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Remote sensing of euphotic depth in shallow tropical inland waters of Lake Naivasha using MERIS data

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ABSTRACT

Freshwater resources are deteriorating rapidly due to human activities and climate change. Remote sensing techniques have shown potential for monitoring water quality in shallow inland lakes, especially in data-scarce areas. The purpose of this study was to determine the spectral diffuse attenuation coefficient ($K_d(\lambda)$) of the water column, in order to map the euphotic depth (Z_{eu}) of Lake Naivasha, Kenya using the Medium Resolution Imaging Spectrometer (MERIS). Intensive in situ radiometric and limnological data collection was undertaken at Lake Naivasha. Atmospheric correction was done on the MERIS images using MERIS Neural Network algorithms, Case 2 Waters (C2R) and Eutrophic Lakes processors and the bright pixel atmospheric correction algorithm (BPAC). The Eutrophic Lakes processor gave the most accurate atmospherically corrected remote sensing reflectances at 490 nm compared to the other processors, with mean absolute percentage error (MAPE) of 47% and a root mean square error (RMSE) 43%, with BPAC giving negative reflectances in the blue spectral range. In situ K_d and Z_{eu} models were calibrated and validated using above- and under-water radiometric measurements, and tested on the Neural Network atmospheric correction processed MERIS images. The Eutrophic Lakes estimates were the most accurate, with an RMSE of 0.26 m^{-1} and MAPE of 18% for $K_d(490)$ and RMSE of 0.17 m and MAPE of 14% for Z_{eu}. The Z_{eu} maps produced from MERIS images clearly show the variation of euphotic depth both in space and time. These results indicate the suitability of MERIS to monitor euphotic depth and other water quality parameters of shallow inland water bodies.

1. Introduction

Freshwater ecosystems are limited renewable resources essential for socio-economic development and environmental sustainability (Koehler, 2008; Pimentel et al., 1997). However, many are deteriorating rapidly, due to anthropogenic activities within their catchments exacerbated by climate change (Kundzewicz et al., 2007; Shiklomanov, 1998; Vörösmarty et al., 2010). Increases in water temperature and changes in the timing and amount of precipitation and runoff may result in adverse changes in surface-water quality characterised by increased algal and zooplankton blooms, lower fish stocks and higher turbidity (Paerl, Hall, & Calandrino, 2011; Palaniappan et al., 2010; Parry, Canziani, Palutikof, van der Linden, & Hanson, 2007). The sustainable use of these resources requires a combination of surface water assessment programmes; and decision-making and management tools that are supported by ongoing monitoring and the availability of high quality data. Most developing countries are facing challenges to establishing effective water quality assessment programmes, such as a lack of routinely available data of sufficient quality, lack of adequate technical and institutional capacity and economic restrictions (Biswas & Tortajada, 2011; Mutia, 2006). To solve this dilemma, deployment of real-time, low-cost, rapid and reliable field sampling tools and technologies, as well as data-sharing and management institutions need to be established. Satellite remote sensing potentially provides a tool for monitoring inland water quality and other environmental phenomena because it offers an opportunity for data collection on systematic synoptic and temporal scales (Dekker, Vos, & Peters, 2002; Jensen, 2009; Schmugge, Kustas, Ritchie, Jackson, & Rango, 2002). Satellite data are becoming more freely available from providers such as the European Space Agency (ESA) and National Aeronautics and Space Administration (NASA). However, in situ observation networks need to be developed for calibration and validation of remote sensing data to improve the applicability and usefulness of earth observation technology in developing countries.

Satellite remote sensing of water quality has been undertaken for several decades, especially for the open ocean and coastal waters, providing estimates of primary production, suspended particulate matter (SPM), non-algal particles (NAP), coloured dissolved matter (CDOM) and chlorophyll *a* (Chl *a*) as a proxy for phytoplankton biomass (Cui et al., 2010; Marrari, Hu, & Daly, 2006). The European Space Agency's (ESA) Medium Resolution Imaging Spectrometer (MERIS) on-board the ENVISAT satellite, and the follow-up OLCI mission on the Sentinel

