Using Remote Sensing Techniques for Monitoring Ecological Changes in Lakes: Case Study of Lake Naivasha

KEY WORDS: Archive, Changes in Climate, Ecology, Landsat Imagery, Lake Naivasha, Remote Sensing, Water Abstraction

ABSTRACT:

The ability to use remote sensing in studying lake ecology lies in the promise that satellite sensors can measure the spectral reflectance of constituents in water bodies. This reflectance can be used to determine the concentrations of the constituents in the water column through mathematical relationships. This work identified a simple linear equation for estimating suspended matter in Lake Naivasha with reflectance in Landsat7 ETM+ image. A R^2=0.94, n=6 for suspended matter was obtained. Archive of Landsat imagery was used to produce maps of suspended matter concentrations in the lake. The suspended matter concentrations at five different locations in the lake for 29 years period were then estimated. Interpretations of charts, values, maps and images from these concentrations were done to reflect on the ecological changes the lake has experienced. It was found out that the ecological changes Lake Naivasha is experiencing are due to over abstraction of the water in the lake and the changes in climate the lake experiences in the event of time.

1.0 Introduction

Remote sensing is the discipline of acquiring information from an object without physically being in contact with the object itself. It involves using different sensors to remotely pull together radiation from the object and then analyze to obtain information about the object. Most of these sensors are space-borne and measures the electromagnetic energy that is either reflected or emitted from objects. The recorded energy is calibrated and converted to values of picture elements (pixels) which are interpreted and stored as images of scenes from the object, (Lillesand *et al*, 2008). Remote sensing is a relatively less expensive means of obtaining information which otherwise would have been more expensive to do by ground measurements, (Lillesand *et al*, 2008; Deka *et al*, 2011). However, it will be ideal to recognize that the interpretation of images from satellites is a way of spreading out a limited number of ground measurements to parts and or periods where ground observations could and will not cover, (Lillesand, 2002). Remote sensing has become an integral part of Earth resources data collection process and have been applied across different sectors and regions from Agriculture (e.g. Piccard, I. and Bydekerke, L., 2012), Environment (e.g. Battistion *et al* 2012.), Climate (e.g. Gayet *et al*, 2012; Wheeler *et al*, 2012), Maritime (e.g. Garmo and Radius, 2012; Tangen, 2012), Business (e.g. Born, 2012; Monks *et al*, 2012), Water (e.g. Hartmann, 2012), Atmosphere (e.g. Di Nicolantonio and Cacciari, 2012; Morelli and Flore, 2012). Remote sensing can offer a suitable approach to integrate limnological data taken from conventional measurements, (Duan *et al*, 2007). The launch of the Landsat Multispectral Spectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper (ETM +) as well as different sensors on SPOT, MODIS and MERIS satellites have provided comprehensive data of the globe. The TM, ETM+, MODIS (Terra) (Lillesand, 2002) and MERIS are some of the sensors that have been used in limnological studies.

Remote sensing offers synoptic view of large areas under study (Bresciani *et al*, 2011). The advancement in the satellite technology over the past two decades has provided new-generational satellite systems that can provide almost real time (Gitelson *et al*, 1993) information of the earth with high accuracy. Geostationary satellite systems can provide hourly information about weather patterns with high accuracy. Other near-earth high velocity satellite systems such as the Moderate Resolution Imaging Spectro-radiometer (MODIS) can provide both coarse and fine spatial resolution and high temporal resolution images of the earth surface. Numerous products can also be derived from MODIS images. The Landsat satellite system has also provided comprehensive data of the earth surface. The satellite was developed to provide data of the land surface and has since 1984, captured land surface processes at 16 day time interval. MERIS was specially designed to provide data of water surfaces and can be used to study the variable characteristics of the ocean as well as inland water bodies. Other satellites that are constantly covering and providing data of the earth surface include ASTER, SPOT, Ikonos, Indian Remote Sensing, (Lillesand *et al*, 2004). As such, continuous data of the earth surface are available, which can bridge the gap that exists in the conventional field data capturing process. Most remarkable about these systems is that the images and the derived products obtained from these platforms are made available and free of charge to the public. This has rendered remote sensing applications very cost effective. Also, the advancement in computer technology with the associated high storage and processing capabilities makes remote an efficient technique as data processing has become relatively simple. Thus remote sensing can deliver the extra capabilities needed in providing continuous data on lakes and other inland water bodies so that accurate interpretation of ecological changes that occurs in lakes can be monitored.

