Quantifying water storage within the endorheic Lake Naivasha using low-cost sonar remote sensing and Landsat satellite data

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Highlights

- Low cost remote sensing can be used to quantify lake level and volume.
- Sedimentation within Lake Navaisha is annually displacing >40192 m³ of water.
- Current water abstraction management ignores sedimentation and needs updating.
- Lake health is likely decreasing due to water loss.

Abstract

Study region: Endorheic terminal lakes can be vital water resources for sustaining large populations. However, their land-locked nature can lead to over exploitation and long-term sediment accumulation, reducing water quality and storage. Lake Naivasha supports a rapidly expanding population and agriculture industry. Therefore maintaining good water quality and storage within this endorheic lake is crucial for the Kenyan economy and population. The lake has a long history of level fluctuations and the region is considered to be suffering from chronic water shortage, even though lake levels are monitored and maintained.

Study focus: This study quantifies the sediment deposition rate and its impact on Lake Naivasha's water levels and volume, using inexpensive remote sensing techniques that could be easily replicated for future monitoring.

New insight: Evidence of sedimentation in the northern area averaging 23 mm yr^{-1} was identified, which is likely annually displacing 40192 to 576086 m^3 of water (40192000 to 57608600 litres). The volume displaced each year is equivalent to the water required to sustain 40 to 1152 people. These results imply that current abstraction management based purely on lake level, are detrimental to the long-term health and survival of the lake. The results suggest imply that lake health is likely decreasing. We recommend that future monitoring of this water resource and other endorheic lakes should focus on volume using the inexpensive remote sensing methods described in this paper.

1.0 Introduction

Some of the largest inland water systems are endorheic with no terminus into the oceans (Rast and Calcagno, 2001). Found between the desert margins north and south of the equator, endorheic basins are important sinks of carbon but can suffer from low water quality with many being saline and few are truly freshwater (Li *et al.* 2017; Rast and Calcagno, 2001). Despite this, endorheic basins are vital to those who live and work around their watershed highlighting the need for robust monitoring of their volume and health. The Aral Sea exemplifies what can happen when the health of an endorheic terminal lake declines (AghaKouchak *et al.* 2015). Whilst the feeder rivers once kept the Aral Sea at a level and quality suitable for supporting thriving and economically important industries, upstream land use and water extraction has reduced the inflows and now the Aral Sea is in rapid decline (Micklin, 2010; Rast and Calcagno, 2001). The surface area and volume of the Aral Sea have decreased by 88% and 92% respectively since 1960 causing the lake to significantly increase in salinity (Micklin, 2010) resulting in a displaced population as it can no longer provide safe drinking water (Lioubimtseva, 2015).

Lake Naivasha, a freshwater lake in Kenya, sits at the bottom of a shallow endorheic basin with no surface outflows and is fed by the Rivers Malewa and Gilgil from the Aberdare mountain range to the North (Otiang'a-Owiti and Oswe, 2010). Of all the Rift Valley lakes, Naivasha sits at the highest elevation at 1890 metres above sea level (masl) (Becht *et al.,* 2006b). All of the open bodies of water in the Rift Valley region are greatly affected by a high evaporation rate and low rainfall (Nyingi *et al.,* 2013). The Naivasha catchment is particularly prone to alternating periods of extended drought and above average rainfall causing lake inter-annual levels to fluctuate by more than 10 m (Figure 4 in Kuhn *et al.,* 2016) over a lake that has an average depth of ~6 m. Becht *et al.* (2006a) have shown that there are subterranean flows in the Kenyan Rift Valley, predominantly dispersing from Lake Naivasha and acting as a freshening mechanism for the Rift Valley system at lower altitudes, including the region's groundwater resource. Lake levels across the region are also considered in part to fluctuate due to changes in these groundwater levels. Hence, the water resource held within the lake is also important for groundwater levels in the wider region.

Like other large endorheic lakes Naivasha supports local industries and is a source of drinking water for the local population (Rast and Calcagno, 2001). In the Kenyan Rift Valley it is one of two freshwater lakes (the second being Baringo) and supports over 60 floriculture and vegetable farms, artisanal fisheries, geothermal industries and an expanding local population (Becht *et al.,* 2006b). Its existence forms a key component of the Kenyan economy, with the flower farming industry alone estimated to be worth ~£472 million to the Kenyan economy in 2015 (Kenya Flower Council, 2016). The town of Naivasha has, as a consequence, has more than doubled from 160,000 people in 1999 to >355,000 by 2019 (Onywere *et al.,* 2012; KNBS, 2019), with workers bringing families from the rural communities to work at the large farms, or the tertiary and quaternary industries that are a by-product of a growing industrial town; all of which has increased the pressure on local water resources. The 2013 water volume within the Lake Naivasha basin were considered to be able to provide 647 m^3 per capita per year (Kyambia and Mutua, 2015), which falls within the definition of 'chronic water scarcity', defined as between 500 to 1000 m^3 (500,000 to 1,000,000 litres) per capita per year, (Falkenmark and Widstrand, 1992). The Naivasha basin is therefore both vital for, and increasingly at risk of over exploitation from, those that live and work around the lake and within the upper catchment (Onywere *et al.,* 2012). The large regulated commercial farms and industry are found in the lower catchment, whereas upstream in the middle and upper catchments there is unregulated subsistence-based land use including logging, agriculture and charcoal production (Nyingi *et al.,* 2013). While historically lake levels have always fluctuated (Becht and Harper, 2002), the demands on the lake as a stable source of fresh water continue to increase.