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3 satellite series, facilitates repeated monitoring of inland water at a moderate spatial scale of 300 m (Matthews, Bernard, & Winter, 2010). MERIS operated in 15 spectral bands distributed over the range from 390 to 1040 nm, with spectral bandwidths varying between 3.75 and 20 nm in the visible-NIR regions and low sensitivity to polarisation (Chami, Santer, & Dilligeard, 2001). The sensor was designed with this spectral and radiometric configuration to make it sensitive to the most important optically active water constituents such as phytoplankton biomass, CDOM, and NAP (Levrini & Delvart, 2011). The upcoming Ocean and Land Colour Instrument (OLCI) on-board Sentinel 3 is an improved continuation of MERIS. It has 21 spectral bands between 400 and 1020 nm, compared to the 15 bands of MERIS (Berger, Moreno, Johannessen, Levelt, & Hanssen, 2012; Donlon et al., 2012; Malenovský et al., 2012).

Light transmitted through the water column interacts with the particulate and dissolved matter present in the water and the water molecules (Mobley, 1994). Hence, it is absorbed and/or scattered by these constituents, resulting in it diminishing exponentially with depth (z). Water clarity is a bulk measure of the attenuation processes and quantifies the penetration depth of light in the water column. Typical parameters used to quantify light penetration include the Secchi disc depth, euphotic depth (Z_{eu}) and diffuse (K_d) – or beam (c) – attenuation coefficients. Secchi disc transparency is a common, easily conducted, but an approximate measure of light attenuation and is widely used as an important overall indicator of the trophic state of a water body: it provides the researcher with first-hand information about transparency and penetration of light in the water (Kirk, 2011; Preisendorfer, 1986), whereas K_d and Z_{eu} give a more quantitative measure of water clarity. The euphotic zone (euphotic meaning 'well lit' in Greek) is where there is sufficient Photosynthetically Active Radiation (PAR) to support photosynthesis (Kirk, 2011). Since Z_{eu} is an integrated measure of the biogeochemical properties of water, its variability illustrates environmental patterns potentially associated with climate and anthropogenic impacts (Chen, Chen, Ju, & Geng, 2005; Shang, Lee, & Wei, 2011). Z_{eu} defines the water depth where the PAR is 1% of its initial value at the surface (Scheffer, 2004) and has been used to describe the trophic status of a waterbody as well as its primary productivity (Haande et al., 2011; Jin et al., 2011; Khanna, Bhutiani, & Chandra, 2009). K_d in turn describes the exponential vertical decrease of irradiance thus quantifying the radiometric attenuation of light in water and the depth of the euphotic zone (Mobley, 1994).

Several approaches have been used to estimate Z_{eu} from remote sensing data. Satellite-derived chlorophyll has been used to estimate Z_{eu} in Case 1 waters where light attenuation is largely due to phytoplankton pigments (Morel & Berthon, 1989). However, this approach is not suitable for inland waters like Lake Naivasha, where light attenuation is caused by all the optically significant water components. An alternative approach is to use the physical relationship between diffuse attenuation coefficient in the PAR region ($K_d(PAR)$) and Z_{eu}. This involves first defining an empirical relationship between $K_d(PAR)$ from $K_d(490)$ using regression analysis. Research in various areas has indicated a very strong linear relationship between the two parameters (Barnard, Zaneveld, & Pegau, 1999; Kratzer, Håkansson, & Sahlin, 2003; Tang, Chen, Zhan, Xu, & Liu, 2007; Zaneveld, Kitchen, & Mueller, 1993). $K_d(490)$ is a parameter that can be derived directly from remote sensing data and is a standard product for the Moderate Resolution Imaging Spectroradiometer (MODIS), Sea Wide Field-of-view Sensor (SeaWiFS) and Medium Resolution Imaging Spectrometer (MERIS) (Austin & Petzold, 1981; Kratzer, Brockmann, & Moore, 2008; Mueller, 2000). Also, taking into account that K_d is an apparent optical property that can be derived from inherent optical properties, various algorithms linking K_d to absorption and backscattering coefficients have been developed based on radiative transfer approximations (Gordon, 1989; Kirk, 1984; Lee et al., 2005; Loisel & Stramski, 2000; Morel & Loisel, 1998).

