Remote sensing based water quality monitoring in Chivero and Manyame lakes of Zimbabwe

M. Chawira a,⁎, T. Dube b, W. Gumindoga c

a University of Zimbabwe, Department of Biological Sciences, Box MP 167, Harare, Zimbabwe
b University of Zimbabwe, Department of Geography and Environmental Science, Box MP 167, Harare, Zimbabwe
c University of Zimbabwe, Department of Civil Engineering, Box MP 167, Harare, Zimbabwe

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Lakes Chivero and Manyame are amongst Zimbabwe’s most polluted inland water bodies. MEdition Imaging Spectrometer (MERIS), a sensor on board the Environmental Satellite (EVISAT) to quantify water quality. In Lake Naivasha, remote sensing has been applied to retrieve diffuse attenuation coefficient and to map euphotic depth in studies carried by Majzoji et al. 2012. In the Zimbabwean situation, no optical remote sensing water quality studies have been conducted to the heterogeneous optical water quality constituents. Thus this paper’s main focus is directed towards testing MERIS resolution Imaging Spectrometer (MERIS), a sensor on board the Environmental Satellite (EVISAT) to quantify water.

1. Introduction

Optical remote sensing techniques provide rapid, temporal and spatial information on the state of the water quality variables which includes the hydro-physical, biological and biochemical with no interpretive problems that are associated with under sampling (Kutser et al., 2012; Koponen, 2006). Using satellite based remote sensing, surface reflectance is measured from a water body or water leaving radiance of concentrations of different water constituents such as coloured dissolved organic matter (CDOM), chlorophyll-a (chl a), total suspended matter (TSM) and many others (Babin and Stramski, 2002; Hu et al., 2010; Kutser et al., 2012). Remote sensing of water quality monitoring came into existence in 1978 when Coastal Zone Colour Scanner (CZCS) sensor was launched although the first satellite was launched in 1961. The spatial resolution (pixel size) of CZCS was not suitable for monitoring small and moderately sized lakes. As a result, it was largely used for monitoring oceans. Thereafter, other satellites which include Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) came into existence with spatial resolution ranging from 250 m to 1000 m. The Land Satellite Thematic Mapper (Landsat TM), a more advanced version observing the earth with TM band 1 developed for bathymetric and mapping coastal areas with a pixel size of 30 m by 30 m came into existence in 1999 (Robert et al., 2004).

In the African continent, a handful studies has been carried out in countries such as Kenya (Lake Naivasha), South Africa (Vaal dam, Bunguela upwelling zone, Zeekoevlei in Cape Town and Natal coast) and in Nigeria Lake Chad. Studies for monitoring algal blooms and TSM in South Africa have been carried out by Matthews et al., 2010; Bernard et al. (2001) in Zeekoevlei eutrophic lake and Bunguela zone respectively whilst studies on phytoplankton primary production in South African lakes have been carried out by Harding (1997). In the studies by Horion et al., 2010, daily bio-optical time series were derived from MODIS/Aqua imagery for Lake Tanganyika to monitor the lakes’ water quality. In Lake Naivasha, remote sensing has been applied to retrieve diffuse attenuation coefficient and to map euphotic depth in studies carried by Majzoji et al., 2012. In the Zimbabwean situation, no optical remote sensing water quality studies have been conducted to the heterogeneous optical water quality constituents. Thus this paper’s main focus is directed towards testing MERIS resolution Imaging Spectrometer (MERIS), a sensor on board the Environmental Satellite (EVISAT) to quantify water quality monitoring in Chivero and Manyame lakes of Zimbabwe.

