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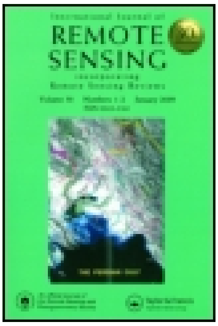

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Evaluation of spatio-temporal variations in chlorophyll-a in Lake Naivasha, Kenya: remote-sensing approach

Jane Ndungu[abc], Bruce C. Monger[d], Denie C.M. Augustijn[a], Suzanne J.M.H. Hulscher[a], Nzula Kitaka[b] & Jude M. Mathooko[b]
[a] University of Twente, 7500 AE, Enschede, The Netherlands
[b] Egerton University, Egerton, Kenya
[c] Kenya Marine and Fisheries Research Institute, Mombasa, Kenya
[d] Cornell University, Ithaca, 14853-2801, NY, USA

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Evaluation of spatio-temporal variations in chlorophyll-*a* in Lake Naivasha, Kenya: remote-sensing approach

Jane Ndungu[a,b,c]*, Bruce C. Monger[d], Denie C.M. Augustijn[a], Suzanne J.M.H. Hulscher[a], Nzula Kitaka[b], and Jude M. Mathooko[b]

[a] *University of Twente, 7500 AE, Enschede, The Netherlands;* [b] *Egerton University, Egerton, Kenya;* [c] *Kenya Marine and Fisheries Research Institute, Mombasa, Kenya;* [d] *Cornell University, Ithaca, 14853–2801 NY, USA*

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Restoration of the ecosystem services and functions of lakes requires an understanding of the turbidity dynamics in order to arrive at informed environmental management decisions. The understanding of the spatio-temporal dynamics of turbidity requires frequent monitoring of the turbidity components such as chlorophyll-*a* concentration. In this study, we explored the use of Moderate Resolution Imaging Spectroradiometer Aqua (MODIS-Aqua) satellite data in studying the spatio-temporal changes in chlorophyll-*a* concentration in Lake Naivasha, a turbid tropical system. The temporal trend of chlorophyll-*a* concentration over the study period in the lake was also evaluated. The temporal trend assessment was achieved through the removal of periodic seasonal interference using Seasonal-Trend decomposition based on the LOESS (Local Regression) procedure. The resultant chlorophyll-*a* concentration maps derived from MODIS-Aqua satellite data give an indication of the monthly spatial variation in chlorophyll-*a* concentration from 2002 to 2012. The results of regression analyses between satellite-derived chlorophyll-*a* and *in situ* measurements reveal a high level of precision, but with a measureable bias with the satellite underestimating actual *in situ* measurements ($R^2 = 0.65$, $P < 0.001$). Although the actual values of the chlorophyll-*a* concentrations are underestimated, the significant relationship between satellite-derived chlorophyll-*a* and *in situ* measurements provides reliable information for studying spatial variations and temporal trends. In 2009 and 2010, it was difficult to detect chlorophyll-*a* from the MODIS-Aqua imagery, and this coincided with a period of the lowest water levels in Lake Naivasha. An inverse relationship between de-seasoned water level and chlorophyll-*a* concentration was evident. This study shows that MODIS-Aqua satellite data provide useful information on the spatio-temporal variations in Lake Naivasha, which is useful in establishing general trends that are more difficult to determine through routine ground measurements.

1. Introduction

An increase in chlorophyll-*a* concentration indicates eutrophication in lakes, which is associated with low biodiversity and hence deprives the aquatic environment of sufficient ecosystem services. Chlorophyll-*a* is considered one of the main components that contribute to turbidity in aquatic ecosystems. Turbidity is one of the variables that define the water quality of aquatic ecosystems (Lloyd 1987), and hence dictates the fate of the entire

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*Corresponding author. Email: ndungu16436@itc.nl

biodiversity, which includes fisheries, mammals, and birds. Increase in turbidity can result in a shift from a clear to turbid state, which adversely destabilizes the ecosystem services and functions (Scheffer 1998). Turbidity is therefore detrimental to the local community livelihood that is largely dependent on income from the sale of fish and tourism-related revenue. Therefore, restoration of the ecosystem services and functions requires an understanding of the turbidity dynamics in order to arrive at informed management decisions. The understanding of the spatio-temporal dynamics of turbidity requires frequent monitoring of the turbidity characteristics such as chlorophyll-*a* concentration. However, it is difficult to acquire such data through routine ground measurements because of the high cost and time involved. Remote-sensing technology has the potential to present synoptic estimates of chlorophyll-*a* in turbid lakes.

