The Use of MODIS Time Series Data To Map Chl_a and CDOM Variability in Lake Victoria

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Abstract

Chlorophyll-a (Chl-a) and Colored Dissolved Organic Matter (CDOM) are key parameters in the assessment of water quality. Traditionally, these parameters are collected by carrying out in-situ measurements or taking of water samples for testing in the laboratory. This is time consuming, costly, cumbersome and irregularly carried out, but more importantly, does not give a synoptic perspective of the water quality variation on the lake. This becomes especially challenging when dealing with a lake the size of Lake Victoria. This paper therefore explores the use of archived MODIS satellite imagery to study the distribution of Chl_a and CDOM on Lake Victoria. Standard Ocean Color Algorithms were used to extract Chl-_a and CDOM concentrations from MODIS imagery. Annual concentrations were then averaged to get an appreciation of the spatial variability of these parameters for the years 2003 - 2010. The Chl_a imagery was further reclassified according to Calrton's index to determine the trophic level boundaries. The results show that in general Lake Victoria exhibits high concentrations of Chl_a implying that it is largely eutrophic. The Chl_a and CDOM results around the shores are particularly high and may be attributed to increased surface run off from the lake's catchment area. These are perspectives of water quality that are only possible with the use of satellite imagery. Given the advantages of high temporal resolution of MODIS imagery and the complete coverage of the lake, it is recommended that relevant stakeholders harness this technology to better improve on the management of their mandates.

1. Introduction

Lake Victoria is one of the most important ecosystems in the East African region and spans across three East African countries namely Kenya, Tanzania and Uganda with coverage of approximately 68,800 km^2 (Carvalli et al., 2009). It is a source of food, water for both domestic and industrial use, and economic development through transport and tourism. It also is home to a wide diversity of flora and fauna, thus rendering it of paramount significance as an ecosystem.

Like many freshwater lakes, lake Victoria has to contend with the challenge of a growing human population in its catchment area and consequently increased water demand through increasing industry, agriculture and urbanization and ultimately increased eutrophication (Stefouli and Charou, 2012; Cavalli et al, 2009). The importance of Lake Victoria vis a vis its challenges faced hence make it important to have a robust monitoring program to assess baseline conditions and provide necessary information to the various stakeholders involved in the management of the lake (Stefouli and Charou, 2012). In the assessment of water quality of any aquatic system, several parameters are considered important such as: Chlorophyll-a (Chl-a) that exists in all algae groups and is also an indicator of bio production of inland water bodies (Thiemann and Kaufmann, 2000; Odermatt et al, 2010); turbidity which is caused by soil erosion and leads to a concentration of suspended particulate material (SPIM), Dissolved Organic Matter (DOM) in freshwater that absorbs light and affects water transparency. This paper focuses on monitoring Chl-a and CDOM to asses water quality on Lake Victoria.

The interest in Chl_a stems from its relevance as a proxy for eutrophication (Koponen et al., 2001) given that it exists in all species of phytoplankton and is regarded as the total amount of phytoplankton biomass (Thiemann and Kaufmann, 2000). Eutrophication is the phenomenon of aquatic ecosystem enrichment due to increased nutrient loading (NOWPAP, 2007). Eutrophication degrades the water quality by accelerating organic matter growth and decomposition as well as decreasing light availability in coastal water beds, hence the importance of monitoring CDOM. This consequently leads to increased costs of treating water for human and animal consumption.

Traditionally, water quality testing is carried out by collecting samples at given locations on the lake, which samples are then taken for further analysis to determine Chl_a and CDOM at the collected location. This process is cumbersome, costly, time consuming, and more significantly does not give a synoptic representation of the lake's water quality (Stefouli and Charou, 2012; Cavalli et al, 2009). Given the size of lake Victoria, effectively monitoring water quality is especially difficult due to the extensive travel and hence only a few points can be sampled. This consequently implies that with conventional determination of water quality it is not possible to establish spatial variation of Chl_a and CDOM patterns and properties (Stefouli and Charou, 2012). This has motivated the consideration of satellite remote sensing technology as a means of monitoring water quality (Chavula et al, 2012), and increasingly research is being carried out to assess its potential (e.g. Plattner et al., 2006; Becker and Daw, 2005). This is motivated by the fact that imagery derived from satellites orbiting the earth enables one to access synoptic and regular data of lakes hence potentially enabling the effective monitoring of water quality (Stefouli and Charou, 2012). This paper presents the results of exploring MODIS-derived Chl_a and CDOM as an alternative or supplement to traditional means of determining water quality variation on Lake Victoria.