Satellite images over Lake Naivasha are widely available, but no extensive interpretation of these images to reflect on the ecological changes of the lake has been done. Most of the changes reported so far are based on ground truth observations and measurements which are relatively costly to undertake and often have discontinuities in their observation. As such, most interpretations reflect only on seasonal changes. Also, most of the models developed to estimate the lake water quality parameters so far are either empirical or semi-empirical algorithms, which are costly to use as ground truth data is mostly required. This has also made previous and future estimations of the changes in the lake a difficult task. In line with these set-backs, this work identified a simple regression relationship between *in situ* data and satellite image values over the lake. It used reflectance suspended matter values in Landsat7 ETM+ band 3 and matched it with the ground observations of suspended matter concentrations to find the coefficient of determination for the suspended matter content in the lake. The mathematical relationship was then applied to archive of Landsat imagery to develop maps of suspended matter concentrations of the lake at different times. The suspended matter values estimated from the produced maps were then compared and analysed to study the changes in the lake. Thorough discussions were done to explain some of the changes the lake has experienced.

2.0 Remote Sensing For Limnology

Over the past two decades the advancement in computer technology and the births of high resolution satellites has provided the grounds for an increase in the use of remote sensing and its applications, (Lillesand, 2002). The capability of using remote sensing to study lakes and reservoirs comes from the promise that the inherent optical properties of water column can be related to measured spectra (Dekker *et al*, 1997; Miller and McKee, 2004) in a sensor through mathematical equation(s), especially when there is a good correlation. Yacobi (1995) obtained a good coefficient of determination (R^2=0.92) of a linear regression between chlorophyll *a* from Landsat (band4/band3) and corresponding ground measurements. He suggested that the challenge in using remote sensing for studying water constituents lies in the difficulties in finding the relationship between the radiance from the surface of the water and the spectra within the water column due to difference in the distribution of constituents in the water. Lee (2001) studied the properties of the bottom and water column from Airborne Visible Infrared Imaging Spectrometer (AVIRIS). The characteristics of the bottom depth, bottom albedo, water absorption and backscattering coefficients observed, were used to estimate the concentrations of chlorophyll, coloured dissolved organic matter (CDOM) and suspended sediments from the shallow water Tampa Bay in Florida. However, the method used included complicated mathematical computations which were difficult to compute manually and thus relied on computer programming to develop the model. Giardino (2001) developed empirical algorithms for mapping chlorophyll *a* concentration and Secchi disk depth from reflectance in a TM image that has been atmospherically corrected. The algorithms gave (R^2 =0.99) for chlorophyll *a* and (R^2 =0.85) for Secchi disk depth suggesting that atmospherically correcting image radiance brings an improvement in the value of R^2 obtained. Liu (2003) used remote sensing to quantify the parameters of shallow lakes. The report stressed on the variability of water quality parameters and the limitations of using remote sensing to carry out such studies, but was however able to quantify parameters such as sediment particles, phytoplankton, CDOM and transparency. The paper reported that the mathematical relation between ground-truth data and their matching remotely sensed reflectance can either be linear or non-linear, depending on the site under study. Conclusion was drawn to the fact that it is of high significance to correct satellite images for the effect of the atmosphere and added that the concentration levels and the spatial variability of constituents influence the accuracy of using remote sensing for estimation. Brando and Dekker (2003) stated that an efficient way of retrieving the concentrations of water quality parameters through remote sensing techniques is by using a linear matrix inversion method (MIM) to relate the remote sensing data and the corresponding ground measurements. The report suggested that this method has the advantage of being applied to a whole region rather than a specific site as reported by Liu. Also, the MIM model is easy to solve and can easily be used in remote sensing applications where each pixel in an image requires a model to evaluate. Reflectance from a Hyperion hyperspectral remotely sensed imagery and *in situ* data was used to estimate estuarine and coastal water quality. However, such an empirical model is relatively difficult to develop and use, rather than a linear regression relation. Wu 2008 obtained (R^2 =0.83, n=25) when Landsat imagery was used to estimate the Secchi disk depth in Poyang Lake in China. Two image sources, Landsat TM and MODIS images were used to develop two multiple regression lines for estimating water quality parameters in the Poyang Lake. It was concluded that MODIS images give a good result for suspended matter estimation than Landsat. However, due to the relatively low spatial resolution of MODIS, difficulties arise when it is being used to study water bodies of smaller spatial extent. Brezonik (2005) also studied the concentrations of chlorophyll *a* and Coloured Dissolved Organic Matter (CDOM) using Landsat imagery. A simple regression line between ground measurements of 15 lakes in Minnesota and Landsat images over the lakes was developed and used to produce water quality maps of the lakes. The report reiterated that it is of less difficulty to predict water quality parameters using simple regression equations and added that band ratios are of advantage when atmospheric effects are significant. The paper also discussed the suitability of using Landsat TM bands for monitoring different water column properties. Under the Water Framework Directive for the European peri-alpine lakes project, Bresciani (2011) used over 200 MERIS images to produce water quality maps of the peri-alpine lakes and generated time series data that can be used for future chlorophyll *a* concentration determination. The report suggested that due to the frequency and the synoptic view of large areas provided by satellite images, studying water quality parameters by remote sensing techniques is very advantageous. The paper concluded that lentic ecosystems are highly affected by meteorological changes and anthropogenic activities which vitally affect the role these water bodies play in serving as a drinking water reservoir. Song (2012) reported that the ratios of Landsat 'band4/band 3 gives the highest correlation' for chlorophyll *a* concentration in the Shitoukoumen Reservoir. The study also confirmed that chlorophyll *a* is a parameter that can be used to characterize the trophic states of lakes. The results obtained also confirm earlier works that used regression analysis to establish relations between reflectance of different band combinations and ground truth data. The paper concluded that the births of new space-borne platforms with high resolutions will improve and reduce the limitations of using remote sensing in limnology.