⁎ Corresponding author. Tel.: +263 772 680 954.
E-mail address: tmarychawira@gmail.com (M. Chawira).
quality parameters (chl\_a, TSM and blue-green algae) in the eutrophic lakes of Manyame and Chivero. The deterioration of water quality in Lakes Chivero and Manyame due to eutrophication is a major public concern. These two inland water bodies stand as the most polluted sources of water in metropolitan Harare. The major sources of pollution consist of point and non-point sources. The point sources consist of raw sewage from illegal industrial and domestic waste disposal as well as poor garbage collection by responsible city authorities (Magadza, 1997). The non-point sources consist of agricultural and partially from mining activities among others. The Marimba and Mukuvisi rivers (5 and 8 km respectively upstream Lake Chivero) are the major effluent receiving rivers and their water quality has been deteriorating over the years (Marshall, 1997; Nhapi et al., 2006). Lake Manyame situated immediately downstream of Lake Chivero, maintained its water quality for some time with nitrogen rather than phosphorus being the main limiting nutrient but recent work suggests that situation has changed and the lake is now showing evidence of eutrophication. This reflects both the deterioration of Lake Chivero, which supplies most of its water, and the growth of the town of Norton, located on the southern shore of the lake.

These two lakes are the primary source of water for Harare and Chitungwiza and, apart from the difficulty and cost of water purification there are concerns about the effects of algal toxins in the water. This issue was first raised in the 1960s (Zilberg, 1966) and other authors have determined the concentration of these toxins in the lake (Ndebele and Magadza, 2006). It is essential, therefore, that the concentration of chlorophyll\_a is monitored in these lakes but conventional methods are expensive and labour-intensive, ecologically destructive and also cannot capture the spatial heterogeneity in the Lakes within the lake (Dube, 2012). Previous studies of Lake Chivero, used remote sensing techniques based on Normalized Difference Vegetation Index (NDVI) to assess the water quality and found that NDVI was correlated with the chl\_a and total suspended matter (TSM) (Shekede et al., 2008). This investigation did not provide full and direct measures of optical water quality parameters, thus leading to an incomplete water quality assessment in the two lakes.

These parameters are spatially heterogeneous and, therefore, point based measurements are not adequate to provide information on their spatial coverage. Therefore, the objective of this study is to combine in situ chl\_a measurements and remote sensing techniques to quantify chl\_a, and phycocyanin (PC) pigment as a proxy for blue-green algae and TSM concentrations from MERIS image.

2. Methods and materials

2.1. Study area

Lake Chivero formerly known as Lake Mcllwaine is a reservoir constructed in 1952 on the Manyame River 35 km SW of Harare, Zimbabwe. It has a surface area of 26 km\(^2\), a volume of 250 × 10\(^6\) m\(^3\) and maximum depth of 27 m. The widest point stretches for about 8 km and shoreline of the entire water body covers approximately 48 km. Lake Manyame formerly Darwendale dam was constructed between 1973 and 1976. It is located some 76 km west Harare downstream of Lake Chivero. Its water covers a surface area of 8100 hectares with a maximum depth of depth of 23.6 m and is much larger than Lake Chivero.

Lake Chivero has, in the past, experienced major outbreaks of water hyacinth *Eichhornia crassipes* but it has been reduced through biological control (Chikwenhere and Phiri, 1999). Its eutrophic state has stimulated the growth of other macrophytes and the shoreline supports a dense growth of alien plants such as *Myriopyllum*, *Hydrocotyle* and *Linnobium*.

2.1.1. Field measurements and sample analyses

Chlorophyll\_a was measured from in samples taken from six locations in Lake Chivero on 23 March, 2012 (Fig. 1) using the laboratory analysis method. Chlorophyll\_a was not determined in Lake Manyame and, instead, chl\_a, TSM and PC concentrations were directly derived from MERIS imagery in both lakes from which concentration and distribution maps were derived. Measured chl\_a concentrations from Lake Chivero for 23 March 2012 MERIS image were used to validate modelled chl\_a concentrations (Table 1). The coordinates of the sampling stations in the lake (Fig. 1) were matched with the satellite images. The locations of the sampled sites are indicated in (Fig. 1). Water samples were collected in 1-l brown bottles from a depth of no more than 1 metre, and stored in cooler box with ice pack to avoid degradation of the chlorophyll by sunlight as recommended in (Bartram and Ballance, 1999). The samples were pre-processed within a period of 24 h. Samples were first filtered using paper fibre filters (Whatman GF/C) and chl\_a was extracted using 90% acetone in an agate mortar, which was then centrifuged at 3000 r.p.m for 10 min. Colour absorbance determination was derived at 665, 643, 630 and 750 nm as indicated in (APHA et al., 2001; World Health Organisation, 2003).