A great deal of prior research has been done on remotely sensed retrieval of chlorophyll-*a* from satellite images in marine systems using the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (O'Reilly et al. 1998), Landsat TM (Ekstrand 1992), Medium Resolution Imaging Spectrometer (MERIS) (Gordoa et al. 2008), and Moderate Resolution Imaging Spectroradiometer (MODIS) (Dall'Olmo et al. 2005; Binding, Greenberg, and Bukata 2012; Gitelson et al. 2009). During the period of this study, Landsat 5 satellite data acquisition failed after having been in operation since 1972. Moreover, Landsat 7 has had a Scan Line Corrector (SLC) failure since 2003. In April 2012, the MERIS satellite also failed. These occurrences necessitate the exploration of operational satellites such as MODIS. Consequently, more research needs to be done to improve the accuracy of the actual values and maybe this could form the basis for the next phase in this work.

Lake Naivasha is a turbid tropical freshwater lake in the Kenyan rift valley where a shift from a clear to a turbid state has been observed over the past decade. In the 1930s, the lake was described as clear (Beadle 1932) but currently it is turbid (Harper et al. 2002; Grey and Jackson 2012; Ndungu et al. 2012). Despite the increase in turbidity in the lake and sporadic studies by several researchers, there is still limited data collection because of the time involved and high cost of *in situ* field data acquisition coupled with limited availability of funds.

In this study, we explore the use of MODIS-Aqua data in the retrieval of chlorophyll-*a* as a measure of the phytoplankton biomass in Lake Naivasha. This is because the imagery is readily available free of charge and has daily temporal resolution allowing frequent monitoring of water quality. This is useful especially for water quality studies in developing countries like Kenya, where continuous data collection is a challenge due to limited research and monitoring funds. Furthermore, successful retrieval of satellite data is fundamental because it allows retrospective analysis of the chlorophyll-*a* in aquatic systems and therefore provides data at times when ground measurements do not exist. The spatio-temporal dynamics of turbidity in Lake Naivasha were evaluated based on chlorophyll-*a* concentration retrieved from MODIS-Aqua 500 m resolution images from July 2002 to June 2012 using the Chlorophyll 2 (OC2) pigment algorithm. The OC2 pigment algorithm is a well-documented standard algorithm in general use by the ocean colour community for chlorophyll-*a* retrieval in lakes (Chavula et al. 2009; Wang, Shi, and Tang 2011). It is implemented in the current SeaDAS processing software (developed by the National Aeronautics and Space Administration (NASA), Ocean Biology Processing Group in Goddard Space Flight Center, Greenbelt, MD, USA) and uses the two 500 m high-spatial resolution bands that were traditionally intended for land remote sensing.

The specific objectives of the study included: (1) estimation of chlorophyll-*a* concentration in Lake Naivasha using MODIS-Aqua satellite data; (2) assessment of monthly spatial variations in chlorophyll-*a* concentration in Lake Naivasha; (3) assessment of the temporal trend of chlorophyll-*a* concentration in Lake Naivasha using time series plot and STL (Seasonal-Trend decomposition based on the LOESS (Local Regression)) procedure; and (4) exploration of possible causes of the spatio-temporal variations. The STL procedure has previously been applied in remotely sensed normalized difference vegetation index (NDVI) (Verbesselt et al. 2010) and leaf area index (LAI) time series studies (Jiang et al. 2010), but has not been applied in remotely sensed water quality data before this study.

2. Study area

Lake Naivasha lies at latitude 00° 46′ S and longitude 36° 22′ E (Figure 1). It is an endorheic freshwater lake situated on the floor of the Eastern Rift Valley in Kenya at 1885 m above sea level (a.s.l). The annual surface water inflow into the lake is estimated to be 217×10^6 m^3 (Becht and Harper 2002). The main discharge into the lake is from the rivers Malewa (80% of the discharge) and Gilgil (10%) at the northern region of the lake, with catchment areas of 1700 km^2 and 400 km^2, respectively. The remainder of the discharge (~10%) comes from other minor rivers around the lake such as Karati. The entire lake's catchment area is 3416 km^2 (Ndungu et al. 2012), while it covers between 120 and 150 km^2 in the dry and wet seasons, respectively. The mean temperature around Lake Naivasha is approximately 25°C. The area receives bimodal annual rainfall in March/April/May and October/November. The average rainfall around the lake is approximately 650 mm per year (Vincent, Davies, and Beresford 1979) but is much higher in the upper catchment. A substantial area of the lake basin is currently under large-scale production of horticultural products for export