3.0 Methodology

3.1 Study Area

Figure 1: Lake Naivasha. © ArcGIS base map Copyright 2013

The study area is Lake Naivasha (Figure 1) in Kenya, which is located at Latitude 0 ° 45'S and Longitude 36° 20' E, in the Eastern Rift Valley, (Hickley *et al*, 1994). This location is about 100 km from Nairobi, the capital of Kenya and in proximity to Naivasha and Nakuru towns. The surface area of the water in the lake fluctuates between 150-100 km² (Harper *et al*, 1990; Becht and Harper, 2002) with a catchment area of 3400 km² (Mireri, 2005). Lake Naivasha is a shallow freshwater body (Gaudet and Muthuri, 1981) with depth varying between 2m to 8m. The elevation of the lake is 1890 m above mean sea level (Harper *et al*, 2011) within an enclosed topography (Ballot *et al*, 2009) and without a surface outlet (Becht and Harper, 2002). The Malewa River, Gilgil River, Karati River, rainwater and underground seepage are the contributors of the water to the lake, (Harper *et al*; 1990, Hickley *et al*, 1994; Bemigisha, 2000) with Malewa River contributing the majority. The region around the lake is characterized by different plant and animal species and that has given the lake and its environment an ecological place of great significance. Water from the lake is also abstracted for the irrigations of flowers with annual abstraction rate estimated to be $60x10^6$ m³/year, (Becht and Harper, 2002). This means that water abstraction is on the rise. Water temperature is between 9°C to 25°C as minimum and maximum temperatures respectively. The lake and its vegetative region has also been a tourist site for about 100 years and have since attracted many studies as well. Though reports (e.g. Harper *et al*, 2011; the Council of Canadian, 2008) have suggested that the number of animal species in the ecosystem have declined; Hippopotamus and different types of birds are still part of the lake's ecosystem. The lake is characterized by four geological depressions which are believed to be the result of volcanic action. These depressions thus created the main lake, the Crescent Island Lake, Lake Sonachi and Lake Olodien (Figure 2). Due to the socio-economic importance of Lake Naivasha and the associated over usage of its resources, the lake is experiencing many ecological changes (Mireri, 2005).

