system (Carpenter & Lodge, 1986). The increased run-off to the water body in the rainy season may cause fragmentation of SAV, obstructing water passing though the turbines of the hydroelectric plants causing significant economic damage (Marcondes et al., 2003). According to Wetzel (2001), excessive growth of macrophytes can curtail or eliminate human use of reservoirs, lakes and river ecosystems; hence several approaches (i.e., mechanical, biological, chemical) have been proposed for the control and management of aquatic macrophytes. Mechanical control primarily involves cutting and removal of the vegetation (Engel, 1990; Armellina et al., 1996; Velini, 2005). Biodegradable or biologically inactive herbicides are commonly used as chemical control (Schmidt, 2009). Sterile Grass Carp are widely used as biological control because of their aggressive grazing (Chilton and Muoneke, 1992; Hanlon et al., 2000; Wells et al., 2003). However, the type and magnitude of the control is mainly dependent on the spatial distribution of SAV extent and biomass (Wetzel, 2001).

Remote sensing technologies have the potential to map and quantify the SAV distribution and biomass at frequent interval. In fact, studies using remote sensing-based empirical and radiative transfer models to identify and map SAVs and other benthic habitats are fairly common in estuarine and coastal environments compared to inland freshwater environments (Dekker et al., 2005; Mishra et al., 2007; Hunter et al., 2010; Roelfsema et al., 2014). Remote sensing techniques have been rarely used to map SAV heights in optically complex inland waters. SAV height, a proxy for biomass, is an important biophysical property and can be used to estimate underwater light availability and plant volume when combined with percent cover. In addition, per-pixel SAV height data is easier to collect in the field compared to biomass which is often the limiting factor in robust calibration of remote sensing models.

Mapping SAV in freshwaters using satellite remote sensing can overcome problems related to access, scale, and distribution; however, high-resolution images are required with appropriate spectral characteristics (Ashraf et al., 2010). However, remote sensing data used in SAV mapping, with a few exceptions, tend to be either *in situ* or airborne multi- or hyperspectral data not satellite data. For example, Mishra et al. (2007) used hyperspectral Airborne Imaging Spectroradiometer for Applications (AISA) Eagle data to detect and classify the seagrasses, coral reef and associated benthic habitats. The importance of removing the effect of the water column in order to achieve accurate mapping of benthic habitats was emphasized in the study. Roelfsema et al. (2014) presented a semi-automated object-based image analysis approach for mapping dominant seagrass species, percentage cover and above-ground biomass of a shallow, clear water seagrass habitat using a time-series of field data and coincident high spatial resolution satellite imagery for the Eastern Banks, Moreton Bay, Australia. Hunter et al. (2010) used data from Compact Airborne Spectrographic Imager-2 (CASI-2) to map the distribution of macrophytes in shallow lakes (< 2.5 m mean depth) in the Upper Thurne region of the Norfolk Broads, UK. Giardino et al. (2015) presented an application of a physics-based method that relies on spectral inversion procedures to estimate benthic substrate types in Lake Trasimeno (Italy) from airborne imaging spectrometry data. Pande-Chhetri et al. (2014) presented methods to classify SAVs in shallow water (< 3 m) using the airborne CASI hyperspectral sensor in St. Johns River, Florida (USA). Zou et al. (2013) studied the spectral characteristics of SAV using *in situ* data in a eutrophic aquatic system (Shanghai, China). They observed a non-proportional decrease in reflectance with the reduction of SAV coverage. Visser et al. (2015) investigated the possibility of creating maps of SAV depth distribution in shallow clear water streams using low-altitude optical remote sensing. At the time of sampling, their study sites had a maximum water depth of around 0.5 m and low turbidity. Similarly, Williams et al. (2003) studied the use of high spatial resolution hyperspectral remote sensing to map SAV distributions and abundance in the Potomac River, Maryland, USA.