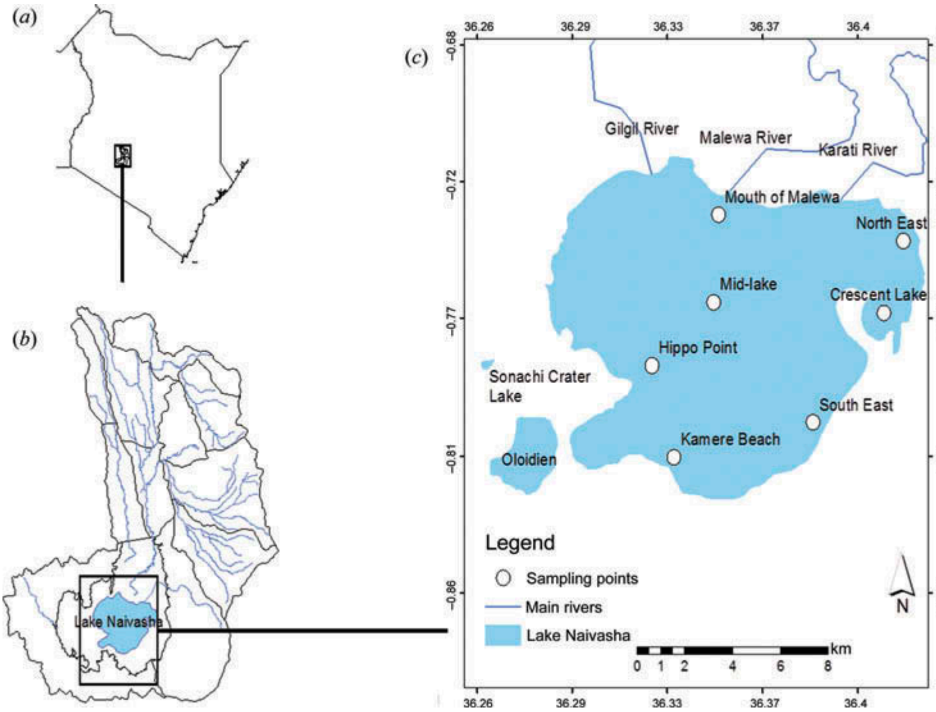

Figure 1. Study area of Lake Naivasha catchment in Kenya (*a*), the extent of the catchment together with the major rivers that drain into the lake (*b*), and the lake area including sampling sites (*c*).

markets. The agricultural production depends heavily on irrigation from the lake, the rivers, and groundwater (boreholes). To sustain these intensive agricultural activities, farmers use large amounts of fertilizers and pesticides.

3. Material and methods

3.1. Field data collection and analysis

The chlorophyll-*a* field data used in this study were part of a larger field survey on water quality in Lake Naivasha from January to November 2011 (Ndungu et al. 2012). Chlorophyll-*a* concentrations were only analysed between February and May 2011 from surface water samples collected at 0–0.5 m depth from the seven sampling sites shown in Figure 1(*c*). The water samples were transported to a laboratory in a cooler box immediately after collection. The samples (100 ml) were filtered using an electric filtration unit through pre-washed Whatman GF/F 0.47 μm diameter filters and were extracted overnight using 10 ml of 90% acetone. Chlorophyll-*a* absorption was then determined using a Thermo Scientific GENESYSTM 10S Bio UV/visible spectrophotometer by measuring the absorbencies at 663 and 750 nanometre wavelengths after standardizing using acetone. The formulae by Talling and Driver (1961) were used to calculate chlorophyll-*a* concentration.

3.2. MODIS data processing

MODIS radiance images (Level-1A) were downloaded from the NASA Goddard Space Flight Center website (http://oceancolor.gsfc.nasa.gov/cgi/browse.pl?sen=am). Data processing from Level-1A to reflectance images (Level-2) and chlorophyll-*a* concentration maps (Level-3) were done using SeaDAS 6.3 software (Fu, Baith, and Mcclain 1998). To improve estimates for chlorophyll-*a* concentration, the threshold value for high cloud albedo quality control flagging was set to 0.054. This was done because in turbid lakes, the cloud albedo threshold is much higher than the default SeaDAS software value of 0.024. The clouds were then masked in accordance to the top of atmosphere (TOA) reflectance at the 859 nm band (Chen, Hu, and Muller-Karger 2007). Atmospheric correction was done using the shortwave infrared bands (SWIR) ocean colour procedure (Wang, Shi, and Tang 2011; Son and Wang 2012; Shi and Wang 2009) that is embedded in the SeaDAS 6.3 software. The Proc_land routine was also applied to ensure that the processing was extended to land. The OC2 algorithm (O'Reilly et al. 1998) was used to derive 500 m resolution chlorophyll-*a* maps. This process was automated using the Interactive Data Language (IDL) scripts. The processing steps are summarized in Figure 2.