2. Bio-Optical Modelling Using MODIS Imagery

MODIS (Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra and Aqua satellites. Terra's orbit around the Earth is timed so that it passes from North to South across the equator in the morning, while Aqua passes South to North over the equator in the afternoon. In combination, Terra and Aqua satellites are able to view the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands at moderate resolution (250 -1000m). In the process, the satellites collect data about land and ocean surface temperature, primary productivity, land surface cover, clouds, aerosols, water vapor, temperature profiles, and fires. Bio-optical modeling provides a means by which geophysical parameters (e.g. Chl_a and CDOM in this case) can be extracted from satellite imagery using an algorithm (Morel and Maritorena, 2001).

2.1 Extraction of Chl_a from MODIS Imagery

Chl_a is extracted from MODIS imagery using the Ocean Colour algorithm version 5 (OC3v5) (O'reily et al. 2000). The algorithm form describes the polynomial best fit that relates the log-transformed geophysical (in this case Chl-a) variable to a log-transformed ratio of remote-sensing reflectances (of the MODIS imagery):

$$\text{Log}_{10}(\text{Chl}_a)=0.241-2.477r+1.530r^2+0.106r^3-1.108r^4 \quad [1]$$

where

$r = \text{Log}_{10}\,\{(R_{rs}\,443>R_{rs}490)/R_{rs}555\}$

R_{rs} – electromagnetic wavelengths used for Chl-a extraction

The input radiances are in the form of either remote sensing reflectance or normalized water leaving radiance.

2.2 Extraction CDOM from MODIS Imagery

CDOM is extracted by determining the absorption coefficient of gelbstoff at 400 nm aCDOM(400nm) calculated from (Dareckia and Stramskib, 2004):

$$a_{CDOM}(400) = 1.5[10^{-1.147+1.963r_{15}^2-0.856r_{25}+1.702r_{25}^2}] \quad [2]$$

where:

$r_{15}= \log[R_{rs}(412)/R_{rs}(551)]$,

$r_{25}= \log[R_{rs}(443)/R_{rs}(551)]$.

3. Methodology

MODIS data was used to monitor Chl-a and CDOM on lake Victoria for the years 2003 - 2010. SeaDAS version 6.2 software was used to visualize, process and analyze MODIS Level-2 (L2) data. The MODIS L2 images were corrected for both geometric and atmospheric errors during the image pre-processing stage. Chl-a and CDOM was extracted using equation [1] and [2] respectively and applied to all the available cloud free daily images. The extracts for each parameter where averaged over the whole year for display. In order to better assess the Chl_a data, it was reclassified according to Carlson's index. Carlson's index is one of the common indices used to categorize trophic levels (Trophic State Index) in fresh waters. The Carlson's index for lakes (Carlson, 1977) yields continuous values scaled between 0 and 100, based either on secchi disk transparency, Chl-a concentration and total phosphorus content (Thiemann and Kaufmann, 2000). The index enables the comparison of the trophic state of lakes where only one parameter is measured and is a good measure for the nutrient supply and change detection in eutrophic waters (Thiemann and Kaufmann, 2000).The Carlson index for Chl-a uses the algal biomass as an objective classifier of a lake's trophic status (Carlson, 1977). Table 1 shows the trophic categorization used in this paper based on Chl-a concentration.

Table 1: Trophic classification

Trophic category	**Chlorophyll-a (mgm^{-3})**
Oligotrophic	$\leq$2.6
Mesotrophic	2.6 - 20
Eutrophic	20 - 56
Hypertrophic	56+

4. Results and Discussion

From Figure 1, Figure 2 and Figure 3, it is obvious that one of the advantages of employing satellite imagery is the ability to derive a synoptic view of the Chl-a and CDOM distribution on Lake Victoria. To be able to extract this perspective from in-situ measurements would call for heavy investment that may be beyond the means of the organizations interested in this sort of data. Thus MODIS time series data can go a long way in better managing the water resources.

Figure 1 and Figure 2 depict the annual averaged Chl-a and CDOM distribution and variation respectively over the entire lake for the period 2003 to 2010. From the scale bar, it is evident that chl-a and CDOM concentrations are higher at the shores than the middle of the lake. This is because the shores are more susceptible to nutrient enrichment as compared to the rest of the lake since it is at the shores that most of the waste disposal from various human activities takes place. The high CDOM concentration at the shore line is attributed to the Dissolved Organic Matter (DOM) from runoff in the terrestrial neighborhood of the water body during the rainy season. However it is also important to note that, nutrient enrichment due to surface runoff is dependent on the topography of the catchment area (Wetzel 2001). There were high concentrations of CDOM observed in 2004 unlike in the other years. This can be attributed to change in land use and rainfall patterns which might have brought about a change in nutrient loads in the lake as compared to other years.

