Remote Sensing of Environment 163 (2015) 186–205

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Canopy modeling of aquatic vegetation: A radiative transfer approach

Guanhua Zhou, Chunyue Niu *, Wujian Xu, Wenna Yang, Jiwen Wang, Huijie Zhao

School of Instrument Science and Opto-electronics Engineering, Beihang University, Beijing 100191, China

A R T I C L E I N F O

Article history:
Received 29 July 2014
Received in revised form 20 March 2015
Accepted 21 March 2015
Available online 11 April 2015

Keywords:
Aquatic vegetation
Radiative transfer
Optical shallow water
Monte Carlo
BRF

A B S T R A C T

Aquatic vegetation in shallow waters can absorb nitrogen and phosphorus from eutrophic waters, and effectively control water bloom. However, our knowledge of the interaction between solar radiation and aquatic vegetation is limited. This restricts the protection of aquatic vegetation. This paper proposes a radiative transfer approach for homogeneous aquatic vegetation canopy, based on the theories for terrestrial vegetation and Case II water. The effects of rough water surface and bottom reflection are also taken into consideration. Validations against an independent Monte Carlo model and field experiment data exhibit well consistencies on the bidirectional reflectance of homogeneous aquatic vegetation canopy. As expected, the results for sparse canopy degenerate. This model can be used for canopy modeling of emergent, floating or submerged aquatic vegetation. Potential applications include retrieval of biophysical or biochemical parameters based on hyperspectral data and physical process.

1. Introduction

Much of polluted water is poured into coastal and inland waters due to human activities. As a consequence, rapid increase of total nitrogen and phosphorus creates eutrophic waters. This in turn causes a massive reproduction of algae. Water bloom may appear more frequently and unexpectedly (An et al., 2013). Fortunately, aquatic vegetation can absorb nitrogen and phosphorus from these eutrophic waters, and effectively control water bloom (Abe, Komada, & Ookuma, 2008). Aquatic vegetation usually grows in the transition regions between land and water, typically a wetland ecosystem. However, these regions are generally difficult for humans to set foot due to the presence of marshes and mires. As a non-contact detection method, remote sensing has unique advantages in the monitoring and information extraction of aquatic vegetation. Various applications based on multispectral or hyperspectral data have been reported, e.g. classification (Schmidt & Skidmore, 2003), mapping (Gilmore et al., 2008) or monitoring (Barducci, Guzzi, Marcoionni, & Pippi, 2009) of aquatic vegetation, and retrieval of biomass (Proisy, Couteron, & Fromard, 2007) or leaf area index (LAI) (He, Quan, & Xing, 2013). Detailed reviews can be found in Adam, Mutanga, and Rugege (2010) and Klemas (2011, 2013). But the majority of the present methods belong to the empirical or semi-empirical category and greatly rely on field survey and measurement. The relationship between reflectance spectra and parameters (canopy structure parameters, etc.) is not described in detail. Further research on the radiative process in aquatic vegetation is also needed (Adam et al., 2010).

The habitats of aquatic vegetation usually have a shallow water depth and the incident radiation can propagate to the bottom. This is the so-called optical shallow water (Ackleson, 2003). Based on the relative position of canopy and water, aquatic vegetation can be divided into three categories, namely emergent aquatic vegetation (EAV), floating aquatic vegetation (FAV) and submerged aquatic vegetation (SAV). Aquatic vegetation together with its habitat has the following one or more characteristics compared with Case I ocean water and terrestrial vegetation: (1) the simultaneous appearance of canopy and water results in a more complicated radiative transfer process, and the mixed spectra differ from those when either exists separately; (2) the water is relatively turbid, and the influences of water components (suspended particle, etc.) and bottom reflection on the spectra measured above water surface cannot be neglected (especially SAV vs. Case I water); (3) either part of or the entire canopy is immersed in water periodically or permanently, and the water surface has significant directional reflectance characteristics (especially EAV vs. terrestrial vegetation) (Vanderbilt et al., 2002); and (4) aquatic vegetation communities have high spatial complexity and temporal variability (Klemas, 2013), and their reflectance signals are easily affected by adjacent land, especially for airborne or spaceborne sensors. Thus the canopy modeling of aquatic vegetation needs to adhere to relevant theories, and grasp its own characteristics as well.