3.3. Data analysis

After the processing of daily chlorophyll-*a* concentration maps, composite averaging was done to acquire monthly images from July 2002 to June 2012. This was done to improve the spatial coverage, which includes gaps as a result of cloud cover and/or macrophytes. To assess the temporal changes in chlorophyll-*a* concentration over the years, a lake-wide spatial average was computed for each of the monthly composite images. The 2002 and 2012 data were omitted in this computation because the data were partial and did not cover the whole year. The data were then plotted in a time series plot and according to gaps noted from May 2009 to August 2010; trend assessment was only done for the period between July 2002 and May 2009. Decomposition of the time series into seasonal, trend, and residual

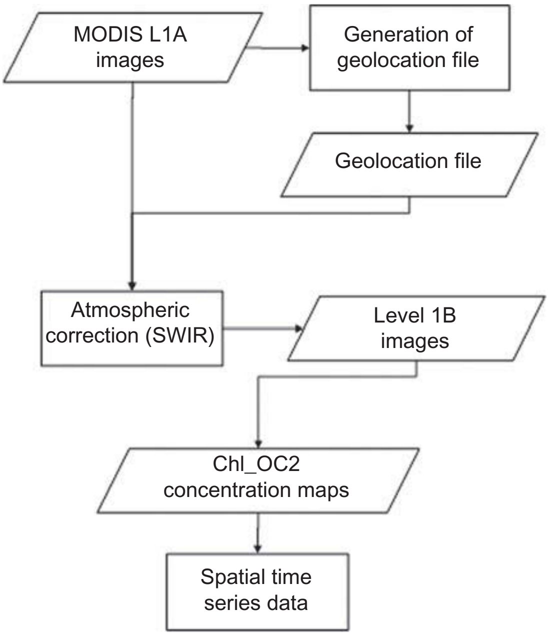

Figure 2. Flow diagram of the procedure to obtain chlorophyll-*a* concentration maps.

components was done using the STL procedure in R software (R Development Core Team 2008). The details of the procedure are stipulated in Cleveland et al. (1990). The seasonal component was calculated for a periodic seasonal window of 12 months. This method has the capability of smoothing out the seasonal effect, which results in a more visible long-term time series trend of chlorophyll-*a* concentration. This basic analysis approach was similarly applied to monthly lake-level data.

3.3.1. Validation

For validation purposes, *in situ* chlorophyll-*a* data from seven field sampling sites (Figure 1(*c*)) were assessed for suitability as a match-up data set. Unfortunately, the *in situ* data did not match with the exact date and location in the MODIS data. Therefore, accuracy assessment between the *in situ* and retrieved chlorophyll-*a* was done within a weekly time span. If a direct match was found, the value was picked for validation purposes. If not, the search was extended gradually to a maximum of 5 × 5 pixels range. Regression analysis showed a significant variation in the concentrations of chlorophyll-*a* ($R^2 = 0.65$, $P < 0.001$, $N = 25$), but the concentrations derived from MODIS systematically underestimated the field data. The 65% variation was considered sufficient for this study because it focuses on the overall spatio-temporal variation and trend of the chlorophyll-*a* concentration and not absolute values. The MODIS data should, therefore, be interpreted as an index rather than actual chlorophyll-*a* concentration values.

4. Results

*4.1. Spatio-temporal variation in chlorophyll-*a *concentration*

Monthly climatological patterns of chlorophyll-*a* concentration in the lake, derived from the composite average of respective monthly images between 2003 and 2011, are presented in

