Monitoring Water Quality on Lake Victoria Using MODIS Imagery

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ABSTRACT

Lake Victoria is one of the key ecosystems in East Africa. With a size of 68,800 km^2, it is the largest lake in Africa. It supports the livelihoods of more than 20 million people directly and indirectly as a source of portable water and fish, for recreation, industrial use etc. This renders the monitoring of its water quality of paramount interest. Traditionally water quality testing is carried out by in-situ measurements or taking of water samples for further testing in the laboratory. This approach has been seen to be costly, cumbersome, it is irregularly carried out and does not give a synoptic perspective of the water quality variation on Lake Victoria, especially given its size. This has motivated the need to explore the use of MODIS satellite imagery in monitoring water quality on the lake. This paper explores the use of archived MODIS satellite imagery to study Lake Surface Temperature (LST) and Chlorophyl_a (Chl_a) variation from 2003 – 2010. The results show that from the time series dataset, in general the northern region of the lake exhibits annual seasonal LST variation which can be characterized as bimodal. These seasonal peaks coincide with the occurrence of the region's rain season, which information could potentially be useful in modeling experiments. The Ocean Color (OC v5) algorithm was used to extract Chl_a from the dataset. The daily Chl_a extracts were averaged over a year and mapped. These annual images were then reclassified according to Carlton's Index for Chl_a. The results show that on average, closer to the shores the lake is largely hypertrophic whereas the lake is largely eutrophic. The lake also exhibited traces of Mesotrophic behaviour in some of the years. This has potential implications about the identification of breeding/fishing zones. These results show that the use of satellite imagery in monitoring water quality, its challenges notwithstanding, can be operationalized for the effective management of Lake Victoria.

Keywords: Chlorophyll_a, Lake Surface Temperature, Lake Victoria, MODIS, Water quality

1.0 INTRODUCTION

Lakes are a vital component of the Earth's fresh water resources, and are crucial for the survival of terrestrial life (MacCallum and Merchant, 2012; MacCallum et al, 2011). In the heartland of Africa is the main source of the River Nile – Lake Victoria, the largest fresh water lake in Africa, spanning 68,800 km^2 and supporting a rich diversity of flora, fauna and the economic livelihood of over 20 million people directly and indirectly (Cavalli et al, 2009). At 1134m above sea level, it has a maximum depth of 84m and an average depth of 40m. Its maximum length (North to South) is 337km and maximum width (East to West) 250km. Lake Victoria is a trans-boundary lake surrounded by Uganda, Kenya and Tanzania. Through the river Nile, Lake Victoria continues to sustain the livelihoods of South Sudan, Sudan and Egypt. Like many inland lakes, Lake Victoria is faced with a challenge of growing human population around it and consequently increased water demand, 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 make it imperative to have a robust research and 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, a number of parameters are considered important. Some of these parameters include 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) and Dissolved Organic Matter (DOM) in freshwater that absorbs light and affects water transparency. Lake Surface Temperature (LST) is important because it gives an indication of a lake’s biological and chemical activity (MacCallum and Merchant, 2012; Stefouli and Charou, 2012). Knowledge of LST can for instance give an indication of the breeding grounds or potential occurrence of different lacustrine species since they have preferred temperature ranges within which they survive. Beyond these preferred ranges their survival is compromised and may diminish their population counts. In similar measure, the rate of chemical reactions is directly proportional with temperature increase, which in turn affects biological activity. Knowledge of LST can also be used in the identification of upwelling zones, and hence enables better monitoring of lake productivity (Chavula et al, 2012). LST is also an important indicator of the lake state and a driver of regional weather and climate near large lakes (Austin and Colman, 2007). LST hence enables the modeling of the hydrological cycle and other metrological phenomena e.g. heat flux, energy balance and evaporation (Oesch et al, 2003; Schwab et al, 1992). This paper focuses on Lake Surface Temperature (LST) and Chlorophyll_a (Chl_a) as key parameters used to asses water quality on Lake Victoria.

As already mentioned, Chl_a is contained in all species of phytoplankton and can be regarded as the total amount of phytoplankton biomass (Thiemann and Kaufmann, 2000). Chl_a enables the monitoring of the mass generation of phytoplankton and is used as an indicator of eutrophication (Koponen et al., 2001). 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. This consequently leads to increased costs of treating water for human and animal consumption, and more importantly could potentially expose users to harmful algal blooms.