The relationship between measured chl\_a for 23 March 2012 was assessed with other optically active constituents (TSM and PC) derived from the MERIS of same day. It is usually assumed that, if weaker relationships among pigment concentrations for example, chl\_a and PC and residents such as TSM exist, it would suggest higher amounts of non-algal constituents in a water column and vice versa (Randolph et al., 2008).

2.2. Remote sensing data acquisition and pre-processing

MERIS full resolution (FR) level 1b imagery with a high spectral resolution and an on-spot re-visitiation period of 2–3 days was used to determine the concentrations of chl\_a, PC, and TSM. MERIS spectrometer was found to be well suited to view Lakes Manyame and Chivero as these lakes are relatively larger in size, more than 1 km\(^2\) in total area. The sensors' narrow spectral bands are also well suited for deriving water quality constituents (Matthews et al., 2010). An atmospheric correction (AC) was done using the Case 2 regional processor (C2R), which is a tool developed by Doerffer and Schiller, 2007. Path radiance and transmittance of bands between 412 nm – 708 nm, derived from the top of atmosphere (TOA) directional radiance reflectance in the NIR spectral range band of 708–870 nm, using a neural network (NN) algorithm (Guanter et al., 2010). The AC is a pre-requisite for quantitative remote sensing methods that require images to be calibrated for surface reflectance. Literature points out that the removal of adjacency effects (an effect which results when photons are reflected and scattered towards the sensor and where a substantial contrast exits between the dark target/water and its surroundings) is crucial as it can cause inaccuracies in the estimation of aerosol optical thickness (AOT) at the wavelengths used for the estimation of water quality parameters (Brockmann Consult, 2010; Guanter et al., 2010; Kratzter and Vinterhav, 2010). Fortunately, correction schemes such as ICOL take this effect into account, otherwise the increased radiance is mistakenly associated with other physical processes, and the derived geophysical quantities have an increased error. ICOL is a prototype ocean and land processor which corrects for stray land reflection in the dark object pixels in relation to the sun angle, taking the coupling between Rayleigh scattering and Fresnel reflection into account Santer et al. (2007). Thus, the Improved Contrast over Ocean and Land (ICOL) methodology was considered in this study.
2.3. Blue-green algae and chl_a

The semi empirical band ratio model developed for optically complex waters (Simis et al. 2005) was used to estimate PC and chl_a concentrations from the 620 nm and 665 nm bands, respectively. The algorithm uses the band configuration of the MERIS channels 6, 7, 9 and 12 centered at 620, 665, 709 and 778.75 nm respectively. The 620 nm band is dominated by both phycocyanin pigment (PC) and chl_a, and the 665 nm band by chl_a alone.

Table 1
MERIS match-up sites in Lake Chivero.

<table>
<thead>
<tr>
<th>Date</th>
<th>Sensing start time</th>
<th>Lake Chivero Longitude</th>
<th>Lake Chivero Latitude</th>
</tr>
</thead>
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<tr>
<td>21/12/2011</td>
<td>07:54:34</td>
<td>30°49'49&quot;E</td>
<td>17°54'52&quot;S</td>
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<tr>
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<td>07:44:33</td>
<td>30°47'35&quot;E</td>
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<tr>
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<td>30°46'56&quot;E</td>
<td>17°53'16&quot;S</td>
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<tr>
<td>23/03/2012</td>
<td>07:47:19</td>
<td>30°48'03&quot;E</td>
<td>17°54'52&quot;S</td>
</tr>
</tbody>
</table>

* Chl_a data used for validation.

Fig. 2. Reflectance spectra and absorption troughs of PC and chl_a pigments derived from MERIS over (a) Chivero and (b) Manyame.

Table 2
Characteristics of Lake Chivero MERIS Satellite Derived Water Quality Parameters from selected pixels.