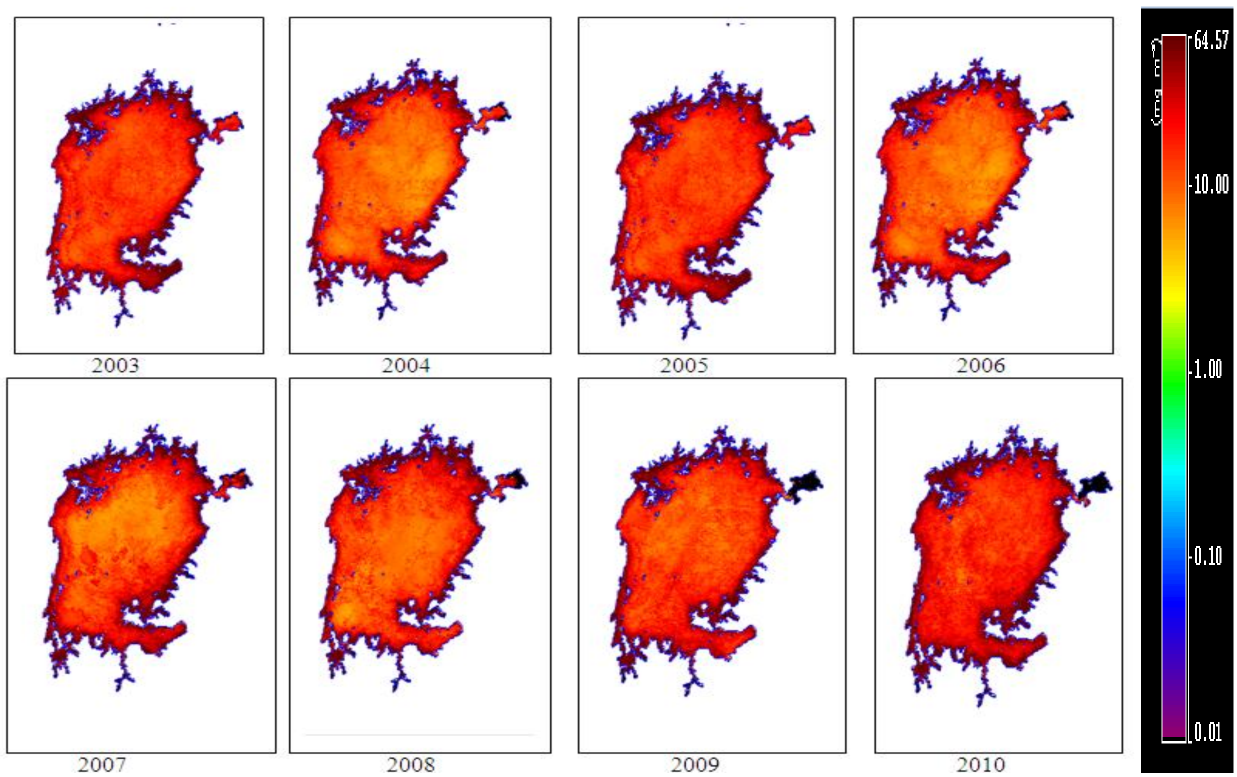

Figure 1: Annual Averaged chl-aimages for the period 2003-2010

From the annual averaged images in figure 1, Carlson's Index was used to obtain the different trophic states of Lake Victoria as shown in figure 3. The figure shows that the lake exhibits hypertrophic and eutrophic characteristics in the shore regions. Mesotrophic characteristics are observed to occur in the middle of the lake and there are no oligotrophic characteristics depicted by the lake for all the years.

These observations are attributed to the high nutrient enrichment at the shores that decreases with increasing distance to the middle of the lake. Nutrient enrichment is as a result of surface run off especially during the rainy seasons, constant mixing of the lake especially in shallower regions and waste disposal from the various human activities that take place in the lake's catchment area. Some of the human activities are industrial and agricultural which involve waste discharge into the lake directly or indirectly through its channels. These provide favorable conditions for increased development of algae resulting in high chl-a concentrations. It should also be noted that the width of the hypertrophic and eutrophic regions seems to be constant and that the lake is largely eutrophic as the years advance. This implies that water quality problems are serious and almost continuous especially at the shores. If there are no mitigation measures, this will lead to the development of harmful algal blooms (cynobacteria) which produce toxins that are poisonous to both the humans and the fish (Hecky 1986 and Tusseau-Vuillemin, 2001).

