GIS and Remote Sensing Based Assessment of Water Quality Changes in Lake Malawi

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Abstract

The aim of this paper is to evaluate the changes in water quality. The parameters used in this study include Secchi Disk Transparency, Chlorophyl and Total Suspended Sediments as they are highly correlated with satellite datasets. Data processing and analysis included spectral correction, radiometric correction, mosaicking, water index calculation, water mask creation, water quality parameter calculation based on Krizanich (2009) model, Trophic State Indices, significance tests, land cover changes and areal coverages. The results of the study indicate that there were both positive and negative changes in the absolute water quality parameters between 1990 and 2011. There was a similar scenario for coverages of water with diminishing and improving water quality values. Thus, there were both spatial and temporal none uniform variations of water quality in the study area. Significant tests for the water quality changes for 10 year epochs yielded the following P values; 0.752, 0.909, 0.998, 0.750, 0.965 for Chlorophyll, Suspended Sediments, Secchi Disk Transparency, Trophic State Index (Chl) and Trophic State Index (SDT) respectively. This entails that there has been significant changes in water quality parameters. Strong relationships were established when coverages of declining water quality were used against the land cover changes in correlation analysis. The results suggested that human activities have played an upper hand in the depletion of forest resources on the catchment and has resulted in the decline in water quality in the lake.

Keywords: Chlorophyl, GIS, Lake Malawi, Remote Sensing, Secchi Disk Transparency, Trophic State Index, water quality.

1.0 Introduction

Bootsma (2006) suggests that there is an increase of nutrients deposition in Lake Malawi due to anthropogenic activities. Chidammodzi (2015) argues that pollutants of Lake Malawi originate from the catchment and beyond. Human activities (land use) that includes but not limited to deforestation, inorganic pollution from agricultural activities and poor crop husbandry leading to soil erosion act as the major catalysts for the deposition of pollutants into the lake (Chidammodzi, 2015). Such pollutants are also a threat to biodiversity within the lake through eutrophication, algal blooms, decreased water transparencies and low oxygen concentrations (McConnell, 2013; Tranvik, 2009).

There has been unprecedented population growth in Malawi where a greater percentage of the catchment of Lake Malawi is located. According to Bootsma (2006), the population in Malawi has doubled between 1980 and 2005. Human activities have led to declines in water quality in both the absolute values of the water quality parameters as well as the extents of the changes in water quality parameters.

It is worth noting that Shire River acts as the only outlet to lake Malawi. This entails that Lake Malawi has a long retention time. Thus, resources as well as pollutants within the lake can be held for long periods of time. This could lead to a situation whereby degradation of water quality within the lake goes unnoticed over a long period of time. Such a characteristic of a lake leads to catastrophic conditions of the aquatic ecosystem overtime (Bootsma, 2006). Bootsma (2006) suggests that the water quality in Lake Malawi is slowly degrading over time and it is very difficult to notice these changes if appropriate monitoring systems are not put into place. According to Xiaoying (2006), the eutrophication process has several stages. Different types of lakes take different periods in those stages. A lake's eutrophication stage can only be determined through continuous monitoring (Xiaoying, 2006; Hook, 2010).

Thus, a decline in water quality in the lake is not only caused by depletion of resources on the catchment. Rather, the inefficiencies in the conventional approach of monitoring the lake's eutrophic conditions can be said to be a major player to the declines in water quality. The current conventional approach of monitoring the lake is costly, tedious, limited in coverage, takes longer period to process the data and is manifested with irregularities in routine observations leading to unavailability of historic data as it relies on in situ observations only. The monitoring stations are located along the shoreline for the convenience of data collection leading to bias in sampling. Thus, the samples collected are not a true representative of the entire lake. Unavailability of historic data on nutrient concentrations in water bodies due to poor data management poses a challenge to the assessment of the changes in nutrient levels in the lake. Such factors have affected the efficiency of the monitoring system (Bootsma, 2006).

As such, remote sensing is seen as an alternative to the conventional system as it offers synoptic views of the entire lake, free online data, electronic data for easy dissemination, routine observations are easily done and less processing periods.

1.1 Remote Sensing and water quality monitoring in water bodies

Despite the fact that there are GIS and remote sensing based efficient approaches in water quality monitoring, the Malawi Government has not yet adopted such technologies. This has been the case due to lack of expertise in remote sensing technology by the people responsible for the monitoring of water quality. Further to that, remote sensing data was initially thought to be expensive. However, satellite data is now readily available online either for free or at a reasonable fee depending on the resolution of the data (Olmanson, 2011).