Conventionally, water quality testing is carried out at sampling points on the lake. Whereas LST can be measured in-situ, to determine Chl_a, a sample has to be taken to the laboratory for further testing. Invariably this is expensive, cumbersome, time consuming and not representative of the condition of the entire lake (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 LST and Chl_a patterns and properties (Stefouli and Charou, 2012). It is challenges such as these that have prompted 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 LST and Chl_a as an alternative to conventional means of determining water quality variation on Lake Victoria.

2.0 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. LST and Chl_a in this case) can be extracted from satellite imagery using an algorithm (Morel and Maritorena, 2001).

2.1 Extracting LST from MODIS Imagery

The LST algorithm makes use of MODIS bands 31 and 32 at 11µm and 12µm. The algorithm for computing LST from observed brightness temperatures is shown in equations 1 - 5 (Bryan, 2006):

For dBT<= 0.5

$$LST = a00 + a01*BT11 + a02*dBT*bLST + a03*dBT*\left(\frac{1}{Cos(ø)-1}\right) \quad (1)$$

For dBT>= 0.9

$$LST = a10 + a11*BT11 + a12*dBT*bLST + a13*dBT*\left(\frac{1}{Cos(ø)-1}\right) \quad (2)$$

For 0.5 <dBt< 0.9

$$LST(lo) = a00 + a01*BT11 + a02*dBT*bLST+ a03*dBT*\left(\frac{1}{Cos(ø)-1}\right) \quad (3)$$

$$LST(hi) = a10 + a11*BT11 + a12*dBT*bLST + a13*dBT*\left(\frac{1}{Cos(ø)-1}\right) \quad (4)$$

$$LST = LST(lo) + \frac{dBT-0.5}{(0.9-0.5)*(LST(hi)-LST(lo))} \quad (5)$$

Where:

BT11 = Brightness temperature at 11 µm, in deg-C (i.e. band 31)
BT12 = Brightness temperature at 12 µm, in deg-C (i.e. band 32)
dBT = BT11 - BT12
LST (lo)= Low LST when dBT>= 0.5
LST (hi) = High LST when dBT>= 0.9
bLST = Baseline LST
Cos(ø) = Cosine of sensor zenith angle

The coefficients a00, a01, a02, and a03 and a10, a11, a12, and a13 are based on match-ups between the satellite retrievals of brightness temperature and field measurements of sea surface temperature.

2.2 Extracting Chl_a from MODIS Imagery

The extraction of Chl_a from the imagery is effected by 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):

$$Log_{10}(Chl_a)=0.241-2.477r+1.530r^2+0.106r^3-1.108r^4 \quad (6)$$

where

$r = Log_{10} \{(R_{rs} 443 > R_{rs} 490)/R_{rs} 555\}$

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.

3.0 METHODOLOGY

MODIS data was used to monitor LST and Chl_a 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. LST was extracted using the National Aeronautics Space Administration (NASA's) SST algorithm (SST4). The mapped daily LST for Lake Victoria was averaged for each year. The daily LST were also used to extract two areas (Entebbe and Jinja on the northern shores of Lake Victoria) whose LST over the years was analyzed as well as their respective time series trends. On the other hand, Chl_a was extracted using the Ocean Colour (OC v5 algorithm) applied to all the daily images. In order to better assess the data, the annual Chl_a was averaged and 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 or 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	≤2.6
Mesotrophic	2.6 - 20
Eutrophic	20 - 56
Hypertrophic	56+

4.0 RESULTS AND DISCUSSION

4.1 Lake Surface Temperature

Figure 1 depicts the mapped annual averaged LST for Lake Victoria. The main apparent advantage of using MODIS is the synoptic view of the spatial distribution of LST in the lake. By observing the temperature scale, the lake has an average temperature of about 24ºC. Whereas this archived Satellite data is available and can be revisited time and again, unfortunately the same cannot be said about the corresponding in-situ data.