Since drying out completely in 1946 (at a level of 1882.0 masl), lake levels have fluctuated with notable high periods after heavy rains in 1997 (1888.9 masl) linked to a large El Niño event (Becht and Harper, 2002). Natural variability of precipitation is a major driver of lake level change in the short term with high rainfall closely followed by an increase in average lake level. However, it is thought that anthropogenic activity and abstraction are likely responsible for reducing lake levels (Becht and Harper, 2002; van Oel *et al.,* 2013; Kuhn *et al.,* 2016). Current management guidelines and community plans aim to control water levels through licensing extraction, setting water quotas and discouraging wastage. Signs on towers surrounding the lake display the current water level and what the level means in terms of the Water Allocation Plan (WAP) and accompanying extraction regulations as defined by the Lake Naivasha Water Resource Users' Association (LaNaWRUA, 2016b). A traffic light system displayed on these towers indicates whether or not users can continue extraction to the level of their licence. However, it is only within the last 5-8 years that attempts have been made to enforce these licences and quotas. Between 2007 and 2009 there was a ~3 metre drop in lake level, which prompted international concern. Many Non-Governmental Organisations (NGOs) have attempted to identify the reasons for this low level towards proposing new regulations and controls on water extraction. For example, one report found that 97% of water users were either unlicensed or their licenses had expired (Harper *et al.,* 2013). The low level in 2009 has created increased interest in lake research at Naivasha exploring the practices of water extraction and problems of land use change within the catchment, with the aim of identifying new management practices (van Oel et al*.,* 2013; Kuhn *et al.,* 2016). The low level also highlights the fragility of this and other endorheic basins and systems.

The two main rivers replenishing Lake Naivasha transport sediment down from the upper catchment. The lack of a significant natural outflow infers that the sediment brought into the lake must accumulate there and this sediment accumulation is a feature of endorheic systems. Bathymetric surveys of the lake by Åse (1987) and Yihdego and Becht (2013) observed that the pan-like basin with its wide expanses of low-gradient topography is in distinct contrast to the highly fractured volcanic outcrops, mountains and escarpments that surround it. This suggests that sediment does indeed flow into the lake, levelling the rough topography of the lakebed.

Based on this understanding, there appears to be a significant oversight in the current lake monitoring and management plans, as measurements of lake level as an indicator of total water volume are unable to account for a changing, and potentially rising, lakebed. Nor do the current management plans consider the health of the upper catchment that dictates the replenishment rate and sediment flow into the lake. In addition, a shallower lake with an expanding surface area is more susceptible to evaporative losses, and a decreasing volume is likely prone to contain a higher concentration of pollutants.

It is clear that sedimentation is likely occurring in Lake Naivasha and this could be the reason for the somewhat paradoxical increase in lake level whilst demand and abstraction have increased despite no significant net increase in precipitation. The example of the Aral Sea suggests that the health of any endorheic lake is highly sensitive to deposition. Here we identify and quantify a decline of water volume in Lake Naivasha by identifying areas of significant fluctuation in lake boundary and then measuring depth in these locations to identify the effect of sedimentation. This allows the efficacy of the current lake management plan to be assessed.

2.0 Methods

2.1 Lake Naivasha and the focus of the bathymetric survey

Within the Rift Valley, volcanic and tectonic activity has created large sedimentary basins that have been subdivided into closed local basins by volcanic damming (Becht et al., 2006a). Drainage from the rift flanks runs into these basins, creating a chain of lakes with no surface outflows (Nyingi et al., 2013). Lake Naivasha sits at the highest elevation and has a contemporary average area of 154 km². The basin receives an average annual rainfall of 610 mm yr^{-1} (Kyambia and Mutua, 2015) and the lake supports an expanding population and industry (figure 1).

The bathymetric study focussed on a 13.2 km² portion of the northern part of Lake Naivasha, commonly known as North Lake (figure 1). This area is to the south of the former North Lake swamp described by Gaudet (1977) and was chosen after carrying out a low-resolution bathymetric survey of the lake to identify deposition features. The bathymetry in the North Lake illustrated features normally associated with sediment deposition from river inputs. This area is fed directly by the Malewa and Gilgil rivers that flow into the lake. Maximum river discharge into the lake normally occurs between September-October (Becht *et al.,* 2006b). The northern bounds of the survey area were defined by a combination of the shoreline and the abundance of *Salvinia molesta, Eichhornia crassipes* and *Cyperus papyrus*. This floating vegetation is a well known obstacle to studies on the lake (Rupasingha, 2002).