Table 1: Coordinates of locations selected to monitor ecological changes in Lake Naivasha

POINT	LATITUDE	LONGITUDE
NEAR MALEWA RIVER	0° 43'' 15'	36° 20'' 01'
MID-LAKE	0° 46'' 05'	36° 20'' 58'
HIPPO POINT	0° 47'' 14'	36° 19'' 08'
CRESENT ISLAND	0° 46'' 05'	36° 24'' 42'
LAKE OLIODIEN	0° 48'' 48'	36° 16'' 39'

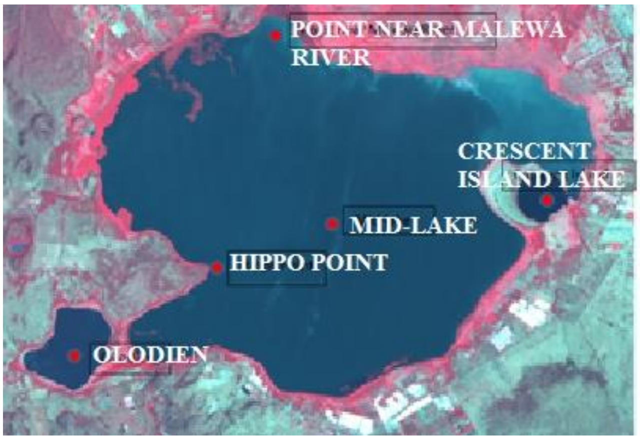

Figure 2: Locations in Lake Naivasha selected to monitor ecological changes © USGS Copyright 2013

3.2 Method adopted for Suspended Matter Estimation

On 28^{th} October, 2010 during a field survey, [1]Girma Adera Kebede recorded the suspended matter concentrations of many selected points in Lake Naivasha. Six (6) of these values were used as the *in situ* data for this study. To estimate the concentrations of suspended matter in Lake Naivasha from satellite imagery, same day satellite overpass of the lake was acquired and then pre-processed. All radiances were then converted into reflection. By matching the coordinates of the field values to the corresponding coordinates in the Landsat7 ETM+ band3 image, the suspended matter values were estimated from the image in Erdas Imagine. A regression analysis of these sets of values was performed in R Statistical Software to obtain the simple linear model (Figure 3).

[1]Girma Adera Kebede recorded the suspended matter values during a research field survey.

3.3 Landsat Imagery

To estimate the suspended matter values in the 30 years Landsat data using this model, Landsat images were downloaded from the USGS websites Glovis (http://glovis.usgs.gov/) and Earth Explorer (http://earthexplorer.usgs.gov/). As over 30 year span of data were needed, the Landsat archive, Landsat 4-present was selected. This archive contains images extending from 12th April 1984 to the present. The sensors include Landsat 4 and 5 of the Multi spectral scanner (MSS), Landsat 4 and 5 Thematic Mapper (TM), Landsat 7 ETM+ with scan-line detector, Landsat 7 ETM+ with the Scan Line Detector off (SLC-off) and Landsat 8 with the Operational Land Imager (OLI). All the images were selected from path 169, row 60, with 30m spatial resolution. Atmospheric adjustment of the image and further processing were carried out in Erdas Imagine. Atmospheric adjustment was done to remove atmospheric effects which can reduce the quality of the reflected signals. The Internal Average Relative Reflectance algorithm was applied. By this means an average scene spectrum is calculated and applied to the entire image. This approach is the best method as ground reference spectra from the lake were not available. All radiances were then converted into reflection. The regression line was then applied to the band3 layers of the 29 years Landsat imagery. This was done by utilizing Erdas Imagine Model Maker so as to estimate the concentrations of suspended matter for the various years. Maps of the different concentrations were also produced in ArcGIS 10.0. Suspended matter concentrations at five different locations in Lake Naivasha were also estimated.