<table>
<thead>
<tr>
<th>Date</th>
<th>Point</th>
<th>Chl_a (mg/m^3)</th>
<th>PC (mg/m^3)</th>
<th>TSM (g/m^3)</th>
<th>Date</th>
<th>Point</th>
<th>Chl_a (mg/m^3)</th>
<th>PC (mg/m^3)</th>
<th>TSM (g/m^3)</th>
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<td></td>
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<td>60</td>
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<td>6</td>
<td>31</td>
<td>77.8</td>
<td>3.68</td>
</tr>
</tbody>
</table>
whilst the 709 nm and 778.75 nm bands are dominated by water alone (Ruiz-Verdú et al., 2008). The absorption by coloured dissolved organic matter (CDOM) and suspended particulate matter (SPM) is considered negligible, which may result in an overestimation of absorption by water that is not necessarily correlated with pigment concentrations (Gons et al., 2005; Simis et al., 2007). Thus, PC and chl_a concentrations derived from MERIS images are expected to be slightly higher than the concentrations measured in the field.

The 620 nm band is dominated by both PC and chl_a, and the 665 nm band by chl_a alone, whilst the 709 nm and 778.75 nm bands are dominated by water alone (Ruiz-Verdú et al., 2008). The absorption by coloured dissolved organic matter (CDOM) and suspended particulate matter (SPM) is considered negligible, which may result in an overestimation of absorption by water that is not necessarily correlated with pigment concentrations (Gons et al., 2005; Simis et al., 2007). Thus, PC and chl_a concentrations derived from MERIS images are expected to be slightly higher than the concentrations measured in the field.

### 2.4. Total suspended matter determination

Total suspended matter is one of the major apparent optical properties (AOPs) of water bodies (Song et al., 2011). In this study, the TSM data were based on the MERIS eutrophic optical model processor and was derived using a scattering coefficient in the region between 690 nm and 730 nm (Dekker et al., 2002).

### 3. Results

#### 3.1. Reflectance spectra of Lakes Chivero and Manyame

The reflectance spectra for Lakes Chivero and Manyame were all similar in their pattern and shape (Fig. 2). The conspicuous absorption dips at 620 nm and 665 nm is can be attributed to high absorption by the blue-green algae (PC) and chl_a pigments respectively. The reflectance of Lake Chivero (Fig. 2(a)) was generally lower than that of Lake Manyame (Fig. 2(b)) indicating that its pigment concentration was much higher.

#### 3.2. Validation of MERIS water quality parameters

Three water quality variables from Lake Chivero (chl_a, PC and TSM concentrations) were derived from MERIS imagery (Table 2) on 21 and 24 December 2011 as well as 12 and 23 March 2012. Generally, optical conditions exhibited a highly (>20 mg/m$^3$) eutrophic state with very high concentrations of pigments, well above those of World Health Organization (WHO, 2003) recreational guidelines. In situ measured chl_a for 23 March 2012 from Lake Chivero was used to validate the MERIS modeled chl_a concentrations. For comparison purposes, MERIS derived Lake Manyame water quality parameters results for 23 March 2012, were also included (Table 3).

#### 3.3. Relationships between optically active water constituents

The relationship assessed on the water quality parameters were based on MERIS data for 23 March 2013. There was a linear

![Fig. 3. Relationships for image dated 23/03/2012; (a) between in situ and predicted chl_a; (b) between modeled TSM and PC concentration; (c) between in situ chl_a and TSM concentration and (d) predicted PC and TSM.](image-url)
relationship between chl_a and PC concentration in Lake Chivero (Fig. 3(a)) with a close correlation between measured and predicted chl_a concentrations in the samples obtained on 23 March 2012 \( (R^2 = 0.9111, \ P < 0.01 \) (highly significant)) and MAE of 2.75 mg/m\(^3\) with 8.5% error). There was also a significant correlation (Fig. 3(c)) and between TSM and PC (Fig. 3(d)) with \( (R^2 = 0.9047, \ P < 0.01) \) whilst TSM had a somewhat weaker correlation with chl_a \( (R^2 = 0.7344, \ P < 0.05) \). However, the model presumably over-predicted chl_a where it reached saturation point (no further increase in living biomass) with TSM continuing to increase after chl_a saturation point. This suggests that very high levels of TSM could have originated from sediment, mineral as well as from dead material of living organisms which includes chl_a, thus an indication of ecological dynamics. The PC values (Fig. 3(b)) estimated by using the semi empirical algorithm were strongly correlated with the measured chl_a concentrations \( (R^2 = 0.9458, \ P < 0.001 \) (very highly significant)).