2.2 Lake level

Lake level was measured using an *in situ* Solinst calibrated digital level logger. These measurements were then used to calibrate and characterise an extensive secondary dataset of lake levels provided by LaNaWRUA (2016a). Verifying the quality of the secondary LaNaWRUA dataset enabled a longer time series of lake levels to be studied and provided an estimate of its accuracy for the uncertainty analysis. Hourly lake levels were measured between January to June 2016 using the Solinst level logger Edge [Model 3001-M5] which records absolute pressure (water pressure plus atmospheric pressure to an accuracy of ±0.05 % across the full sensor range). This is used in conjunction with the Barologger Edge (accuracy of ± 0.05 kPa) for measuring fluctuations in atmospheric pressure enabling barometric compensation. All instruments were calibrated by the manufacturer and collectively they enable water level measurements with an accuracy of ± 0.003 m. The LaNaWRUA dataset provides monthly lake levels for the period 01 July 1880 to 30 June 2016. Daily LaNaWRUA level data were also available for 01 July 2003 to 30 June 2016 (LaNaWRUA, 2016a).

2.3 Lake Area

Freely available Landsat 8 satellite imagery were acquired from Astro Digital for the period 10 May 2013 to 19 March 2016 (Astro Digital, 2016). These 30 m spatial resolution data were used to create false colour images using the three spectral bands, 5, 7, and 2 which have the following spectral bandwidths 5, 0.85 - 0.88 μm; 7, 2.11 - 2.29 μm and 2, 0.45 - 0.51 μm. This enabled the water, land and vegetation to be spectrally and visually identified. From these false colour images it is possible to identify the lake boundary and therefore manually create polygons of the lake extent and area. Polygons were created using QGIS version 2.14 (Codename Essen) The spatial resolution of these data is 30 m at nadir, therefore an epsilon (ε) band or strip (of width $\varepsilon = 60$ m centred on the identified boundary) was identified along the lake periphery (Blakemore, 1984). This strip width represents the positional uncertainty (due to the image resolution) between the labelled and the true boundary between the lake and land.

2.4 Bathymetric Surveys

The bathymetric survey was carried out during January and February 2016 to create a topographical map of the current lakebed. This was achieved using a consumer grade sonar system, the Deeper Fishfinder sonar (DP0H10S10) attached to a small boat that was piloted at a low speed between 3 and 5 ms^{-1} around the survey area (range in speed was depended upon wind chop and conditions). The Deeper Fishfinder sonar is a portable device with an internal battery that connects via Bluetooth to a smartphone running the Deeper Fishfinder application (an Apple iPhone 6S, running iOS 9.2.1 was used). The survey route (sampling grid) was determined using the open source QGIS software package with the aim of creating an approximate grid of the study area. These routes were then exported to a handheld global positioning system (GPS, Garmin eTrex10) to provide a navigation route whilst on the water. The Deeper Fishfinder device was clamped to the side of the boat. The sonar system was continually monitored alongside the depth readout as the device ceases to collect data when it recognises that it is not sitting at the surface of the water. If this occurred the boat was slowed and if required the section was repeated. Expanses of hydrophytic species; *S. molesta, E. crassipes* and *C. papyrus* (Onywere *et al.,* 2012) proved to be problematic and dictated regions where the boat was unable to progress, and this resulted in a modified sampling grid to the regular grid programmed into the handheld GPS (figure 2). The manufacturer stated accuracy of the Deeper Fishfinder sonar depth measurements is ±0.5 m. The accuracy of the sonar was tested in a fresh water estuary in the UK (Fal, Cornwall) to measure water depths of between 1.3 to 1.4 m. The Mean Absolute Difference (MAD) between a manually measured depth and that measured by the sonar was ±0.018 m (n=300, bias 0.0 m), so the sonar accuracy, when used at these depths, is better than the stated manufacturer accuracy.

2.5 Deposition rates

The sonar data collected for this study in 2016 were compared with equivalent data from the survey conducted in the 2001 (Rupasingah, 2002). The 2001 survey employed a similar method and sensor as it used a Garmin Fishfinder 100 sonar to map the lakebed. Both devices operate using a wide beam (Deeper – 90kHz, Garmin – 50kHz) and narrow beam frequencies (Deeper – 290kHz, Garmin – 200kHz). The data collected by Rupasingha (2002) were obtained from *Naivasha Research* (2010). Both sets of sonar bathymetric data were interpolated using the Triangular Irregular Network (TIN) method to create comparative 5 × 5 m grid-based depth charts for the North Lake study site, with each 5 × 5 m grid square (A) being assigned a depth point value, (total number of 2647690 data points) using QGIS version 2.14 (Codename Essen). Depth values (d) were subtracted from the average lake level (l) at the time of data collection to create comparable topographical maps of lakebed level (b) (in masl) i.e. $l - d = b$. Combined measurement uncertainties for each single lakebed level value were estimated based on the calculated accuracy of the sonar instrument and the calculated accuracy of the LaNaWRUA lake level data and standard error propagation methods (Taylor, 1997). The uncertainties in both datasets (the data from this study and the data from Rupasingha, 2002) and both topographical maps were assumed to be the same as 2001 survey were collected using similar instrumentation and methods (but lacked some uncertainty information). The topographical maps of lakebed levels were subtracted from each other (2001 - 2016) so that each point gives an indication of vertical change. A positive difference indicates sediment accumulation and a negative difference indicates erosion. An estimate of the volume of water (v) displaced across the North Lake study site due to a change in the lakebed topography can then be calculated using:

$$v = \sum_{i=0}^{N=2647690} (b_{2001} - b_{2016}) A_i \tag{1}$$

where subscript 2001 and 2016 refer to the year of bed level data, *b*, and A is the grid square of surface area equal to 5 × 5 m.

3.0 Results

3.1 Verification of long-term lake level data

The accuracy of secondary LaNaWRUA water level data was evaluated using the *in situ* level logger data. During the period January to June 2016, the level logger recorded a variation in water of up to 0.46 m (figure 3). The pattern of variation shown in figure 3 coincides with decreasing rainfall in the catchment from February to May. Both datasets recorded comparable changes in levels during this period with the level logger giving 0.46 m and the LaNaWRUA dataset giving 0.52 m. The LaNaWRUA data were calibrated to give lake level change in metres by subtracting the bias between the LaNaWRUA dataset and the level logger data. Following this calibration a linear regression shows that the two datasets were in good agreement ($p < 0.001$, $r^2 = 0.900$, n = 160)**.** Using the level logger data as the reference, the LaNaWRUA data have a MAD of 0.018 m, standard error of 0.014 m, and bias of 0.0 m (n=160).

3.2 Lake area

The epsilon band of 60 m in lake boundary results in an area uncertainty of ±1.5%. The variations in lake surface area appear driven by the lake water level data for the period of May 2013 to March 2016 (linear regression result, $p < 0.001$, $r^2 = 0.95$, n = 33). Linear regression of the data shown in figure 4 identifies an average decline in lake area of 3.3 km^2 per year ($y= -3.255x + 158.8$, $R^2=0.4$, $p < 0.001$, n=33) with upper and lower lake areas of 160.10 km^2 and 146.28 km^2. The notable increase in lake area in 2015 coincides with a large global El Niño event (Jet Propulsion Laboratory, 2015). When the calculated polygon lake areas for 2013 – 2016 were visually compared, the north area of the lake was seen to exhibit the largest areal variation (figure 5). This higher variation in area suggests a shallower and more gradually sloping lakebed. This area of shallow lakebed is within the region studied in the bathymetric survey.

3.3 Bathymetric surveys and deposition rates

Subtracting the results from the two lake bed surveys (Rupasingha survey in 2001 and our 2016 survey) identified potential regions of sediment deposition in the North Lake (figure 6). Figure 6 shows sediment deposition in the north east of the study site where the Malewa river flows into the lake. The bathymetric survey data (figure 6) collected in the North Lake area show alluvial fan features at the mouth of the Malewa River. Comparison of the average lakebed level data derived from Rupasingha (2002) and the data collected for this study showed a net positive change (increase) of lakebed height in the north lake over the past 15 years of 0.35 m. This equates to an average sediment deposition rate of 23 mm yr^{-1} across the study site and gives a volume change, v, (water displacement) of between 40192 – 576086 m^3 yr^{-1}. Assuming that the uncertainties in the lakebed level (l) and sonar depth (d) are uncorrelated, that the uncertainties in both sonar surveys are comparable and the MAD provides the accuracy of each dataset (as the bathymetric and level variations are gradual and linear) gives a combined uncertainty for each data point in our lake bed level data of 0.025 m, or 25 mm (resulting from the uncertainties summed in quadrature, $\sqrt{}0.018^2 + 0.018^2$). The uncorrelated nature of these single point measurement uncertainties, and the lack of any detectable measurement bias, suggests that the measurement uncertainty will have a negligible impact on the reconstructed lakebed data (ie based on the central limit theorem the combined result of these uncertainties will approach zero).

4.0 Discussion

4.1 Implications of sedimentation on loss of water resource

By comparing topographic maps of the lakebed we find there is a clear positive change in lakebed level between 2001 and 2016, which we suggest is caused by sediment deposition from the inflow rivers. The degradation of the papyrus swamps that once covered part of this area (Gaudet, 1977; Morrison and Harper, 2009) may be an additional cause and could be verified by analysing sediment cores. Sediment cores were collected during this study to determine the structure of the lakebed, but the samples were unable to leave the country for analysis due to export conditions. However, the 2001 sonar study (Rupasingha, 2002) was conducted after the deterioration of the swamp, supporting the conclusion that riverine sediment deposition is the main driver of bathymetric change in the North Lake. Our estimate of sedimentation occurring at 23 mm yr^{-1} is consistent with previous studies that used coring as their primary methodology recording rates between 10 and 30 mm yr^{-1} within different areas of the lake (Verschuren, 1996; Tarras-Wahlberg *et al.,* 2002; Maina *et al* 2018). This shows that in the future using a low-cost fish sonar which can be mounted on many different types and sizes of water craft may be a cost effective and efficient method for monitoring lakebed change across endorheic lakes. Our north lake displacement estimates of 40192 – 576086 m^3 yr^{-1} of water are equivalent to the loss of water required to sustain 40 to 1152 people per year. These upper and lower ranges are determined based on lower and upper limits of chronic water scarcity of 500 m^3 per person per year and 1000 m^3 per person per year respectively (Falkenmark and Widstrand, 1992; UN-Water, 2006).