4.0 Results

The result of the regression analysis shows a good correlation between the measured and the estimated suspended matter values, Figure 3.

$$\mathbf{R^2 = 0.94,\ n = 6}$$
$$\boldsymbol{y = 1.175X - 0.0635}$$

A root mean square error of 2.278 mg/l was obtained. A chart of suspended matter concentration against dates was produced for the ecological analysis. The table (appendix) and chart (Figure 4) shows the suspended matter values obtained at the five different locations in the lake. The chart shows that the five different points selected have different concentrations of suspended matter throughout the years. However, it can be seen that the mid-lake and the Hippo-point have closer values at some points in time. There are three major peaks around 23rd October, 1999, 13th June, 2004, and 28th September, 2010 respectively. In the first two peaks, the point near the Malewa River had the highest concentrations whiles the Hippo point and the mid-lake had the highest concentrations in the third peak. Concentrations measured on 23rd October, 1999 at the five points are very close compared to the peaks at other dates. There are three major troughs which occurred on 21st January, 1995, 4th February, 2003 and 8th June, 2009. The Crescent Island had the lowest concentration value of 11 mg/l. The point near the Malewa River also had the maximum concentration of 53 mg/l in 2004. It can also be seen from the chart that the suspended matter concentration in the lake has almost doubled from 1984 to 2013.