Figure 2 shows the annual LST variation for Entebbe and Jinja (Extracted from the Northern shores of Lake Victoria), while Figure 3 depicts the time series LST observation for the period 2003 – 2010. From Figure 2, it is evident that the annual LST variation in Lake Victoria, as represented by Entebbe and Jinja, exhibits an annual seasonal pattern best described as bimodal. The first LST peak is between March - May the second between September – November. Generally the earlier LST peaks are higher than the second peaks. The lower annual temperatures are generally observed between June – July and December - February. These temperature patterns coincide with the rainfall season in the Northern part of Lake Victoria and may explain the influence of rainfall on the LST (Burgis and Symoens,1987). High LST during the rainy season may be explained by the fact that in the rainy season there is less evaporation from the water surface and consequently less heat loss through radiation. The link between high LST and rainfall could prove vital especially in hydrological modeling and presents an opportunity for further research. From Figure 3, the results show a minimal increasing trend in the temperature, however the data available was not sufficient to make any generalizations about this trend.

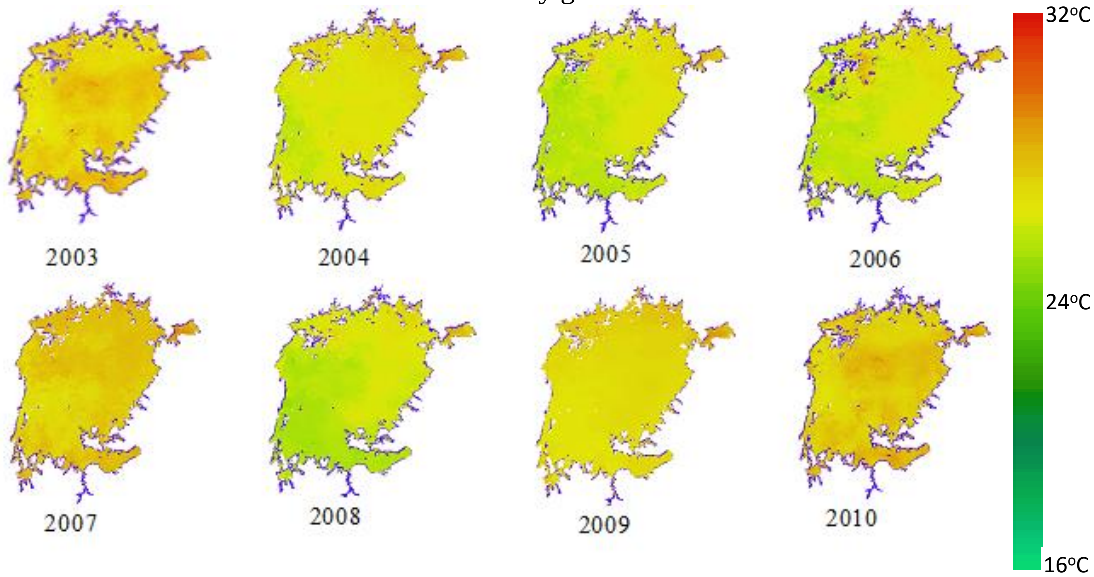


Figure 1: Annual Averaged LST maps for the period 2003 – 2010

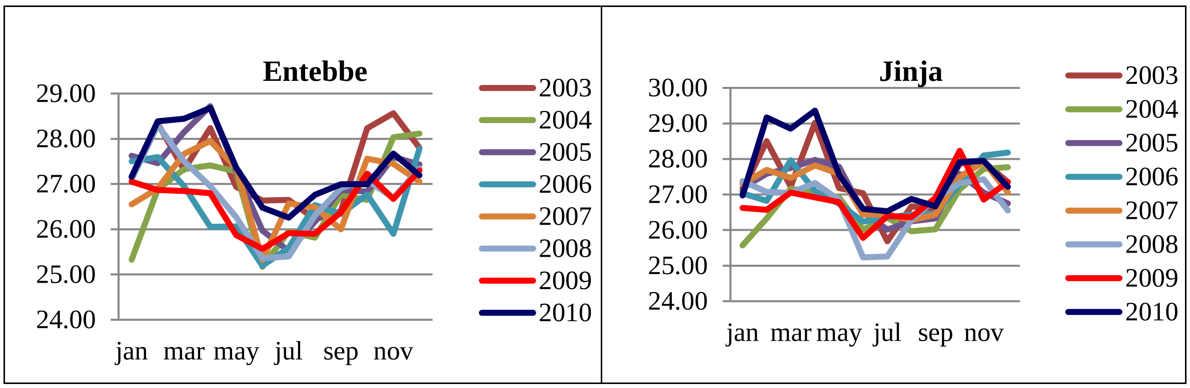
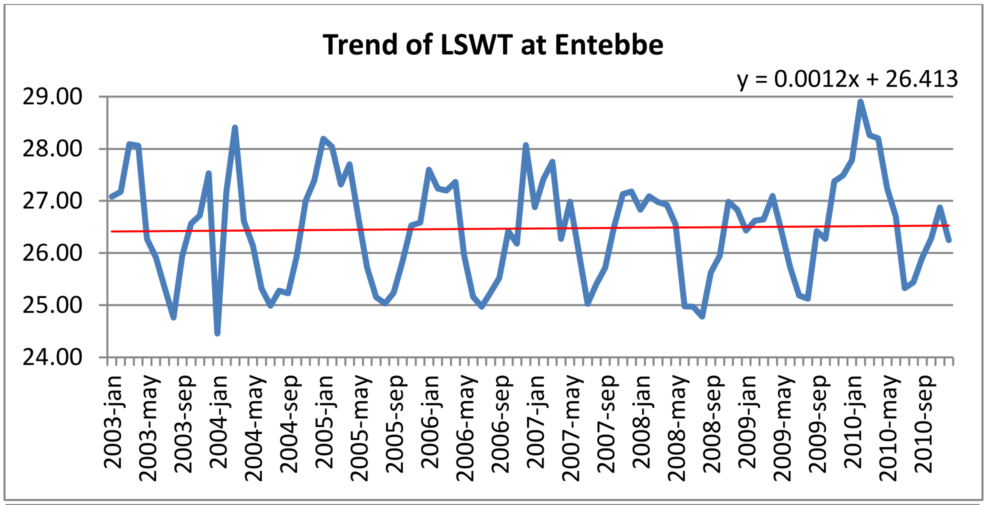


Figure 2: Variations of LSWT at Entebbe and Jinja

The next step in this research will be to collate these temperature results with other water quality parameter variations to model lake productivity, potential fishing zones etc. It is also recommended that Lake Victoria specific algorithms be derived to give more accurate results of LST. This will require collecting in-situ data simultaneous to MODIS overpasses. Being able to extract LST daily will go a long way in improving the management of Lake Victoria water resources.



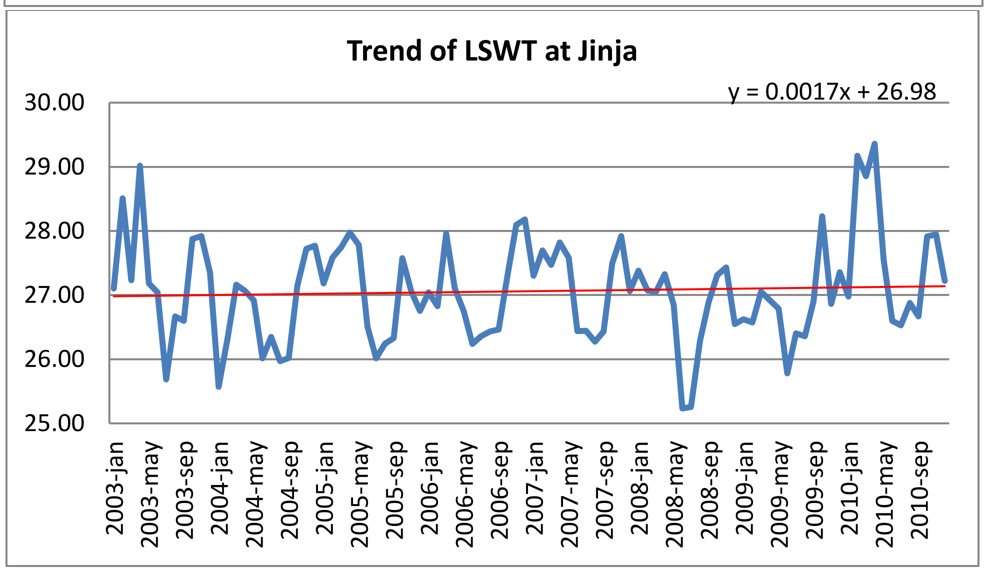


Figure 3: Trend of LST at Entebbe and Jinja

4.2 Chl_a

From Figure 4, it is obvious that one of the advantages of employing satellite imagery is the ability to derive a synoptic view of the Chl_a 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. The other advantage of the MODIS imagery is that it has a daily temporal resolution implying that the daily synoptic perspective of Chl_a on Lake Victoria can be accessed and can go a long way in better managing the water resources.

