TOWARDS OPERATIONAL WATER QUALITY MONITORING WITH AN ANALYTICAL RADIATIVE TRANSFER MODEL

Amanda de Liz Arcari[1], Juliana Tavora[1], Bas Retsios[1], Daphne van der Wal[1,2] and Mhd. Suhyb Salama[1]

[1]Department of Water Resources, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands - a.delizarcari@utwente.nl; [2] Department of Estuarine and Delta Systems, NIOZ Royal Netherlands Institute for Sea Research, Yerseke, The Netherlands

ABSTRACT

Water quality monitoring is essential for effective water resources management. Present state of the art satellite sensors provide high spatial and temporal resolution required for operational monitoring of key water quality variables in coastal and inland waters. Nonetheless, most of the retrieval models currently available require regional tuning and are therefore not applicable to other geographic areas and not useful in detecting anomalies. This study introduces an operational model to process Sentinel-2 images from any part of the world and derive water quality indicators based on the analytical solution of the two-stream radiative transfer equations. The potential of the model for monitoring distinct water bodies is demonstrated with two case studies in Brazil and Kenya. Scientific and technical improvements to the model can provide additional robustness and usability.

Key words **—**water quality, operational, model, monitoring

1. INTRODUCTION

While water quality is essential for the maintenance of ecosystem services provided by aquatic systems, human activities threaten it with different forms of pollution and alterations (e.g. agricultural runoff, wastewater, dredging, erosion, etc.) [1]. Knowing the current conditions and changes in a water body supports informed decisions regarding use, control and recovery actions [2]. Therefore, water quality monitoring is the corner stone of effective water resources management [3].

Remote sensing is a powerful complement to the customary labor-intensive in-situ monitoring of water quality. It can provide frequent and spatially comprehensive observations of water bodies of varied sizes, often free of charge. Although developed for land applications, the enhanced spatial and temporal resolutions of sensors such as the Sentinel-2 Multispectral Imager (MSI) and Landsat 8/9 Operational Land Imager (OLI) offer opportunities for operational monitoring of key water quality variables in coastal and inland waters [4]. Inherent optical properties (IOPs) of water constituents, which can be derived from remote sensing, reflect physical and biological properties of the water column [5] and are therefore characterized as water quality indicators (WQIs). Despite the suitability, there is limited offer of a systematic processing chain to use Sentinel-2 MSI and other high-resolution satellite images for water quality monitoring on a global scale.

In this study, we introduce an operational model to derive water quality indicators at 10 m resolution from Sentinel-2-MSI images. The operational model is based on the analytical solution of the two-steam radiative transfer model of Salama and Verhoef [6]. The use of radiative transfer allows a better representation of the actual process of light attenuation in turbid media. Complemented with analytical solutions, the 2SeaColor model does not depend on empirical relationships, and provides a generic approach to derive water quality information from a diversity of water bodies with various optical complexities.

This study demonstrates the suitability of the suggested operationalization of 2SeaColor model in deriving globally distributed WQIs in two distinctive systems: Conceição Lagoon (Brazil) and Lake Naivasha (Kenya). The results of the model have the potential of being used for different monitoring purposes by stakeholders at the local scale.

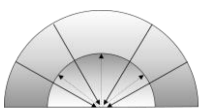
2. MATERIAL AND METHODS

2.1. The 2SeaColor Model

The 2SeaColor solves the two stream radiative transfer and provides additional numerical stabilization as detailed in [6]. Validation has been performed for aquatic systems of varied characteristics across the world [6]–[9].

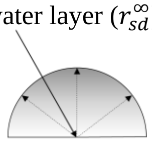
The model considers the diffuse and direct radiant fluxes and derives elegant formulation, as shown in Figure 1 and Equations 1 and 2 (published in [6]) . For the diffuse component, the bi-hemispherical reflectance of the semi-infinite water layer (r_∞) is:

$$r_\infty = \frac{x}{1 + x + \sqrt{1 + 2x}} \quad (1)$$



For the direct component, the directional-hemispherical reflectance of the semi-infinite water layer (r_{sd}^∞) is:

$$r_{sd}^\infty = \frac{\sqrt{1 + 2x} - 1}{\sqrt{1 + 2x} + 2\mu_w} \quad (2)$$



Where x is the ratio between backscattering (b_b) and absorption (a) coefficients: $x = b_b/a$; and μ_w is the cosine of the solar zenith angle beneath the water surface.