4.2 Drivers of catchment degradation within endorheic systems

In 2009 lake Naivasha shrunk significantly, dry beds encroached deep into the North Lake study site and from our results we can infer an average depth across this site would have been less than 0.5 m. All industry that relied on the lake was affected, including the artisanal fisheries who struggled to access the lake and its remaining fish stocks (Harper *et al*., 2011). This is reminiscent of the problems faced by the Aral Sea: as the lake began to shrink, the water quality dropped and the fishing industries and other industry that relied on the lake collapsed (Micklin, 2010). Replenishment from a healthy upper catchment should be slow and gradual. The sudden change in lake levels over a relatively short period suggests that the Aberdares 'water tower' feeding lake Naivasha is less than healthy. If lakebed deposition continues and the volume held remains constant then the surface lake level will increase, despite no actual increase in water volume. Under current management approaches water extraction would likely continue, or could even be allowed to increase. A stable volume of water spread over a shallower wider area will increase evaporation and thus water loss, causing an increase in the concentration of pollutants and reducing the health of the lake. These characteristics are consistent with the significant increases in the levels of nitrogen and phosphorous that have already been recorded in the lake (Otiang'a-Owiti and Oswe, 2010), which is thought to have helped the further expansion of the invasive *E. crassipes* (Onywere *et al.,* 2012).

As with all endorheic basins, any change in land use in the catchment will have an effect downstream in the terminal lake. In Central Asia the anthropogenic redirection of the Syr Darya and Amu Darya rivers for irrigation has caused the Aral Sea level to fall far quicker than any previous natural fluctuations (Micklin, 2010; Rast and Calcagno 2001). In the upper and middle catchment of the Naivasha basin land use ranges from protected forest, moor and bamboo zones to subsistence farming, illegal deforestation practices and legal quarrying (Nyingi *et al.,* 2013). The latter anthropogenic uses reduce water retention in the catchment, increase erosion and therefore increase the amount of sediment carried in suspension down to Lake Naivasha. Throughout Kenya, subsistence communities find it increasingly necessary to encroach onto protected land for herding and arable farming (Campbell *et al.,* 2000) and this conversion from forest and grassland to arable land results in decreased infiltration, decreased evapotranspiration, and increased surface runoff. Reversing land use change through restorative measures can provide a simple and positive response to create healthier streams and catchments (Lake *et al.,* 2017). Illegal logging occurs extensively on the western and particularly southern slopes of the Aberdares and Eburru forests for timber and charcoal. For example, the conservation trust Rhino Ark counted over 10,000 charcoal kilns in the same region as the source of the Malewa River (Nyingi *et al.,* 2013).

In an attempt to reduce the sediment and agrochemical loads entering the lake, the Lake Naivasha Riparian Association (LNRA) has in the past attempted to work with inhabitants of the upper catchment to promote good management practices. However, whilst beneficial, a lack of funding and support from the relevant government authorities limits the ability to make a significant impact (Becht *et al.,* 2006b). The curbing of the encroachment of legitimate quarrying activities on the north and eastern slopes of the Aberdares is an example of successful management at a time when these quarries are under pressure to produce material for expanding towns (Nyingi *et al.,* 2013).

4.3 Future monitoring of endorheic lakes by satellite and sonar remote sensing

The relatively simple approach used within this study of utilizing open source data and software has clear potential for the future monitoring of Lake Naivasha. The deployment of multiple Sentinel 2 satellites (that collect data of comparable spectral and spatial resolution to the Landsat series) by the European Space Agency (ESA) and European Union within the Copernicus programme (ESA, 2016), provides the potential to observe the area of lake

Naivasha every 3-9 days. The expected lifetime of the Copernicus programme (15+ years) will enable long-term monitoring. Therefore, we suggest that future lake Naivasha management and water extraction plans and monitoring, and those of other endorheic lakes, should consider the use of such satellite data.

The low-cost and simplicity of the Fishfinder sonar system would allow annual surveys of the lakebed to be undertaken so that sediment deposition can be monitored. This combined with lake level monitoring would allow the volume of the lake to be easily monitored and identify the impact of changes in management of the upper catchment (i.e. identify any evidence of reduced sedimentation). Similarly, the same methods could be used to monitor other endorheic lakes, as these lakes typically support artisanal fishing boats and such boats provide ideal platforms for mounting the small sonar.