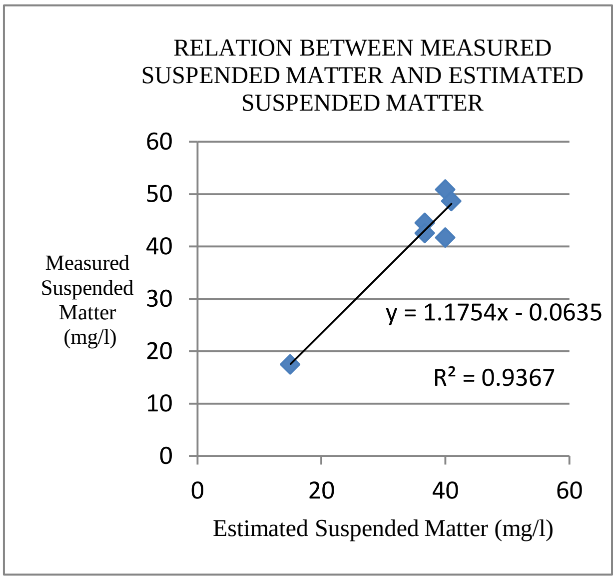

Figure 3: Relation between Measured and Estimated Suspended Matter

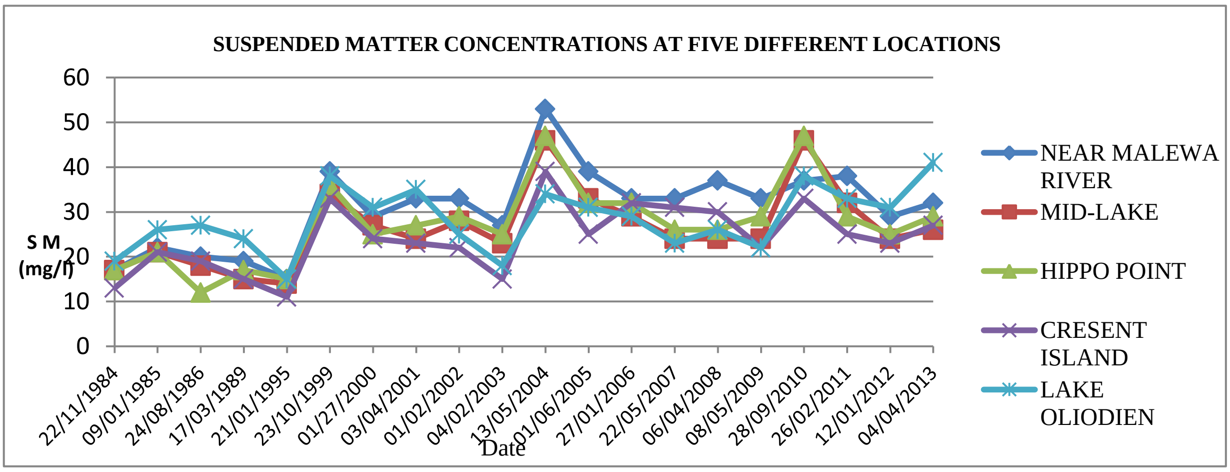

Figure 4: Suspended Matter Concentrations in Lake Naivasha

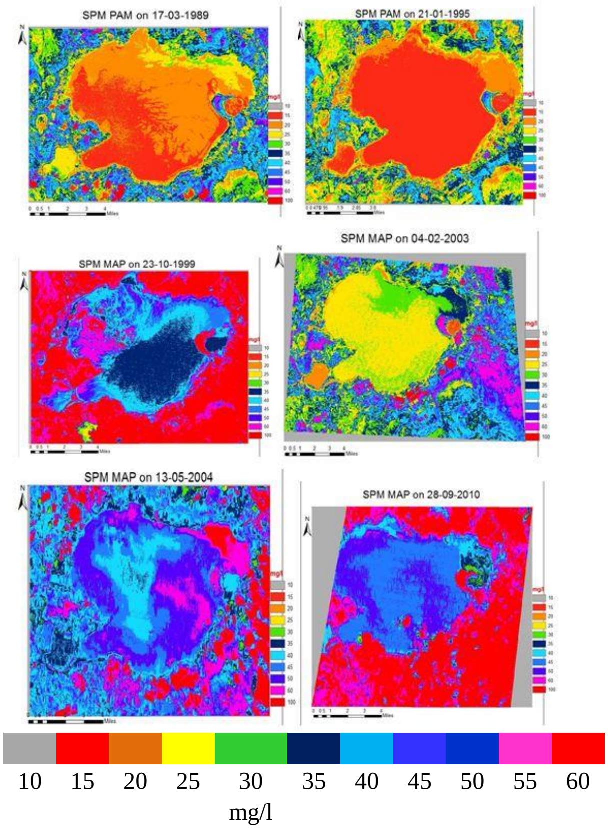

Figure 5: Suspended Matter maps of Lake Naivasha

5.0 Discussion

The root mean square error of 2.278 mg/l shows a good correlation between the measured suspended matter values and the estimated image (28th October, 2010) values. The results obtained show that Landsat has the ability to measure suspended matter contents of water bodies. The band 3 gives good reflectance of suspended matter and can thus be used to study suspended matter in lakes. There is a direct proportional relation between band 3 reflectance and suspended matter concentrations in lakes.

From the satellite images (appendix), areas where the water is clear or the brightness levels are high, are usually areas of shallow depth. Such places show relatively high amount of suspended matter than the dark places where the water is deep. Visual inspection of satellite imagery indicates that Lake Oliodien is relatively shallow. As such particles near the bottom of the water are easily distributed in the lake by any disturbance such as the little wave action. The bottom albedos are easily detected by sensors which thus show the high concentrations of suspended matter in the lake. As this is true, the Crescent Island and the Hippo point which are relatively deeper show the least amount of suspended matter. As stated in the literature, the Crescent Island has the highest depth of 18m (Harper *et al*, 1990); this therefore explains the reason why the Crescent Island had the minimum suspended matter concentrations for the 29 years period of observation. The high abstraction of water from the lake by flower farmers has caused reduction in the water level. As low water levels usually show high suspended matter concentrations, deductions are that the ecological changes the lake is experiencing is attributed to the effect of water abstraction (as also stated in Harper *et al*, 2011).

The peaks of suspended matter concentrations on 23rd October, 1999, 13th June, 2004, and 28th September, 2010 is however the result of high influx of sediments from the Malewa River. This is usually due to rainfalls that cause surface run-offs from the catchment into the lake. Moreover, the suspended matter concentrations at different part of the lake are close which suggest that the suspended matter measured is not a result of the bottom albedo but the presence of particle from the catchment that is near evenly distributed throughout the lake. High suspended matter concentration with high water level can be attributed to the increase in phytoplankton production in the lake. From the literature, the use of agro-chemical in farming activities around the lake is on the rise (Mireri, 2005). Thus rains transported agro-chemicals (such as phosphorus and nitrogen) through surface run-offs into the lake. This caused bloom of algae in the lake. This process therefore caused the rise of suspended matter in the lake. From literature, El Nino rains have caused variable effect on the land-cover in Kenya. The high influx of suspended matter in the lake can be attributed to the El Nino rains depositing chemical compounds (Gitahi, 2002) into the lake. This resulted in the bloom of algae in the lake and hence increased suspended matter concentration in the lake. However, this phenomenon changes when the water levels goes down due to water abstraction or other natural means such as the dry seasons. It can therefore be deduced from this that meteorological changes is also one of the main causes of ecological changes in Lake Naivasha, as the latter been been determined to be the major cause of ecological changes in freshwaters in the region, (O'Reilly *et al*, 2003; Muhoza *et al*, 2006; Verburg *et al*, 2006; Assefa, 2010).