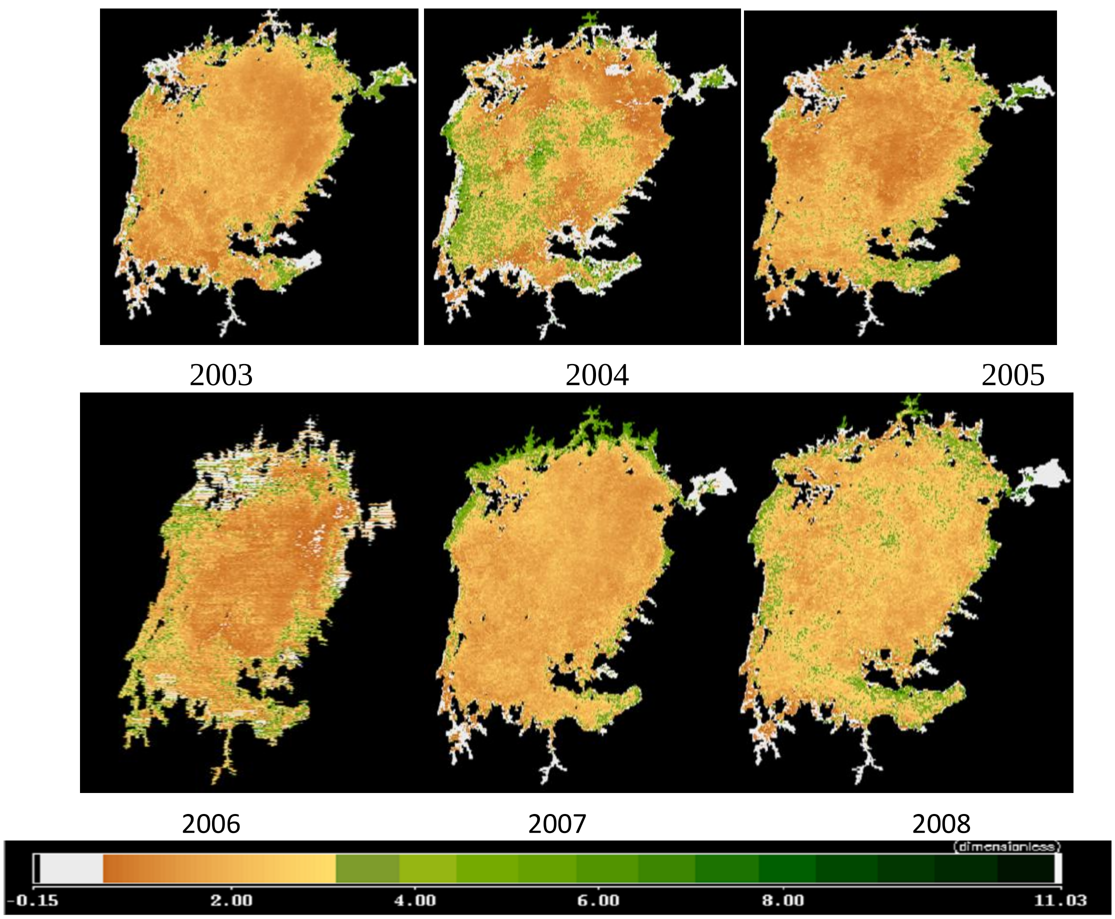

Figure 2: CDOM Distribution for the period 2003-2010 on Lake Victoria

The variability in nutrient concentrations at the different depth not only has an impact on water quality but also the various ecosystems for example the fish. Different fish species have different favorable conditions for chl-a concentrations. The Nile Parch for instance prefer conditions where the chl-a concentrations are relatively lower and have high transparency. Therefore mesotrophic zones could be potential breeding areas for such fish. On the other hand, other fish species such as the Tilapia prefer shallow waters with higher chlorophyll concentrations since they mainly feed on the phytoplankton that are mostly in the shore region due to the high nutrients.

The black portions in the north eastern part of the 2009 and 2010 images indicate areas with cloud cover and therefore CDOM and chl-a data could not be extracted from these portions of the lake. This therefore indicates one of the limitations of using data derived by optical sensors for such studies.