The canopy modeling of aquatic vegetation cannot be completely beyond the scope of the modeling of vegetation canopy. Various

* Corresponding author at: School of Instrument Science and Opto-electronics Engineering, Beihang University, No. 37 Xueyuan Road, Haidian District, Beijing 100191, China.

E-mail addresses: zhouguanhua@buaa.edu.cn (G. Zhou), chunyueniu@163.com (C. Niu), hjzhao@buaa.edu.cn (H. Zhao).

http://dx.doi.org/10.1016/j.rse.2015.03.015
0034-4257/

approaches have been summarized in Qin and Liang (2000), Disney, Lewis, and North (2000) and Chen, Li, Nilson, and Strahler (2000). Actually some early researches are based on the traditional vegetation canopy models. An example is the submerged vegetation canopy model by Suits (1984) (noted as Suits84) which is based on the Suits canopy model (Suits, 1972). The media below water surface was divided into two parts: turbid water (the upper layer) and mixed vegetation and water. Calculation of attenuation and scattering coefficients for mixed medium was given (Suits, 1984). Similarly, Ackleson and Klemas (1986) also built a radiative transfer model for submerged vegetation canopy by extending the Suits canopy model, namely Extended Suits Model (ESM). ESM uses matrix formulation and can be applied to multilayer media. However, the canopy morphology of Suits model is simplified to horizontal and vertical leaf area projections, and this leads to deviations of bidirectional reflectance profiles (Verhoef, 1984). Furthermore, only submerged canopy was discussed in Suits84 and ESM. Despite such deficiencies, these models lay a foundation for further research. Lee, Carder, Mobley, Steward, and Patch (1998) built a semi-analytical (SA) model for optical shallow water. The contribution of water column to remote sensing reflectance R_{rs} is separated from that of the bottom. This SA model was validated by the simulation results of Hydrolight (Mobley, 1994). However, bottom albedo is only a boundary condition in the SA model. No descriptions about the bidirectional reflectance distribution function (BRDF) of the bottom can be found. Mobley, Zhang, and Voss (2003) analyzed the effects of BRDF of non-Lambertian bottoms on R_{rs}, and errors were quantified if these bottoms were replaced by Lambertian ones. The Rahman model (Rahman, Pinty, & Verstraete, 1993) was used as an ersatz aquatic vegetation BRDF. However, as noted by the authors, BRDFs of aquatic vegetation, e.g. seagrass, may differ from those described by the Rahman model (Mobley et al., 2003). Zimmerman (2003) built a parameterized two-flow model of plane irradiance distribution for seagrass canopy. Impacts of canopy architecture on irradiance distribution were explored, and field measurements were used for validation. But this model pays more attention to irradiance distribution and photosynthesis rather than the BRDF of submerged canopy. Hedley (2008) proposed a three-dimensional (3D) radiative transfer model for shallow water environments based on spatial and directional discretization. This model can solve radiative transfer problems in anisotropic scattering media, and achieve good performances in a plane parallel configuration. In a later paper (Hedley & Enríquez, 2010), this 3D model was applied to seagrass canopies. Their BRDFs were demonstrated to be non-Lambertian and exhibited different features with those used in Mobley et al. (2003). However, computer simulation models are usually difficult to retrieve despite their high accuracy and capability of handling complicated 3D problems. It is notable that most of the models mentioned above have a spectrum mainly within the visible bands (400–700 nm). Although this is a general configuration in water color remote sensing, it is insufficient for exploring aquatic vegetation. Based on field experiments of several emergent vegetation species, Kearney, Stutzer, Turpie, and Stevenson (2009) demonstrated significant reflectance reductions in near infrared bands (900–1100 nm) with progressive inundation. Turpie (2012) added a shallow water background (Lee et al., 1998) to a two-layer canopy reflectance model (ACRM) (Kuusk, 2001) and developed the Wetland Canopy Reflectance Model (WCRM). WCRM can calculate the reflectance spectra of aquatic vegetation in visible and near infrared (VNIR) bands (400–1000 nm). Simulation results indicated a shift in the red-edge position, but a simple relationship to the relative inundation level could not be confirmed (Turpie, 2013). Moreover, WCRM can simulate the bidirectional reflectance characteristics of emergent vegetation, the hot spot of canopy and the specular reflection of water surface, simultaneously (Turpie, 2012). However, water surface together with the media beneath is regarded as background in WCRM, and increasing inundation levels are simulated by decreasing the LAI values above water. Interactions between radiation and submerged canopy are not discussed. Beget, Bettachini, Di Bella, and Baret (2013) built a radiative transfer model for flooded vegetation named *SAILHFlood*. Two vegetation layers, the emerged vegetation layer and the submerged vegetation layer, are included. However, a flat water surface is used in *SAILHFlood*, and the vegetation is assumed to be submerged into clear water without particles.