The current monitoring system is based on in situ observations. Water quality parameters used include pH, electrical conductivity, total dissolved solids, carbonate, Bicarbonate, chloride, sulphate, nitrate, fluoride, sodium, potassium, calcium, magnesium, iron, manganese, silica, turbidity, suspended sediments, Hardness, alkalinity, radioactivity, chlorophyll, oil and grease and Secchi Disk Transparency. Thus, the samples collected are not a true representative of the entire lake.

Olmanson (2011) suggests that adoption of remote sensing technology in water quality assessment and resources management also provides an opportunity to develop a comprehensive water quality and resources database.

Hu (2010) emphasizes that aims of water quality monitoring can only be met if there are long term commitments as well as tools that enable frequent, widespread and consistent observations. This is hardly the case with the current water quality monitoring system in Malawi.

1.2 Estimating water quality parameters from landsat images

There has been a lot of research that has established the relationship between satellite data and water quality parameters. These include but not limited to Kloiber (2002), Lathrop (1992) Krizanich (2009), Olet (2010), Mayo (1994) and Yang (2016). These research papers have revealed the strong relationship that exists between satellite data and ground based measured water quality parameters. These papers have argued and demonstrated that there is a correlation between water quality parameters and reflectance values of satellite data. It is realisation of such a relationship that has enabled the development of equations that are used to calculate water quality parameters Such water quality parameters include Secchi Disk Transparency, chlorophyll and suspended sediments.

The papers by Krizanich (2009) and Olet (2010) whose aims were to establish a relationship between estimated and observed Secchi Disk Transparency through regression techniques have yielded a strong linear relationship between the two. The results had an R square no greater than 0.4. Low R square values denote good model performance. Results derived from such models are reliable and were adopted in this research.

The results of Karabulut (2005) indicate that suspended sediments causes increasing spectral response in surface waters. Such a relationship creates a possibility of estimating and recognising the type of organic components in the various layers of a water body. Suspended sediments do not only affect water quality of a water body. Rather, suspended sediments shorten the life of a water body, impact the biologic life in a water body by limiting the penetration of sunlight. Suspended sediments are also said to be carriers of pollutants from anthropogenic activities (Karabulut, 2005).

Karabulut (2005) explains that chlorophyll is another water quality parameter that has also been used to assess water quality by various researchers using remote sensing technology. Karabulut (2005) argues that chlorophyll concentration is indicative of the trophic state of a water body likely caused by anthropogenic activities. Thus, it provides an insight of pollution in water bodies as well as distribution of harmful algae.

Lim (2015) demonstrates how chlorophyll concentrations in water bodies can easily be calculated based on the established linear relationship between observed chlorophyll concentration and estimated chlorophyll values using landsat data. Just like Krizanich (2009), Lim (2015) realises that there is a correlation between observed and calculated values of chlorophyll content. This entails that landsat data is a good candidate for the monitoring of chlorophyll concentrations in water bodies.

The models for the estimation of water quality parameter values are as follows:

$$\ln(SDT) = -10.061(TM1/TM3) + 1.788(TM1) + 0.06$$

where TM1 and TM3 are bands 1 and 3 respectively.

$$\ln C = 48.31 - 1.55TM2 - 5.579[TM3/TM1]^2$$

where TM3 and TM1 are bands 3 and 1 respectively.

$$SS = 6.7571 + 0.298858TM1 + 2.922987TM3$$

where TM1 and TM3 are bands 1 and 3 respectively.

It should be noted that mere calculated water quality parameter values do not provide an insight in the condition of a lake. Rather, Trophic State Indices are vital to the understanding of water quality trends. The equations that were used to calculate the Trophic State Indices for Sechi Disc Transparency and chlorophyll are illustrated below.

$$TSI(SDT) = 60 - 14.41 \ln(SDT)$$

$$TSI(CHL) = 9.81 \ln(CHL) + 30.6$$

2.0 Material and Methods

2.1 Study Area

Lake Malawi is one of the world's greatest lakes in the world. It is ranked number five of the world's lakes based on its volume estimated to be 7775.00 km^3. The surface area of the lake is 29500.00 km^2 with a mean depth of 264.00m. It covers 20 percent of the total land in Malawi. The water residence time of the lake is estimated to be 114 years (Jorgensen, 2004). The lake has a biodiversity of up to 1000 aquatic species. Not only does the lake provide habitat to the aquatic life, it also provides economic as well as recreational services to the Malawian society (Chavula, 2008).