In terms of satellite-based studies, Dekker et al. (2005) used Landsat images to detect the change in seagrass and macrophyte communities of Wallis Lake, a shallow estuarine lake in New South Wales, Australia over a period of 14 years. Dogan et al. (2009) used QuickBird satellite image to identify and map SAV, with high accuracy, in a shallow lake (i.e., mean and maximum depths were 2.1 and 3.5 m, respectively). Heblinski et al. (2011) monitored and assessed the status of littoral vegetation in Lake Sevan (Armenia), with a depth up to ~ 3 m using QuickBird data. These studies concluded that accurate mapping of SAV species relies on the condition of the water column being sufficiently transparent to obtain a significant discriminatory part of the spectrum of the substrate. Epiphytic growth over SAV could also be a confounding factor and hyperspectral remote sensing could resolve this issue more clearly, however, there would be a significant increase in the cost of data acquisition.

Several other studies have concluded that high resolution airborne or satellite images may not be able to extract information about SAV in relatively deep reservoirs using frequently adopted simple methods such as image classification or empirical band ratios because of the target's low signal to noise ratio (Rotta et al., 2016, 2013; Boschi, 2011; Malthus, 2017). Semi-analytical models have been proposed as an alternative to remove the water column influence and to retrieve bottom reflectance in water bodies to study submerged targets. However, most models used to retrieve the bottom signal were developed for clear, shallow coastal environments (Lee et al., 1994; Lee and Carder, 2002; Mishra et al, 2005, 2007, 2006; Palandro et al., 2008; Brando et al., 2009). Semi-analytical models for estimating SAV height in inland waters such as lakes and tropical reservoirs by satellite remote sensing remains a challenge to overcome, particularly when SAV in these water bodies can survive at relatively deeper depths. SAV in Brazilian reservoirs can survive and grow at depths greater than 6 m (Rotta et al., 2012; 2016). Rotta et al. (2012) mapped SAV in the Porto Colômbia Reservoir (Uberaba River, Minas Gerais State) using an echosounder detecting presence of SAV up to 7 m depth. The densest SAV was observed by Batista et al. (2012) at depths between 2 and 4 m in Taquaruçu reservoir (Paranapanema River, between Paraná and São Paulo State), showing SAV growing even at the depth range of 6–8 m. The status of SAV in Nova Avanhandava Reservoir (Tietê River, São Paulo State) was analyzed by Rotta et al. (2016) who reported their occurrence at depths up to 9 m. The detection of bottom signal is difficult at such deeper waters even when using *in situ* sensing due to the attenuation and scattering of radiation in the water column. Rotta et al. (2016) concluded that it is necessary to recalibrate and tune existing radiative transfer models with lots of field data in order to achieve the desired accuracy in mapping SAV biomass and height using satellite data.

The initial assumption made in this study was that benthic reflectance produced by applying radiative transfer models on satellite data may reveal the true absorption characteristics of SAV canopies which can then be incorporated in empirical models using existing vegetation indices (VIs) to estimate SAV heights. VIs based on red (~ 660 nm) and green (~ 560 nm) bands can be used in aquatic environments, such as green–red vegetation index (GRVI), Slope, and band ratio (G/R). Tucker (1979) evaluated and quantified the relationships between linear combinations of several VIs, including GRVI and G/R, and experimental plot biomass, leaf water content, and chlorophyll content. Motohka et al. (2010) evaluated *GRVI* as a phenological indicator for several representative ecosystems in Japan. It was able to detect subtle differences in the middle of the growing period for accurately classifying ecosystem types. The sensitivity of chl-*a* scattering at green to chl-*a* absorption at red is the underlying foundation of the Slope model (Mishra and Mishra, 2010). The simple ratio between reflectance at NIR and Red has been used in numerous studies as an indirect method of measuring vegetation biophysical properties such as leaf area index (LAI) (Jordan, 1969; Jensen, 2009). The simple ratio (NIR/R) from Landsat TM data was correlated to ground-based

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