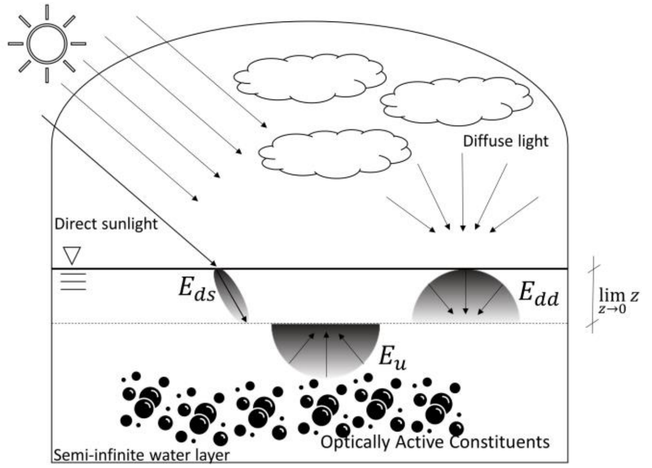


Figure 1. Schematic diagram of the radiant fluxes in 2SeaColor: downwelling direct irradiance (E_{ds}), downwelling diffuse irradiance (E_{dd}) and upwelling diffuse irradiance (E_u).

The irradiance reflectance just beneath the water surface (R_∞) is then calculated according to the fraction of diffuse light (f):

$$R_\infty = r_\infty f + r_{sd}^\infty (1-f) \quad 3$$

Ultimately, the forward model gives the above surface remote sensing reflectance (R_{rs}) considering the differences between the two media (air and water):

$$R_{rs} = \frac{t(a,w)t(w,a)}{n_w{}^2[1-r(w,a)R_\infty]} \times \frac{R_\infty}{Q} \quad 4$$

Where Q is the radiance to irradiance conversion factor equal to 3.25 sr^{-1} [10], n_w is the index of refraction of water, $t(a,w)$ and $t(w,a)$ are respectively the air-to-water and water-to-air Fresnel transmittances and $r(w,a)$ is the water-to-air Fresnel reflectance.

Parametrizations are implemented as in [7]. Spectral optimization based on non-linear least-squares fitting is used for the inversion of the model and retrieval of water quality indicators: diffuse attenuation coefficients-k_d, absorption by chlorophyll-a-$a_{chla}(440)$, absorption by combined detritus and coloured dissolved organic matter-$a_{dg}(440)$, backscattering by suspended particulate matter-$b_{b_{spm}}(440)$, spectral slope of a_{dg}-S and spectral slope of $b_{b_{spm}}$-Y. Initialization values for those are defined based on [11].

2.2. Operationalization

The implementation of the operational 2SeaColor is carried out in Python and it is available on the following GitHub repository: https://github.com/suhybsalama/2SeaColor

The code is optimized for parallel computing and processes Sentinel-2 Level 2 images to produce WQIs maps according to the flowchart in Figure 2.

2.3. Application

Two Case Studies are shown to demonstrate the suitability of the operational model for different systems and purposes:

- Case I – Conceição Lagoon: Brackish coastal lagoon in Southern Brazil; for identifying main spatial-temporal patterns of WQIs.
- Case II – Lake Naivasha: shallow freshwater lake in Kenya; for detecting floating vegetation.