2.2 Sampling Technique

A random sampling technique was utilised in this paper. Three areas of interest with radii of 5km were clipped from the landsat images where values of Secchi Disk Transparency (water clarity), chlorophyll and suspended sediments were calculated. Sample 1, sample 2 and sample 3 are located in northern, central and southern parts of lake Malawi respectively. Same sites were utilised in understanding seasonal variability in water quality Parameter values(Figure 1).

On the other hand, systematic approach was used to select months (December and October) for which seasonal variations of water quality were going to be based. The dry (October, 1999) and wet (December, 1998) seasons.

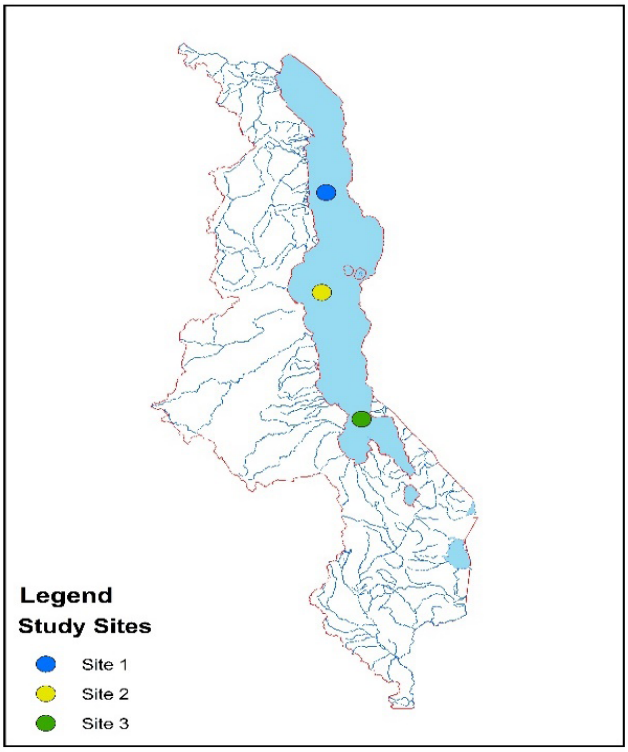

Figure 1 Study sites in Lake Malawi

2.3 Data collection

Satellite images were downloaded from the Landsat archive through United States Geological Survey website (https://earthexplorer.usgs.gov/). This is an open-source archive that dates back to 1970s. Datasets for three epochs were downloaded from the archive. These included for the years 1990, 2000 and 2011. Due to vastness of the lake, each epoch had 7 images to cover the entire lake. These images were of a course resolution of 1km by 1km.

Despite the course resolution of the dataset, it is the vastness of the lake that provides the possibility of using this data for water quality assessment. According to Olmanson (2011), the width of water surface should be no less than three times the resolution of the image if it is to be used in water quality assessment. This is to ensure that the results obtained from the analysis are reliable. Further to that, the established correlations between observed and estimated value for water quality parameters from landsat images justifies the use of landsat images in this research (Kloiber (2002), Karabulut (2005), Krizanich (2009), and Arpaslan (2010).

2.4 Data Analysis

2.4.1 *Spectral correction*

The downloaded data underwent a process of layer stacking due to the spectral resolution of the landsat data. The data had a minimum of 7 bands (Band 1, Band 2, Band 3, Band 4, Band 5 and Band 6 for Blue, Green, Red, Near Infrared, Short-Wave and Thermal respectively) which were downloaded as independent files. However, band 6 was a thermal band and was ignored in the layer stacking process as it is not used in the models of water quality parameter calculations. The rest of the bands were stacked to create a composite image for subsequent analysis.

2.4.2 *Radiometric correction*

The downloaded images were raw in nature. This entails that the images had raw digital numbers. However, the calculation of water quality parameters require that the data be that of reflectance. This necessitated the conversion of the raw digital numbers to reflectance. Reflectance values are equivalent to those of a sensor at the moment of data capture. These values are important if different features on the earth's surface are to be differentiated.

Parameters for this conversion were obtained from a text file. Each satellite image had unique parameter values due to differences in both dates of acquisition as well as atmospheric conditions. Atmospheric conditions have an important role in the propagation of signals to and from the sensor thereby introducing errors. Such errors need to be eliminated if reliable results are to be yielded from the analysis (Baruah, 2001).