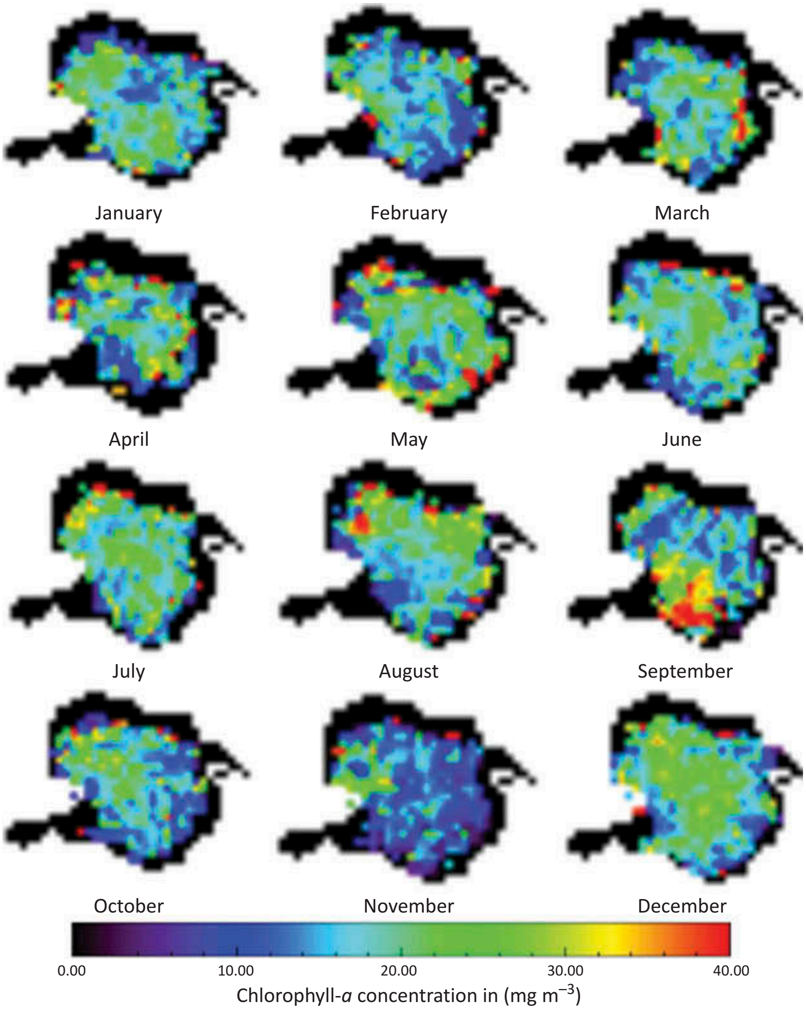

Figure 3. Monthly average of chlorophyll-*a* concentration maps from 2003 to 2011.

Figure 3. In January, a major part of the lake showed medium chlorophyll-*a* concentrations (green colour), except near the mouth of the Malewa river where low (blue colour) concentrations were evident. In February, the lower concentrations seemed to spread over a larger part of the lake, whilst from March to July these were in the medium range. In August, the concentrations in the south sector of the lake were lower than in the north, while in September the opposite occurred but with a much higher concentration (red colour) in the south. In October and November, the concentrations seemed to diminish again, with November showing the lowest concentrations among all months. In December, the concentrations increased again. The black areas denoted pixels without data and occurred especially around the border of the lake, where the lake is too shallow or covered by macrophytes. This was not unusual since the pixels on the fringe (edge) of the lake are generally based on fewer data than those in the centre of the lake due to land adjacency effect and changes in lake levels.

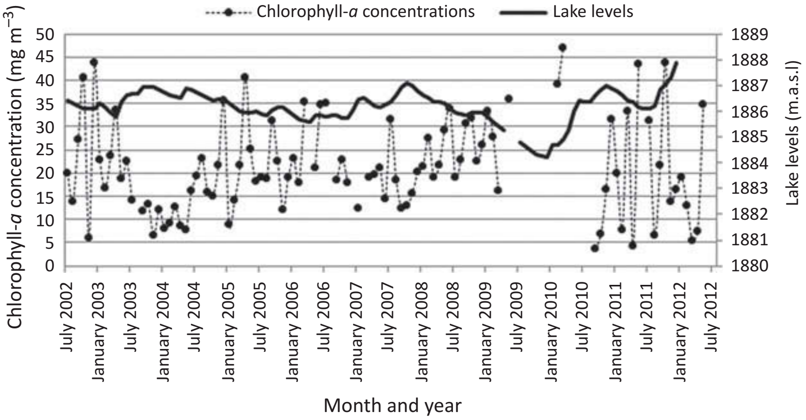

Figure 4. The time series of chlorophyll-*a* concentration based on MODIS data (dotted line) and lake water levels (line graph) in Lake Naivasha from July 2002 to May 2012.

The time series of the spatially averaged monthly chlorophyll-*a* concentration and lake levels are shown in Figure 4. After a decline in 2003, the chlorophyll-*a* concentration showed a general increase until the end of 2009. Throughout the study period, chlorophyll-*a* concentration was higher when lake levels were low and vice versa.

Between April 2009 and August 2010, the detection of chlorophyll-*a* concentration from the MODIS images was limited. This period coincided with the lowest lake water levels (1884 m a.s.l) in the last century as a result of prolonged drought. In September 2010, the lake levels steadily increased and chlorophyll-*a* concentration became detectable again and exhibited unpredictable and erratic behaviour.

The STL decomposition of the temporal trend of chlorophyll-*a* concentration is shown in Figure 5. The upper panel shows the time series of chlorophyll-*a* concentration from 2002 to 2009 (Figure 5). The decomposition of the data series into seasonal and trend components is given in the second and third panels of Figure 5, while the fourth panel shows the residuals. The grey bar on the right shows the data range for scale comparison. The seasonal component shows similarities with the monthly patterns (see Figure 3), with relatively low concentrations in February and November compared to the other months. The data exhibit a trend whereby a decline in chlorophyll-*a* concentration was observed from 2002 to 2003, followed by a general increase until 2009 with a slight decline in 2007.