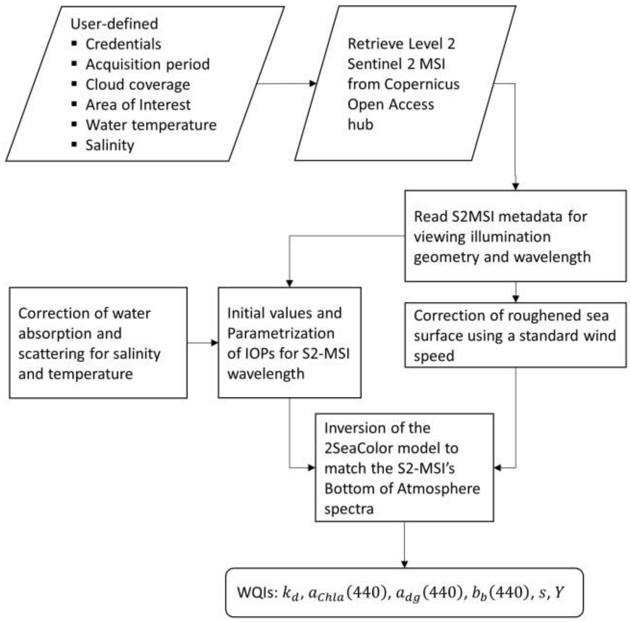


Figure 2. Operational 2SeaColor flowchart

3. RESULTS

3.1. Case I - Conceição Lagoon

The operational 2SeaColor model was applied to a time-series of 139 Sentinel-2 images acquired between 2019 and 2021 for Conceição Lagoon.

Figure **3** shows an RGB composite of the mean $a_{chla}(440)$, $a_{dg}(440)$ and $b_{b_{spm}}(440)$ (stretched for 0.5 standard deviation in each channel) for the period, which give an indication of the main spatial patterns of the WQIs in the area. It is possible to observe that absorption by organic matter is higher in the south segment and the northernmost branch of the lagoon compared to the rest of the lagoon. This is supported by evidence that the south segment is strongly influenced by freshwater inputs from intensely occupied basins and there is reduced exchange with the rest of the water body, whereas the north branch is where the largest watershed (João Gualberto river) empties [12], [13]. On the western margins of central-north lagoon the absorption by chlorophyll-a is comparatively high, while in the middle of central lagoon all of the constituents show high relative contributions to the attenuation process.

Useful information can also be inferred from the trend of WQIs. In this case, a linear trend was calculated via least-square fitting for the time-series (95% confidence). Backscattering of suspended material had a uniform negative trend throughout the lagoon for that period (not shown here). It could indicate solids deposition in response of mixing dynamics of the lagoon, mainly influenced by wind and hydrological conditions [12]. For $a_{dg}(440)$ a positive trend is seen especially in the south lagoon, where urbanization is strongest (Figure **3** b).

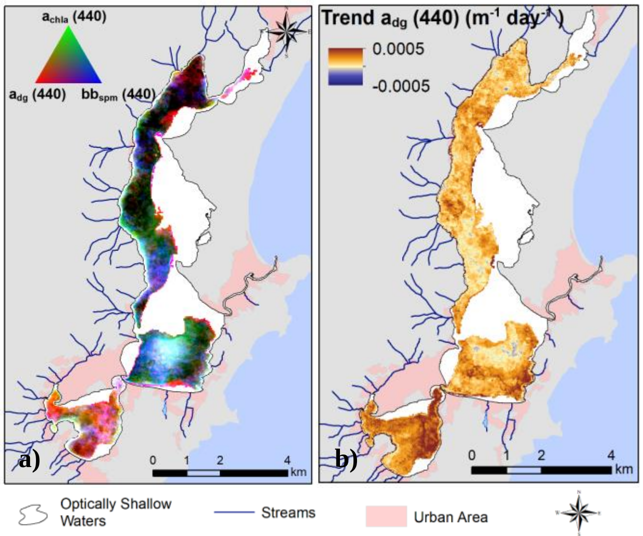


Figure 3. a) RGB composite of $a_{chla}(440)$, $a_{dg}(440)$ and $b_{b_{spm}}(440)$ stretched for 0.5 standard deviation and b) Trend of $a_{dg}(440)$ per day for the 2019-2021 period in Conceição Lagoon

3.2. Case II - Lake Naivasha

The model was applied to three images of Lake Naivasha in October 2021. From the RGB composites of $a_{chla}(440)$, $a_{dg}(440)$ and $b_{b_{spm}}(440)$ (Figure 4) it is possible to identify features appearing in white color, which reflect high values for all of the WQIs. According to local expertise, these are likely associated with spotted floating mats of invasive vegetation species of water hyacinth during the same period of the images acquisition. The model can therefore be useful for monitoring the mats and how they develop and move over time.

4. DISCUSSION

The results indicate the potential of the operational model for different monitoring purposes in distinct systems. Nevertheless, there are still scientific and technical limitations that need to be addressed for a wider use of the tool.

Firstly, due to its analytical solution, the 2SeaColor is sensitive to noise in reflectance, often caused by sun glint, clouds and atmospheric correction issues [14]. At the current stage, the model uses atmospherically corrected Sentinel-2 (Level-2) images, processed with sen2cor, which was mainly developed for land studies.