Figure 4 depicts the annual averaged Chl_a distribution and variation over the entire lake for the period 2003 to 2010. From the scale bar, it is evident that Chl_a concentration is 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 due to surface run off and waste disposal from the various human activities taking place. However, nutrient enrichment due to surface runoff is dependent on the topography of the catchment area (Wetzel, 2001).

The annual Chl_a distributions in Figure 4 were then reclassified according to Carlton's Index and are depicted in Figure 5. Both Figure 4 and 5 show that on average the areas closer to the shores are hypertrophic while Lake Victoria is largely a eutrophic lake. Generally, the results demonstrate that the hypertrophic and eutrophic regions have been consistent throughout the study period. The figures also indicate that there are instances when the lake depicts mesotrophic characteristics (as evidenced by the yellowish color scale i.e. Chl_a varying between 2.6 – 20 mg m^{-3}). The 2009 and 2010 images also have a portion in black (in the NE part of the lake) which means that no Chl_a data for that portion was obtained, in this case due to cloud cover. These observations are attributed to the high nutrient enrichment at the shores that decrease towards the middle of the lake. The major contributors of nutrient enrichment along the shore regions are: surface run off; 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 (Cavalli et al, 2009). These provide favorable conditions for increased development of algae resulting in high Chl_a concentrations. Left unmitigated, there is a potential that this will lead to the development of harmful algal blooms (cynobacteria) which produce toxins that are poisonous to both humans and the fish (Tusseau-Vuillemin, 2001) as well as the birds and animals that drink from the lake.

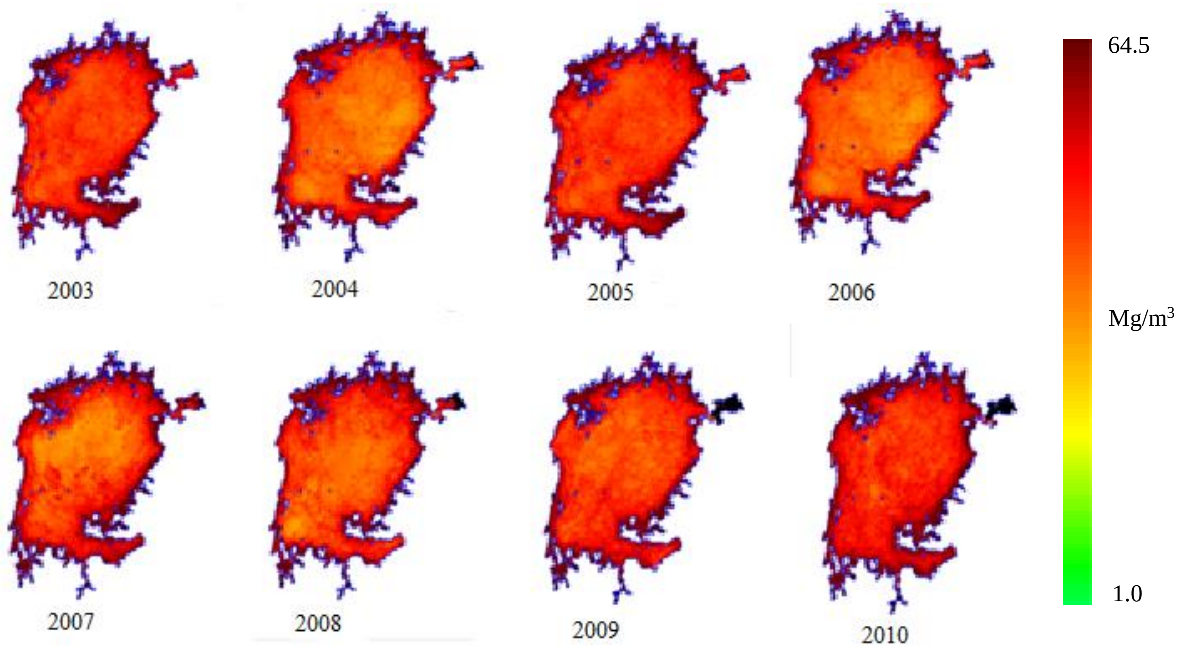


Figure 4: Annually Averaged Chl_a images

One of the main benefits of being able to map out the trophic zones as seen in Figure 5 is that the maps can be used to predict potential breeding/fishing zones for different fish species. For instance, the Nile Perch is known to 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, Tilapia is known to 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. By regularly mapping out the trophic zones, these fishing zones can be identified hence potentially increasing on the revenue from fish. This information, however, would have to be considered together with other water quality parameters such as LST, Secchi depth etc.