2.4.3 *Mosaicking*

Due to the vastness of the lake, 7 landsat scenes were downloaded to cover the entire lake for each epoch. For the easy of processing, these scenes were mosaicked. Artefacts as a result of variations in weather conditions at the time of data capture were eliminated by using the 'feather' option in Erdas Imagine

2.4.4 *Water Mask creation*

Normalised Difference Water Index was used to create a water mask. This is an index that is calculated to differentiate water bodies from other features on satellite imagery. This calculation is based on Near Infrared and green bands because the green band has high reflectance for water whereas NIR has high reflectance for land and vegetation. The NDWI enhances water features and suppresses both land and vegetation.

2.4.5 *Water quality parameter values estimation*

Due to limited availability of in situ observations in the study area, water quality parameter values were calculated based on Krizanich (2009) models. Uniform models were used to estimate parameter values for each epoch. This was done for easy comparison of the results.

3.0 Results and Discussions

The results from the study have revealed that changes in water quality parameters has not been uniform across the lake. This led to assessment of these parameter values at Areas of Interest (AOI) from the three regions of Malawi. AOI 1, 2 and 3 were from northern, central and southern regions refered to as sample 1, 2 and 3 in the figure, respectively (Figure 2).

3.1 Chlorophyll concentrations

The results of chlorophyll analysis (Figure 2(a)) indicate that there was an increase of chlorophyll concentration between 1990 and 2000 at AOI 1 in the northern region. AOI 2 and 3 experienced a decline in Chlorophyll concentration between 1990 and 2000. Chlorophyll concentration declined at AOI 1 between 2000 and 2011. This is contrary to what occurred at AOI 2 and 3 between 2000 and 2011. Despite the changes being minimal for all the Areas of Interest, they can eventually accumulate. It is also observed that there is greater deviations in chlorophyll concentrations across the southern tip of the lake as compared to the other parts of the lake.