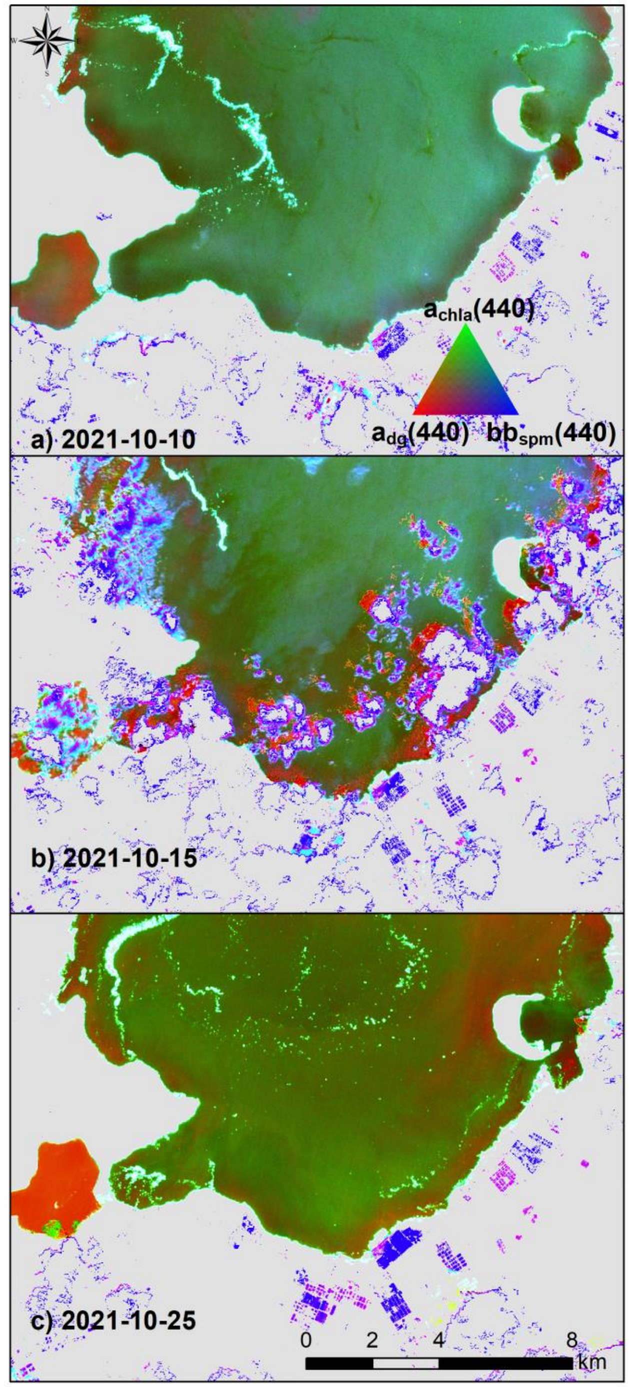


Figure 4. RGB composites of $a_{chla}(440)$, $a_{dg}(440)$ and $b_{b_{spm}}(440)$ in Lake Naivasha

Improvements in that sense can therefore include atmospheric correction of the Level-1 images with Polymer, specifically designed to deal with water bodies under sun glint conditions [15]. A more efficient algorithm for cloud and cloud shadow masking over coastal and inland waters, such as WiPE [16], could also benefit the model. Furthermore, the 2SeaColor still relies on some simplifications. For instance, it assumes an infinitely deep water layer, and hence does not yield accurate values in optically shallow waters.

Regarding the technical aspects, the code still requires relatively high processing capabilities. To make it more accessible and user-friendly, a cloud computing version of the code in Google Earth Engine platform shall also be implemented.

5. CONCLUSIONS

With this study, a physically-based inversion method founded on the solution of the two-stream radiative transfer equations, was presented as an operational tool for water quality monitoring. With two case studies we show that the model is capable of deriving water quality indicators in fresh and saline, inland and coastal waters without the need for regional tuning. The capability of the model in detecting floating mats of water hyacinth in fresh water was also demonstrated. Finally, the model is module and can be extended to include the bottom reflectance of shallow waters and the atmosphere effect.

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