4.4 Implications for catchment and endorheic lake management

Our findings imply that lake management plans should not focus purely on maintaining lake levels and on controlling industry water extraction. Instead, improved regulation and upstream land management practices are likely to be needed alongside improved monitoring of the water volume and regulation of its extraction. For Naivasha we have shown that sedimentation is likely reducing lake volume and hence could also be concentrating pollutants within the water, despite the water level being maintained.

5.0 Conclusion

This study aimed to explore the sediment, water level and volume dynamics of the endorheic Lake Naivasha basin. Using a combination of *in situ* and historical hydrological measurements and remote sensing approaches, we have quantified the change in the topography of the North Lake (of Lake Naivasha) that has occurred over the last 15 years, and what this means for the water volume that the lake holds. We identified that the bathymetric features and the north location that shows an increase in lakebed height is consistent with the accumulation of sediment from the Aberdares catchment that feeds the lake. Current management plans should be improved to account for sediment deposition and some estimation of the variation in the lake volume. This would enable water extraction limits to be set based on the volume of water held in the lake. The issue of sedimentation is not unique to lake Naivasha and will be occurring in other endorheic lakes. The combination of satellite and sonar remote sensing can be used to enable the lake level and volume to be monitored and the same low-cost approaches could be used to monitor other endorheic basins. Such monitoring is likely to be vital to ensure the long-term existence of endorheic lakes as freshwater resources and the populations and industries that they support.

6.0 References

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Figure 1

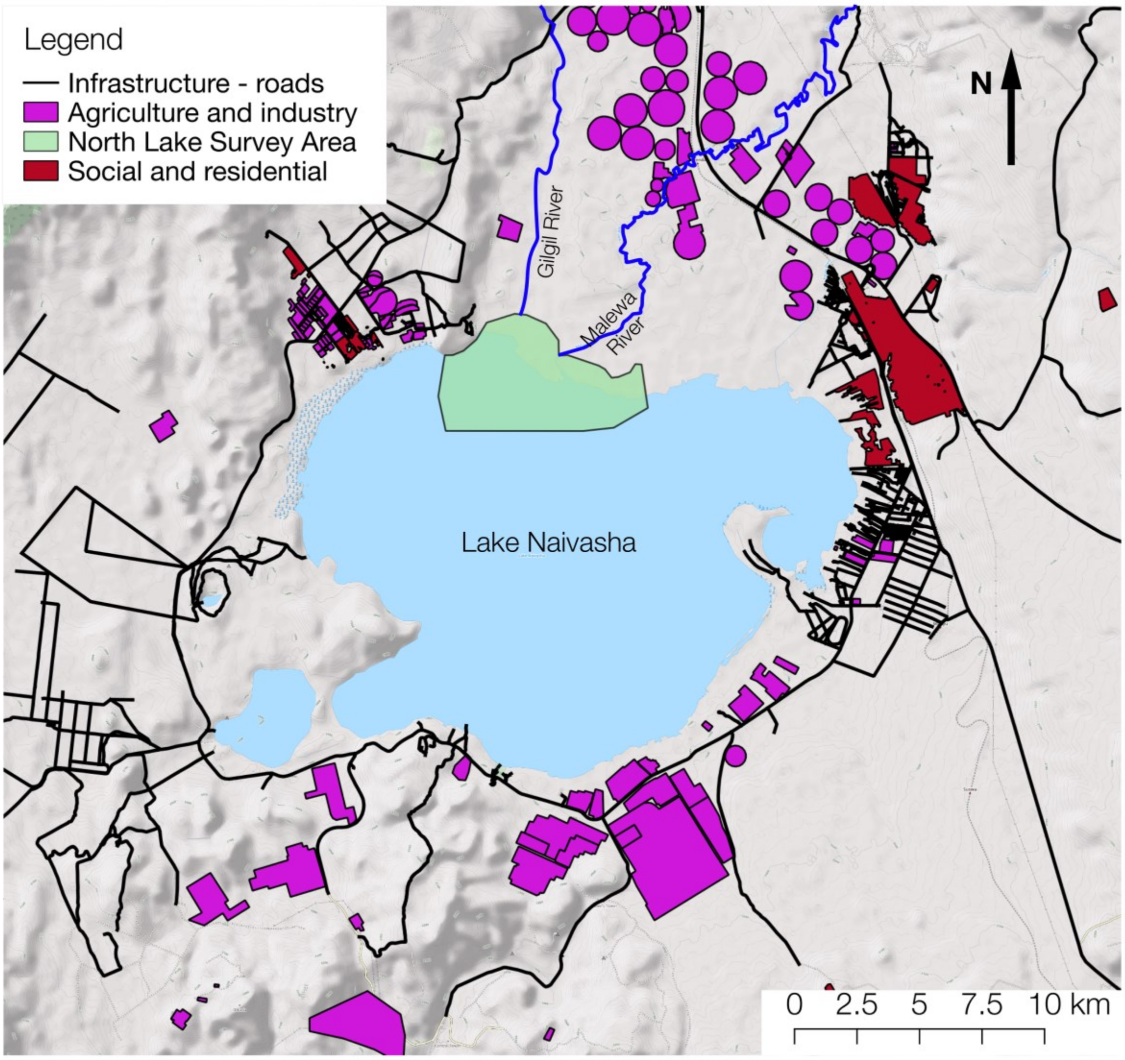

Legend
Infrastructure - roads
Agriculture and industry
North Lake Survey Area
Social and residential
N
Gilgil River
Malewa River
Lake Naivasha
0
2.5
5
7.5
10 km