The main objectives of this study are to quantify Z_{eu} from MERIS images in Lake Naivasha and to evaluate associated errors in the technique using in situ measurements. First, the spectral relationship between remote sensing reflectance and light attenuation was explored by plotting $K_d(\lambda)$ against the inverse $R_{rs}(\lambda)$. An above-water spectral range K_d model was then developed from in situ remote sensing reflectance, after which an empirical relationship between $K_d(490)$ and $K_d(PAR)$ to be used to estimate Z_{eu} was defined. Three atmospheric correction approaches were also evaluated for their suitability in shallow tropical lakes like Lake Naivasha, namely the MERIS Neural Network processors, Case 2 Regional and Eutrophic Lakes, and the Optical Data Processor of the European Space Agency (ODESA) Bright Pixel Atmospheric Correction (BPAC). The K_d and Z_{eu} algorithms were evaluated using atmospherically corrected MERIS data.

2. Methods

2.1. Site description

Lake Naivasha (0°45′ S; 36°26′ E), its name derived from the local Maasai name *Nai'posha* meaning rough water, is a shallow freshwater lake situated approximately 80 km North-West of Nairobi, in a dry, water-scarce zone of the Kenyan Rift Valley. With an average area of 145 km^2 and an average depth of 5 m, it is the second largest freshwater lake in Kenya after Lake Victoria in a region dominated by soda lakes. The lake has no surface outlet; its freshness has been explained by the interaction of the lake with the groundwater (Ayenew & Becht, 2008; Becht, Mwango, & Muno, 2006; Becht, Odada, & Higgins, 2006; Bergner, Trauth, & Bookhagen, 2003). Lake Naivasha comprises three lakes: the main lake, Crescent Island and Crater Lake.

Rich in biodiversity, the lake supports a thriving fishing industry, intensive horticulture and floriculture industries, as well as a geothermal power generation station. It shares the water table with groundwater aquifers that provide water to Naivasha town and its surrounding population. Hence, it plays a key role in local and national economic development (Harper & Mavuti, 2004), and was thus declared a wetland of international importance in 1995 under the Ramsar Convention (Becht et al., 2006,). The lake is, however, under enormous anthropogenic pressure from activities within the catchment. These have contributed to the deteriorating water quality of the lake, posing a threat to the aquatic life as evident from reports on the death of the fish in the lake (Becht & Chesterton, 2010; Kona & Mwiti, 2010; Otian'a-Owiti & Abiya Oswe, 2007). The increased input of nutrients such as phosphorus and nitrogen and increased sediment load through Gilgil and Malewa Rivers have caused an increase in the nutrient load of the lake. This has, in turn, fuelled the growth of phytoplankton and led to increased turbidity levels (Harper, Phillips, Chilvers, Kitaka, & Mavuti, 1994; Hubble & Harper, 2002; Kitaka, Harper, Mavuti, & Pacini, 2002b). The fringing *Cyperus papyrus* around the lake, protecting it against silt and nutrients has also been reduced, also contributing to the lake's degradation (Morrison & Harper, 2009). Chl *a* concentration increased from 27 mgm^{-3} (Kalff & Watson, 1986) to 56 mgm^{-3} between 1980 and 2002 (Ballot, Kotut, Novelo, & Krienitz, 2009).

2.2. In situ data collection

MERIS satellite overpass times were acquired from the European Space Agency (ESA) during fieldwork planning and preparation stage. During the overpass days, i.e. 17, 20, 23, 26, and 29 September 2010, intensive radiometric measurements were collected within 1 h of the scheduled overpass time for ground-truthing.

Bio-optical measurements were undertaken on Lake Naivasha from 17 September to 3 October 2010 (Fig. 1). These were hyperspectral radiometric measurements: downwelling above-water irradiance ($E_d(0^+;\lambda)$), upwelling above-water radiance ($L_u(0^+;\lambda)$), upwelling underwater radiance and downwelling under-water irradiance at two depths ($L_u(z_0;\lambda)$ and $L_u(z_1;\lambda)$, and $E_d(z_0;\lambda)$ and $E_d(z_1;\lambda)$ where $z_0 =$ 0.3 m and $z_1 =$ 0.75 m, respectively). Water samples were collected to analyse for SPM and Chl *a* concentrations and CDOM absorption. The radiometric measurements were taken using the Trios RAMSES-ARC