Ideally the authors should have made comparisons between the modeled Chl_a from MODIS and in-situ measurements. Unfortunately the data available (e.g from the National Water and

Sewerage Corporation) is not in a format that can be used in this research. The next phase in this research will be to carry out validation of the MODIS derived Chl_a with in-situ measurements coinciding with the satellite overpass.

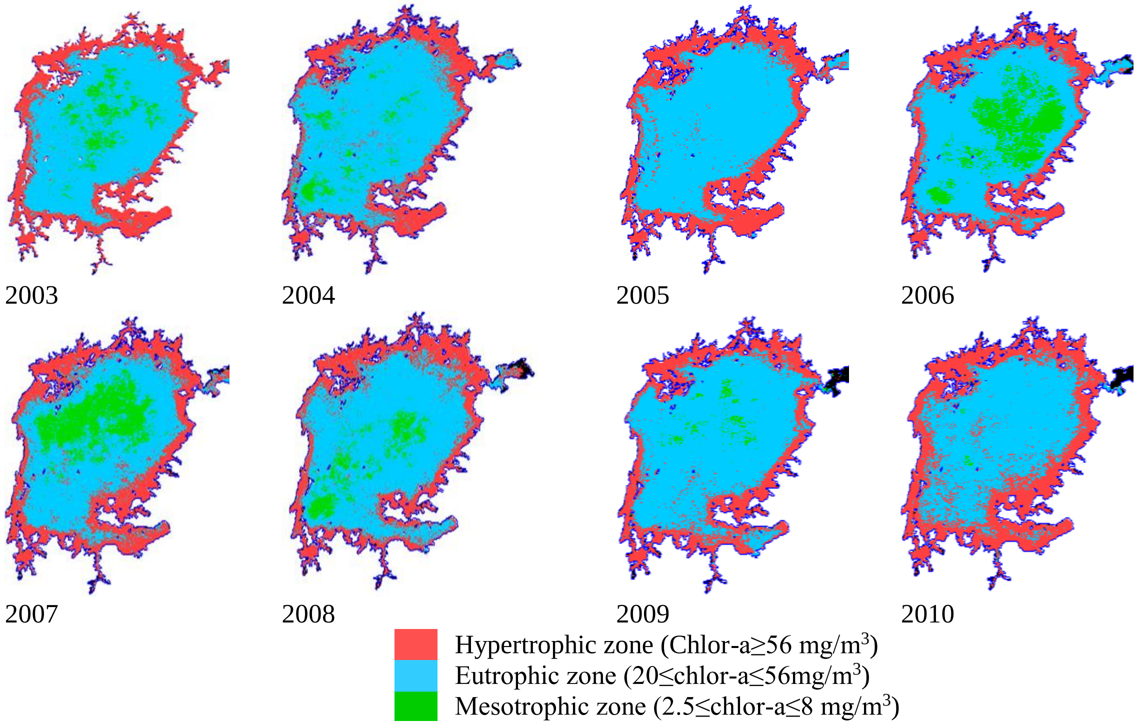


Figure 5: Annual averaged Chl_a distribution according to Carlson's Index Trophic Zones

5.0 CONCLUSIONS

From this study, it is evident that remote sensing provides a novel and efficient way of monitoring Chl_a and LST on Lake Victoria. Once validated and operationalized, it will go a long way in the management and monitoring of this very important ecosystem. Some of the potential beneficiaries will be the National Water and Sewerage Corporation, the Fisheries Sector, the National Environmental Management Authority etc. The aim is not to replace in-situ measurement of water quality on Lake Victoria, but to provide a fast, efficient and reliable means of monitoring its water quality. It is however important to observe that a number of potential challenges to the adoption of Satellite Imagery in monitoring and managing Lake Victoria are anticipated such as: cloud cover, poor access to imagery, poor internet band width to regularly acquire the imagery, shortage of expertise to process the data and the need to be able to present these results in a way that is relevant to the user community.

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