Figure 2

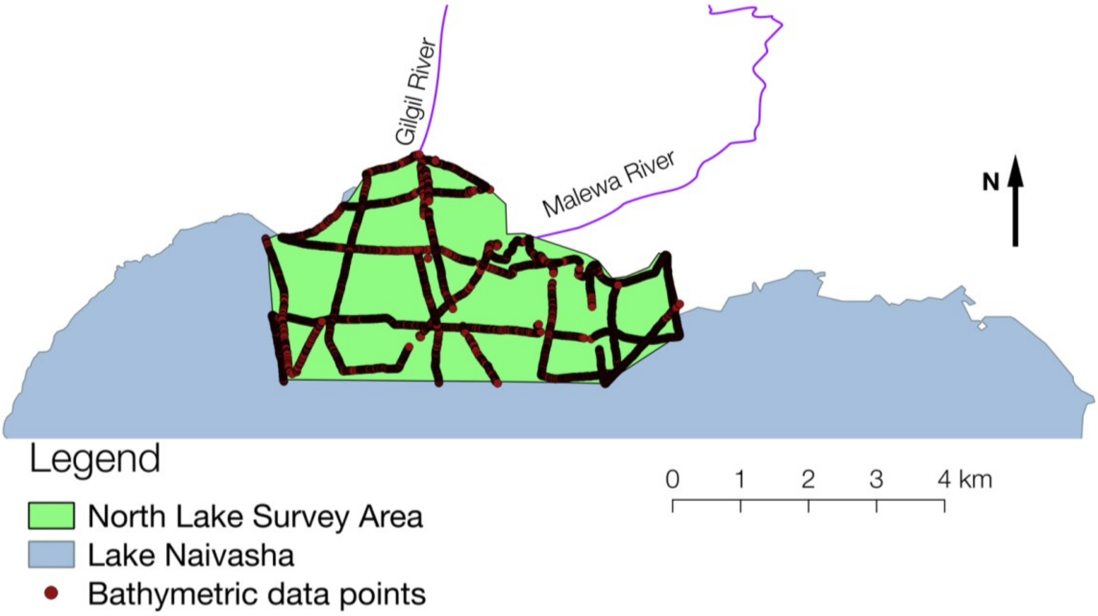

Gilgil River
Malewa River
N
Legend
🟩 North Lake Survey Area
▨ Lake Naivasha
● Bathymetric data points
0
1
2
3
4 km