6.0 Conclusion

Lake management has become a very paramount issue in recent times due to the deteriorating state of these water bodies. In order to bridge the gap that exists in using conventional data collection methods in explaining ecological changes, comprehensive and continuous data embracing such gaps is needed. Remote sensing offers good synoptic view of large surfaces and can be efficient in studying the characteristics of inland waters. This work identified a simple regression relationship between reflectance in Landsat7 ETM+ satellite image and *in situ* data of suspended matter in Lake Naivasha. A good correlation was obtained. The model was then used to estimate the suspended matter concentrations in 29 years archive of Landsat satellite imagery. Interpretation of maps and charts derived from the suspended matter concentrations showed that the ecological changes Lake Naivasha is experiencing are due to over abstraction of the water in the lake and climate changes the lake experiences in the event of time.

Acknowledgement

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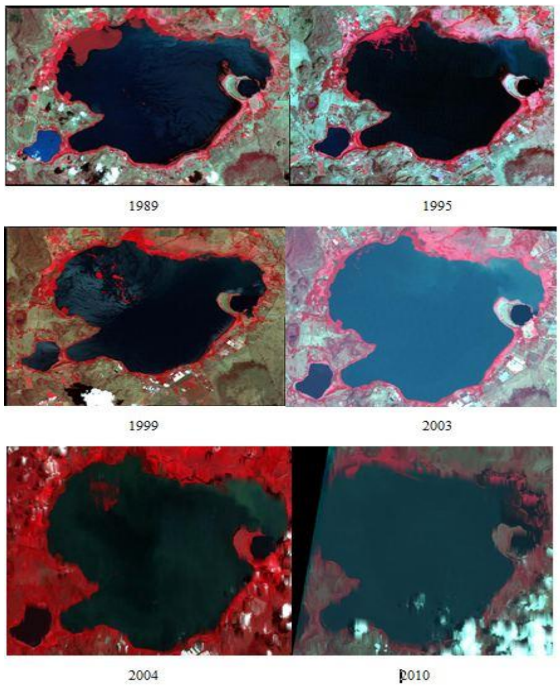
Appendix



Landsat Imagery of Lake Naivasha. © USGS Copyright 2013

Suspended Matter Concentrations at five different locations in Lake Naivasha

DATE	HIPPO POINT (mg/l)	CRESENT ISLAND (mg/l)	LAKE OLIODIEN (mg/l)
22/11/1984	17	13	19
09/01/1985	21	21	26
24/08/1986	12	19	27
17/03/1989	17	15	24
21/01/1995	15	11	15
23/10/1999	36	33	38
01/27/2000	25	24	31
03/04/2001	27	23	35
01/02/2002	29	22	25
04/02/2003	25	15	18
13/05/2004	47	39	34
01/06/2005	32	25	31
27/01/2006	32	32	29
22/05/2007	26	31	23
06/04/2008	26	30	26
08/05/2009	29	22	22
28/09/2010	47	33	38
26/02/2011	29	25	33
12/01/2012	17	14	20
04/04/2013	28	27	41

DATE	NEAR MALEWA RIVER (mg/l)	MID-LAKE (mg/l)
22/11/1984	17	17
09/01/1985	22	21
24/08/1986	20	18
17/03/1989	19	15
21/01/1995	15	14
23/10/1999	39	34
01/27/2000	29	27
03/04/2001	33	24
01/02/2002	33	28
04/02/2003	27	23
13/05/2004	53	46
01/06/2005	39	33
27/01/2006	33	29
22/05/2007	33	24
06/04/2008	37	24
08/05/2009	33	24
28/09/2010	37	46
26/02/2011	38	32
12/01/2012	18	18
04/04/2013	32	29