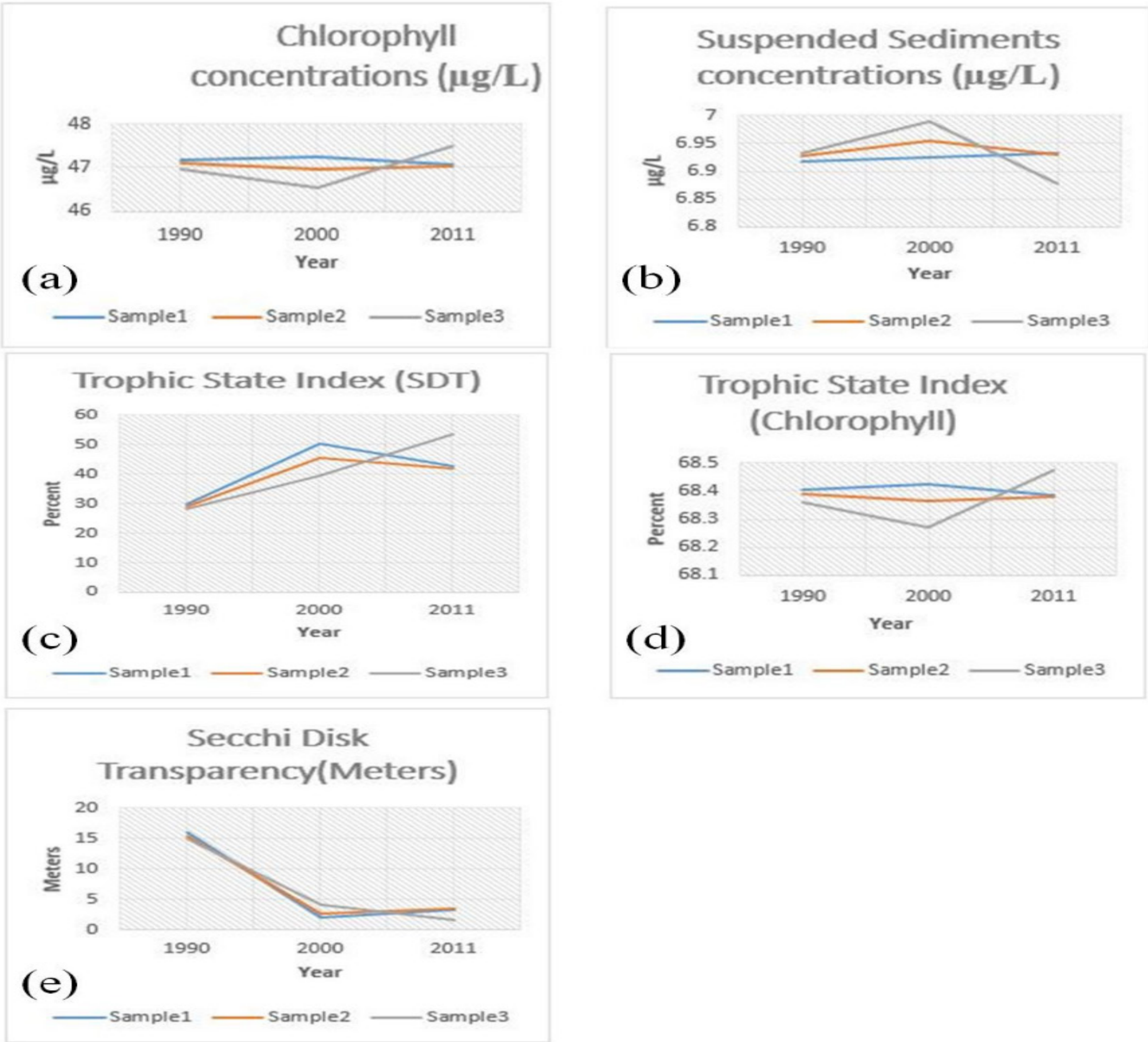

Figure 2: Chlorophyl concentrations (a), Suspended Sediments concentration (b), Trophic State Index for SDT (c), Trophic State Index for Chlorophyl (d), Secchi Disk Transparency (e)

3.2 Suspended Sediments

Suspended Sediments are observed to have increased on AOI 2 and 3 between 1990 and 2000 (Figure 2(b)). These two sample sites experienced a drop in suspended sediments between 2000 and 2011. AOI 1 has experienced positive changes throughout. Greatest deviations are in the southern tip of the lake.

3.3 Secchi Disk Transparency Trophic State Index

Trophic state index based on Secchi Disk Transparency indicate that there has been a decline in water quality in all the samples between 1990 and 2011. However, AOI 1 and 2 experienced improvements in water quality between 2000 and 2011 when sample 3 experienced continued declines in water quality. However, Trophic State Indices for all the sites have remained higher than the base year.

3.4 Chlorophyll Trophic State Index

The Trophic State Index for chlorophyll can be said to be on the higher side as the values are all above 67. The variation in these values can be said to be minimal across the three epochs. However, the chlorophyll blooms can accumulate eventually as is the case with sample three whose final value has surpassed that of the base year.

3.5 Secchi Disk Transparency

The results reveal that there was a drastic drop in Secchi Disk Transparency Parameter values between 1990 and 2000 on all the three sites (Figure 2(e)). However, there was an improvement in this parameter between 2000 and 2011 on AOI 1 and 2. Despite this improvement, the values of the parameter remain on the lower side compared to the base year of the study. Sample 3 continued to experience decline in water clarity. Water clarity is experiencing greater changes compared to the other two parameters. This is illustrated by high standard deviations for this parameter.

3.6 Significance tests for water quality parameters

The significance test of the variations in water quality parameters over time was based on Anova with a single factor. An alpha value of 0.05 was used leading to a confidence level of 95%. Table 1 summarises the P values of the outputs for the water quality parameters over the three samples.

It was observed that the P values were greater than the alpha value in all the water quality parameters. Thus, the variations can be said to be significant at 95% confidence level. Further temporal variations have been illustrated in Figure 3.

Table 1: Results of the significance of the changes in water quality parameters

Water Quality Parameter	Alpha Value	P Value
Chlorophyll	0.05	0.752
Suspended Sediments	0.05	0.909
Secchi Disk Transparency	0.05	0.998
Trophic State Index (Chl)	0.05	0.750
Trophic State Index (SDT)	0.05	0.965