To investigate the apparent relationship between chlorophyll-*a* concentration and lake levels, STL decomposition was also applied to the time series of the lake level data over the same period. The resultant lake level trend is plotted together with the chlorophyll-*a* concentration trend in Figure 6, which shows an inverse relationship between chlorophyll-*a* and lake levels.

5. Discussion

5.1. MODIS data

This study demonstrates the possibility of utilizing MODIS-Aqua 500 m resolution images in the analysis of spatio-temporal variation in chlorophyll-*a* concentration in tropical lakes. The success in the retrieval of chlorophyll-*a* concentration is likely to be attributed to the

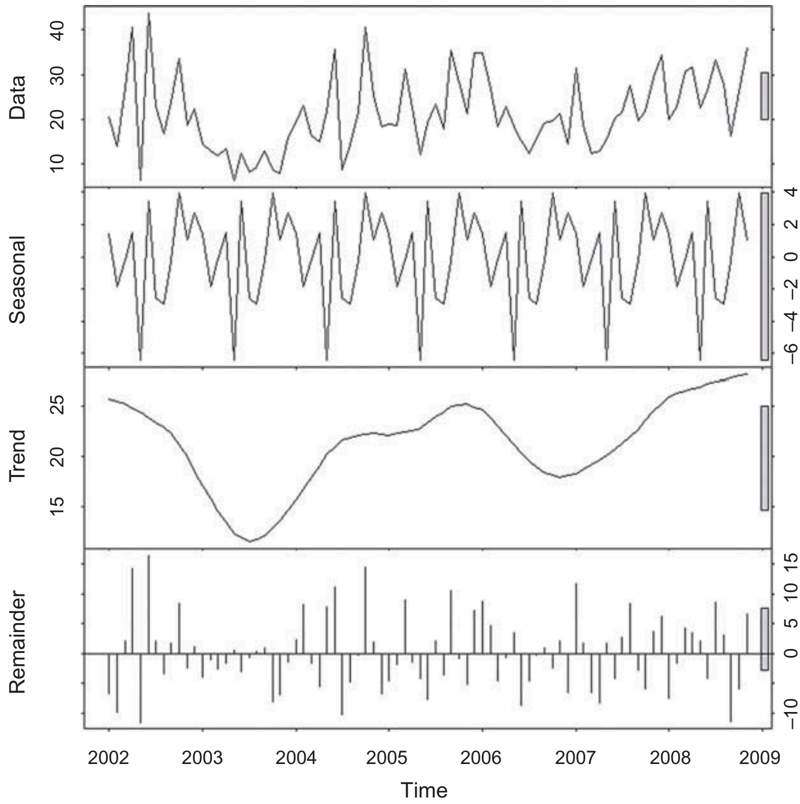

Figure 5. Decomposition of chlorophyll-*a* data into seasonal, trend, and residual components.

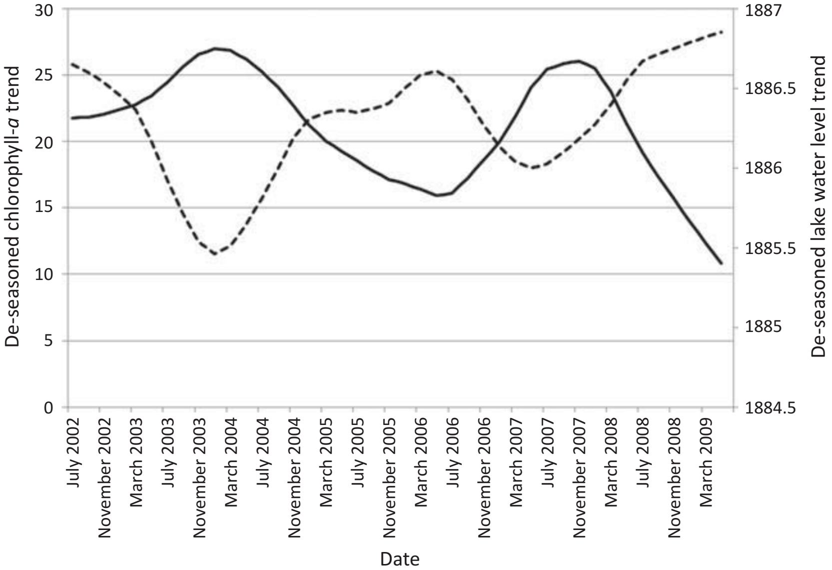

Figure 6. Comparison between the trends of de-seasoned chlorophyll-*a* concentration (dashed line) and de-seasoned lake water levels (solid line) from July 2002 to May 2009.