3.4. TSM distribution maps

The TSM varied from 0.04 g/m\(^3\) to 17.6 g/m\(^3\) on the dates indicated in (Fig. 4). As typical Case-2 water bodies, Lakes Manyame and Chivero had high TSM concentrations due to soil erosion, micro pollutants (Nhapi and Tirivarombo 2004) and non-point source pollution. TSM concentrations were low on 21 and 24 December but increased remarkably between 12 and 23 March 2012 due to high sediment loads feeding into the lakes as a result of the rainy season (from November onwards).

3.5. Chl_a distribution maps

The concentrations of chl_a ranged from 0.05 mg/m\(^3\) to 39.4 mg/m\(^3\) with lower concentrations being noted in the area along the shoreline. This could be attributed to wind effects which sweep algae towards the central parts of the water bodies where they become concentrated and lead to huge blooms. A glance at Lake Chivero and Manyame maps shows that concentrations of chl_a also were in the higher range \( (14–39 \mathrm{mg/m}^3) \) at this time (Fig. 5).

3.6. Blue-green algae distribution maps

The concentrations of PC (Fig. 6) were highest in Lake Chivero while the distribution patterns were almost uniform in Lake Manyame. However, there was a large gradient in PC concentrations between 21 and 24 December in Lake Manyame. The massive bloom on 21 December 2012 could have been triggered by a number of factors, including, high water temperatures, nutrient concentrations and the buoyancy regulating mechanism of blue-green algae. Furthermore, abundances of blue-green algae are known to vary on short time scales, as in hours or days, which also could result in the big difference which was noticed between 21 and 24 December maps. The concentrations of blue-green algae (Fig. 6) ranged between 27 and 121 (mg/m\(^3\)).

4. Discussion

The remote sensing measurements obtained during this investigation were comparable to in situ measurements suggesting that
satellite-based methods may be useful for assessing the trophic status of Zimbabwean water bodies. The distinct reflectance peak in the two lakes at 685 nm appears to be an effect of sun-induced chl_a fluorescence (Xu et al., 2009). The two absorption troughs at 620 nm and 665 nm are an indication similar to those obtained in Lake Taihu, China, and the Geist reservoir, Indiana, with respect to the absorption peaks of the two pigments (Dingtian and Pan, 2006; Randolph et al., 2008).

These water quality parameters variables indicate that Lakes Manyame and Chivero are highly eutrophic and variables were positively correlated with each other. The correlation between TSM and chl_a indicated that TSM included the backscatter caused by the inorganic parts of the phytoplankton (Dekker et al., 2002; Song et al., 2011). The concentrations of TSM (Fig. 3) were higher in Lake Manyame than in Lake Chivero therefore, the reservoir’s apparent reflectance which indicated a high TSM backscattering in the infrared and NIR bands.

5. Conclusions

In this study three conclusions have been drawn:

i. Water quality parameters of the two lakes (Chivero and Manyame) were able to be successfully derived from remote sensing data. Thus MERIS is suitable for real-time monitoring applications and observing changes happening over short time scales.

ii. The semi empirical band ratio based model proved to be a crucial utility in detecting PC and chl_a pigment concentrations and their spatial distributions.

iii. Remote sensing techniques demonstrated that the two lakes are typical Case 2 water bodies dominated by chl_a, blue-green algae and total suspended matter, which ultimately define the lakes as eutrophic.

Acknowledgements

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Fig. 6. Concentration and distribution patterns of PC pigment in lakes (a) Manyame and (b) Chivero.