Until now, seldom general purpose model has been reported on the directional reflectance spectra of aquatic vegetation, much less appropriate descriptions of the interaction between incident radiation and coupled vegetation–water system. In this paper, we propose a radiative transfer approach for homogeneous aquatic vegetation, namely the Aquatic Vegetation Radiative Transfer model (AVRT). The AVRT model can calculate the bidirectional reflectance spectra of emergent, floating and submerged aquatic vegetation in visible and near infrared bands (400–1000 nm). The submerged part of canopy is also taken into consideration besides canopy architecture, optical active components of water, rough water surface, etc. Basic principles and relative models used in the AVRT are given in Section 2. Implementations are given in Section 3, including a schematic diagram. Then a brief description of the Aquatic Vegetation Monte Carlo model (AVMC) and the corresponding validation tests, a model-to-model comparison and a primary field experiment, are given in Section 4. Finally, the conclusions are given in Section 5.

2. Methodology

According to the above review, radiative transfer modeling of aquatic vegetation is recommended to provide a comprehensive description of the interaction between incident radiation and the coupled vegetation–water system at least in VNIR bands. The effects of rough water surface and bottom reflection cannot be overlooked. Model versatility and a good balance between accuracy and efficiency are also important for future applications. Based on these principles, the AVRT takes the following approximations: (1) the coupled vegetation–water system is regarded as homogeneous continuous media, and variations of its optical properties are only allowed in vertical direction; thus (2) the system can be divided into medium layers, and every elemental layer has homogeneous optical properties (only three kinds of medium layers are considered, i.e. canopy layer, water layer and mixed layer of canopy and water); (3) the average height of water surface is taken as zero, and the thickness of water surface is assumed to be zero; and (4) a Lambertian bottom is used for now. The basic framework of the AVRT is based on the methodology of the SAIL model (Verhoef, 1984, 1985). Reflectance and transmittance of a single leaf are calculated by the PROSPECT model (Jacquemoud & Baret, 1990). The PROSPECT and SAIL families are undergoing continuous improvement, and have gone through extensive validations and various applications (Feret et al., 2008; Jacquemoud, Bacour, Poilve, & Frangi, 2000; Jacquemoud et al., 2009; Kallel, Verhoef, Le Hégarat-Mascle, Ottlé, & Hubert-Moy, 2008; Pinty et al., 2004; Verhoef & Bach, 2007). In addition, the hot spot effect (Verhoef, 1998; Kuusk, 2001) of the emergent part of aquatic vegetation canopy, and reflection and transmission across a rough water surface (Cox & Munk, 1956) are also considered.

2.1. PROSPECT

At present, the emergent and submerged leaves are all treated as bi-Lambertian. The PROSPECT-5 (Feret et al., 2008) model is used to calculate the reflectance and transmittance of a single leaf in the 400–1000 nm range (available on the website http://teledetection.ipgp.jussieu.fr/prosail/). The needed leaf biochemical parameters include leaf mesophyll structure (N), pigment contents (C_{ab} for chlorophyll a and b, C_{cx} for total carotenoid, other pigments such as anthocyanin are not considered), water depth (C_w or EWT for equivalent water thickness) and dry matter content (C_m or LMA for leaf mass per area)