choice of the atmospheric correction method and the algorithm applied in retrieval. The SWIR atmospheric correction procedure was preferred in this study because of its robustness in turbid water environments (Shi and Wang 2009). The OC2 algorithm applied in this study is a two-band algorithm empirically derived from the relationship between the ratio of remote-sensing reflectance for MODIS Bands 3 and 4 and archived *in situ* measurements of chlorophyll-*a*. Bands 3 and 4 are centred at 469 and 555 nm, respectively. Both bands have a spectral bandwidth of 20 nm. The OC2 algorithm yielded relatively good estimates of chlorophyll-*a* concentration. Although the OC2 algorithm was first developed for SeaWiFSdata (O'Reilly et al. 1998; O'Reilly et al. 2000; Darecki and Stramski 2004), it has been proved effective in MODIS high-resolution bands (500 m) in turbid waters (Hudson, Taylor, and Schindler 2000; Wang and Shi 2008; Wang, Tang, and Shi 2007). The OC2 algorithm has also been tested in turbid lake environments (Weghorst 2008; Chang et al. 2012). Other studies have found the MODIS medium-resolution bands (250 and 500 m) to be 4–5 times more sensitive than the Landsat 7 bands (Hu et al. 2004). Moreover, the daily temporal resolution of MODIS-Aqua data is high compared to the 16 day revisit time of Landsat images.

*5.2. Spatio-temporal variations in chlorophyll-*a

Annual variations in chlorophyll-*a* concentration depict seasonal and environmental influences. One of the main seasonal factors could be agricultural activities in the catchment, which may be linked to climatic factors such as rainfall (Mageria, Bosma, and Roem 2006). In January, lower concentrations of chlorophyll-*a* were observed at the northern part of the lake near the mouth of the Malewa river, which suggests that the chlorophyll-*a* concentration near the river mouth was diluted by the river water and/or the river water conditions (e.g. velocity, sediment load) that favour only opportunistic phytoplankton species growth. The dilution effect spread over the lake in February, resulting in an overall decline in chlorophyll-*a* concentration. However, February is usually the planting season and farmers use fertilizers on their farms (Ngugi, Karau, and Nguyo 2005). In the event of a first heavy rainfall storm around this period, peaks in nutrients are highly likely. This may translate into higher nutrient concentration in the lake, which is evidenced by increased chlorophyll-*a* concentration (Hansson 1990) from March to May. Chlorophyll-*a* concentration is expected to rise within a window of 3–7 days following an increase in nutrients (Wilkerson et al. 2006).

In addition, the river water flows much farther into the lake during the rainy season, with consequent additional nutrients which provide a favourable environment for phytoplankton development (Kitaka, Harper, and Mavuti 2002). Around August, top dressing of the agricultural plants with fertilizers takes place (Schmidt, Swoboda, and Jätzold 1979). Again, if a heavy storm occurs thereafter, nutrients may be washed down into the lake and consequently lead to flourishing of phytoplankton – and hence chlorophyll-*a* concentration increases. The rains in October and November have a diluting effect on the chlorophyll-*a* concentration. High nutrient concentrations may also have promoted the growth of macrophytes such as water hyacinth (*Eichhornia crassipes*) (Kampeshi and Shantima 1999), which resulted in data gaps in the MODIS-Aqua images of Lake Naivasha. Up to 32 quality control parameters are monitored during processing of raw TOA satellite data to final geophysical values of chlorophyll-*a* concentration. The threshold levels for quality control parameters are tuned for pelagic environments. Processing over macrophytes probably produces scattering and absorption levels that exceed the expected normal ranges for pelagic environments. Cloud cover also affects the spatial coverage of the satellite data, especially during the wet months (March/April/May and October/November).

The general increase in chlorophyll-*a* concentration may be attributed to an increase in the agricultural activities within the catchment (Stoof-Leichsenring et al. 2011; Verschuren et al. 2000; Mergeay 2004; Harper et al. 2011). In addition, common carp (*Cyprinus carpio*), which is a benthic feeder, was accidentally introduced in the lake in 1998 and started being caught by commercial fishermen in 2002 (Britton et al. 2007). The carp's burrowing activities cause resuspension of sediments, thus redistributing and making the nutrients available in the water column of the lake.