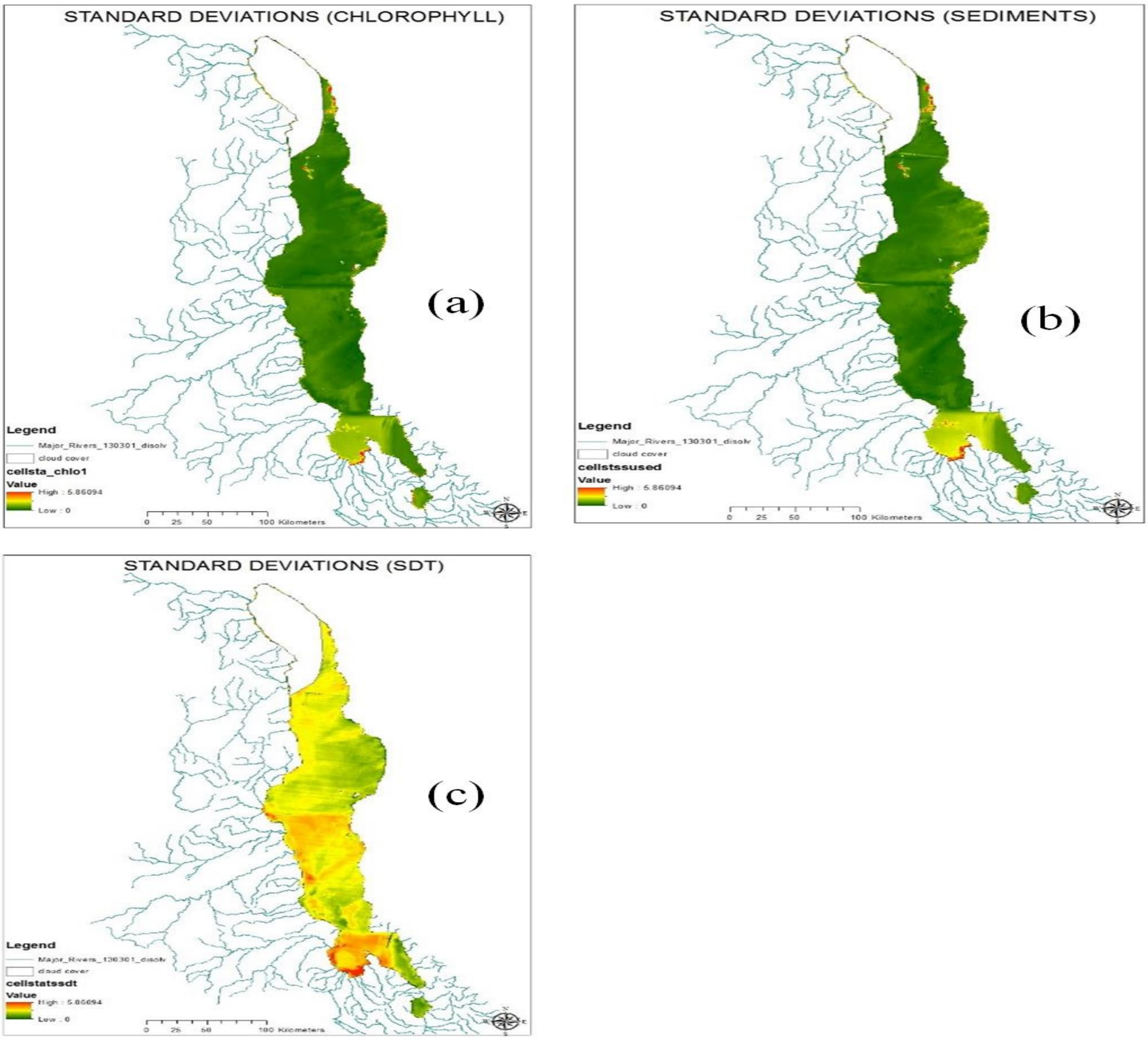

Figure 3: Standard deviation for Chlorophyl (a), suspended sediments (b) and Secchi Disk Transparancy (c)

3.7 Relationship between human activities and water quality.

A correlation analysis was done to determine the relationship between land cover changes and the absolute values for water quality parameters.

Results of the analysis are summarised in Table 2.
It was observed that Forestland and Grassland are significantly correlated to Secchi Disc Transparency based on the correlation coefficients.

Table 2: Correlation between landcover and water quality

Land Cover	Parameter	Coefficient
Cropland	Chlorophyll	0.091
	SDT	-0.441
	SS	-0.484
Settlements	Chlorophyll	0.029
	SDT	-0.429
	SS	-0.429
Forestland	Chlorophyll	0.124
	SDT	0.622
	SS	0.285
Grassland	Chlorophyll	0.399
	SDT	0.818
	SS	0.003

4.0 Conclusions

The results suggest that there is change in the values of water quality parameters. However, this change was minimal except for Secchi Disk Transparency. The results of the significance test on these changes suggests that the changes are significant.
Based on the results of the changes in areal coverage of water with degrading quality, it can be concluded that coverage of water with a declining water quality is increasing in the lake.

5.0 Recommendations

The first recommendation is the incorporation of remote sensing and GIS approaches in the current water quality monitoring system. Second recommendation is Remote sensing and GIS training for people responsible for water quality monitoring in Lake Malawi. Thirdly, determination of localised models for monitoring the various water quality parameters for the lake.

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