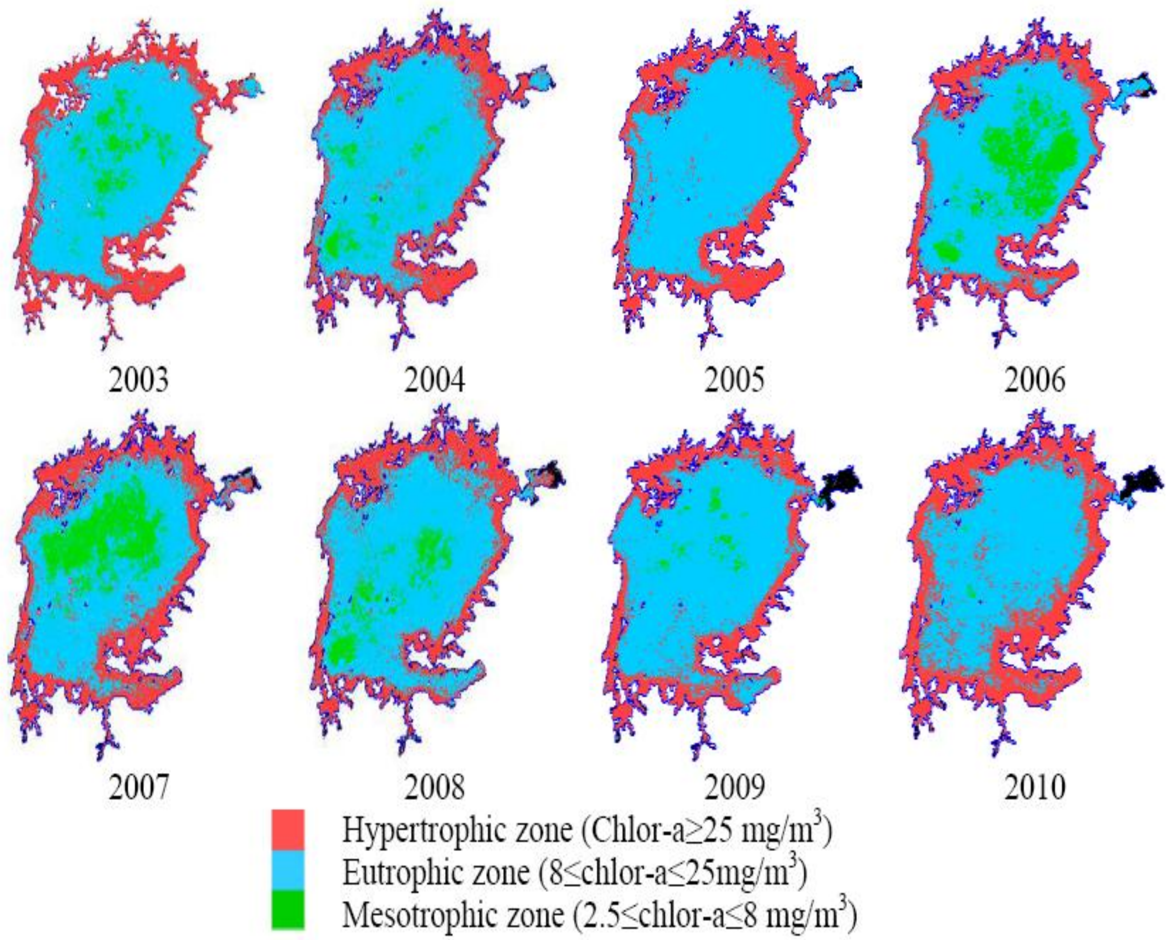

Figure 3 Trophic State Characterization of Lake Victoria for the period 2003-2010

5. Conclusions

This paper has demonstrated that satellite imagery can provide a viable means to supplement the efforts in monitoring water quality in Lake Victoria through effective mapping of water quality parameters like chl-a and CDOM. From the results it can be concluded that Lake Victoria is largely eutrophic with the shore region being highly hypertrophic. Past studies indicate that if the lake experiences a long eutrophication history, reduction of the nutrient loading rates to or below those of the lake prior to accelerated inputs, will take 2-10yrs. This is because lakes with a long eutrophicational history and large accumulation of nutrients respond more slowly to reduction in nutrient loadings (Janus and Vollenweider, 1984; Vollenwieder, 1985; 1990).

The paper has also demonstrated the limitation of MODIS data is cloud cover. Integrating MODIS with other remote sensing technologies such as Radio detection And Ranging (RADAR) could help in overcoming the problem.

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