In 2009 and 2010, chlorophyll-*a* concentration was barely detectable from the MODIS satellite images, which was attributed to either the shallowness of the lake due to low lake levels or high reflectance of turbidity constituents such as suspended solids. Around this period, some researchers described the lake as a muddy fish pond because of the reduced size and dissolved and suspended particulate matter which turned the colour of the water brown (Njogu et al. 2011). In February 2010, a large fish kill occurred apparently due to high organic matter concentrations in the water column (including dead phytoplankton) that cause high oxygen demands and may, in severe cases, lead to anoxic conditions that cause fish kill (Carrick, Moon, and Gaylord 2005). The muddy conditions began to improve in 2011 following a considerable increase in rainfall, which resulted in higher lake water levels compared to the previous two years. In 2012, the lake level started to decline again with a possibility of increased turbidity.

*5.3. Lake levels and chlorophyll-*a *concentration*

The concentration of chlorophyll-*a* depends on the availability of solar radiation (light and temperature) and nutrients that are fundamental to photosynthesis and phytoplankton growth, respectively (Schlüter et al. 2000). Near the equator, daylight is constant, making variations in temperature around Lake Naivasha minimal. This prompts us to plausibly postulate that the main cause of the observed inverse relationship between the chloropyhll-*a* concentration and water levels may have been the nutrient supply. Nutrient availability in lakes is regulated by, *inter alia*, additional input from the inflowing rivers, release from decay of dead organic matter (e.g. macrophytes and phytoplanktons), deposition of atmospheric dust particles, and resuspension of the bottom sediments by wind waves, boats, hippos, and burrowing fish (Kronvang et al. 2005; Likens 1972; Kilham and Kilham 2006; Sickman, Melack, and Clow, 2003; Asaeda, Kien, and Jagath 2000; Breukelaar et al. 1994).

The relationship between lake level and chlorophyll-*a* concentration in Lake Naivasha is associated with complex processes that affect nutrient availability and phytoplankton growth (Scheffer 1998, 2009; Scheffer and Jeppesen 2007). This relationship suggests that nutrient availability, and hence phytoplankton growth, decrease with increasing water level in this lake. Apparently, it appears that the rainfall and river discharge which are responsible for the lake level rise exhibit lower nutrient concentrations than the lake and could probably lead to dilution of nutrients and chlorophyll-*a* concentrations. Furthermore, a combination of low water levels and uniform temperatures allows lakes to mix completely, leading to a recharge of the bottom water with oxygen and raising of nutrients to the surface (Michaud 1991). This condition favours phytoplankton growth, thus explaining the rise of chlorophyll-*a* concentration in Lake Naivasha during low water levels, and is in agreement with the findings of Zinabu (2002). Moreover, nutrient input depends on the combination of fertilizer application and rainfall patterns. Other studies have shown the dependence of shallow lakes on both internal and external environmental changes that influence the prevailing processes and mechanisms (Scheffer 1998, 2009; Scheffer and Jeppesen 2007). Wang et al. (2012) found a non-linear relationship between water level and chlorophyll-*a* through wavelet modelling. Contrary to this finding, the inverse relationship of de-seasoned chlorophyll-*a* and lake water levels observed in this study is a significant contribution to aquatic science because, to the best of our knowledge, it has not been observed or reported before. This finding re-emphasizes and enhances our understanding of the hydrological influence on the ecology of the lake and could therefore assist in controlling and management of chlorophyll-*a* concentration and subsequently improve the trophic state of lake Naivasha.

6. Conclusions and recommendations

The findings in this paper affirm the possibility of estimating chlorophyll-*a* concentration using data from the MODIS-Aqua satellite to enhance the understanding of turbidity dynamics in Lake Naivasha. Although the chlorophyll-*a* concentrations are underestimated by MODIS compared with field data, the significant relationship provides reliable information for studying spatial variations and temporal trends. The results reveal the possibility of capturing a synoptic view of spatio-temporal variation of chlorophyll-*a* concentration in Lake Naivasha, a highly turbid tropical lake in Kenya. Indeed, the satellite data allow retrospective analysis of the chlorophyll-*a* in aquatic systems and therefore provide data at times when routine ground measurements do not exist.

This study demonstrates the existence of a large inter-annual spatial variation in chlorophyll-*a* concentrations over the lake, which is evident in the monthly composite maps. The results portray a large temporal variability which is partly caused by seasonal influences such as climate (rainfall) and seasonal agricultural practices. The decomposition of the time series from 2002 until 2009 reveals seasonal variations that correspond to the monthly averaged maps. This is also evident in the long-term trend variations that correlate to the lake level, which plausibly could be explained by dilution and concentration effects. The significant relationship between chlorophyll-*a* and lake level trends provides the much needed information to managers and decision-makers in controlling and managing chlorophyll-*a* concentration, which will subsequently lead to improvement of the trophic state of Lake Naivasha.

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