Figure 3

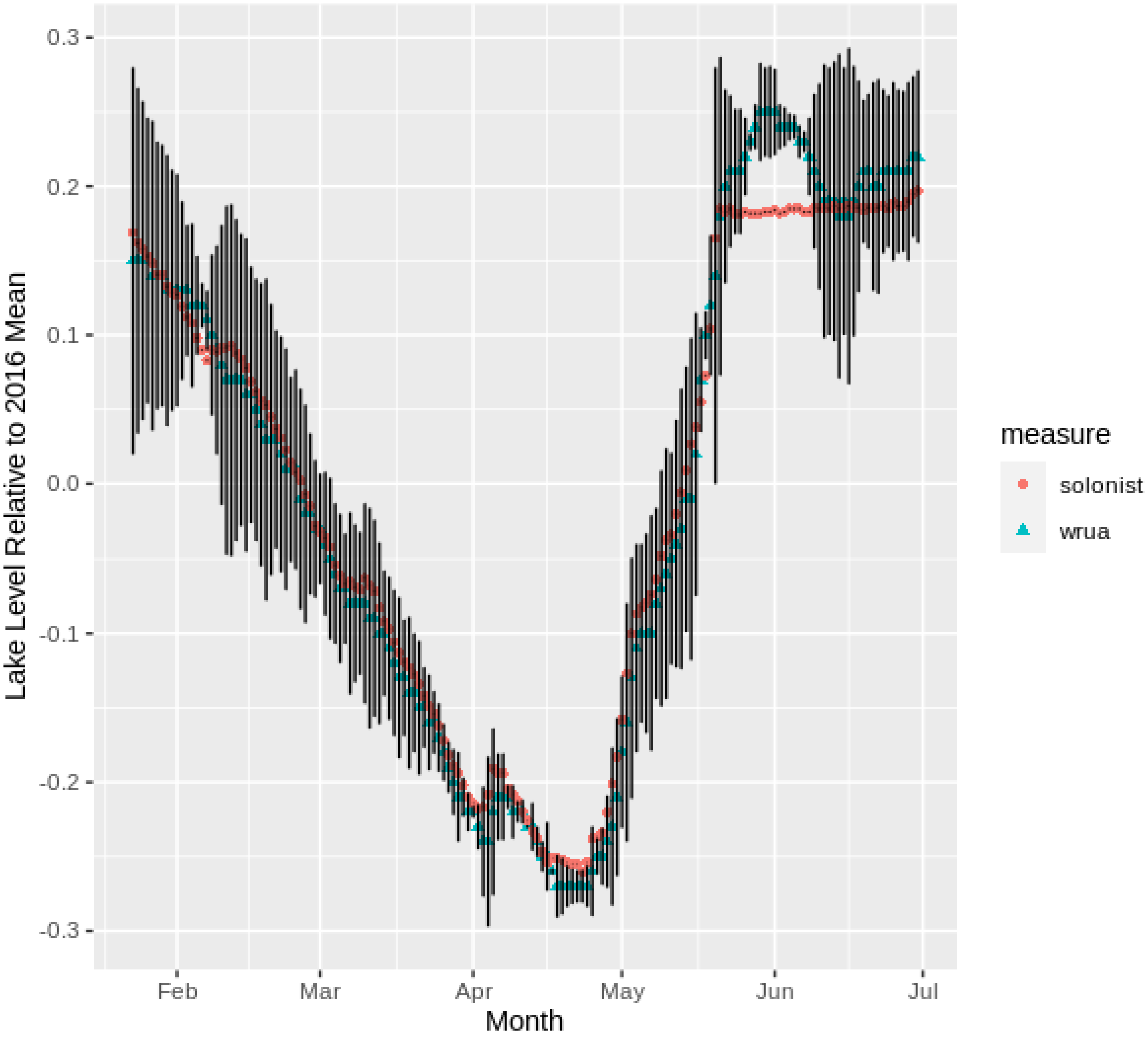
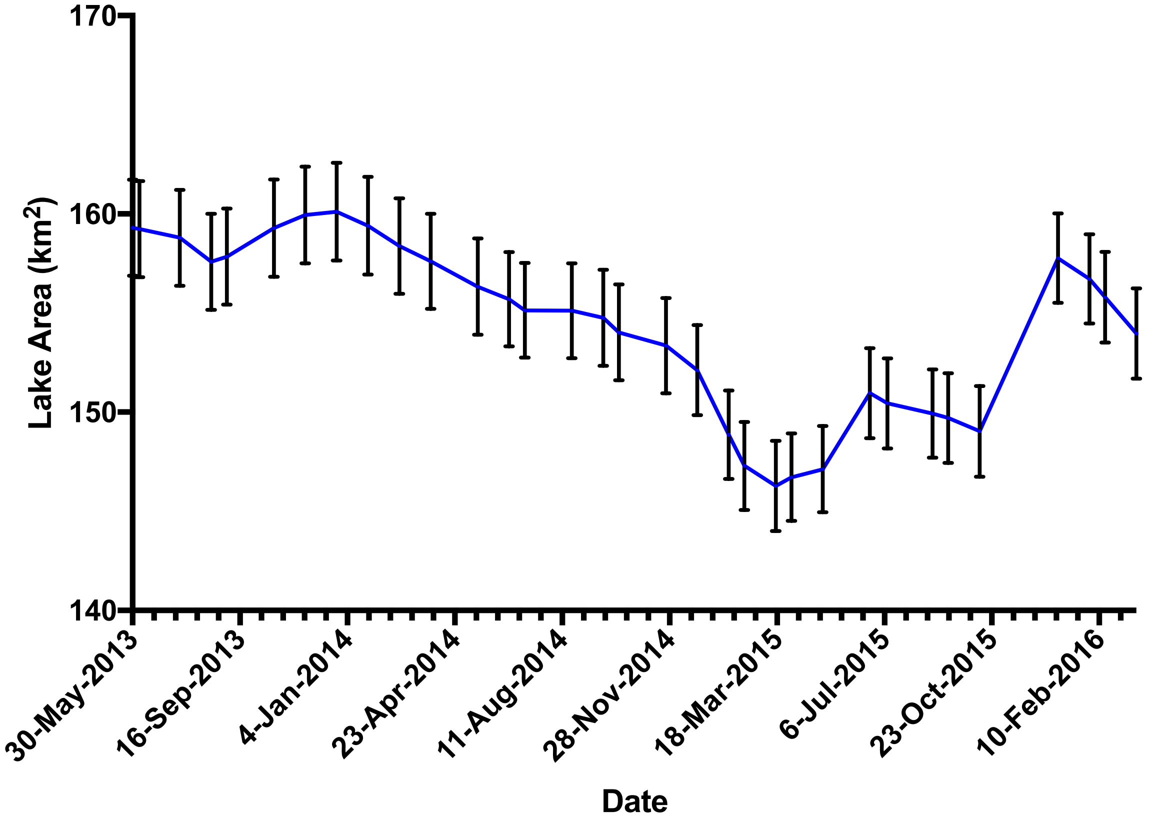
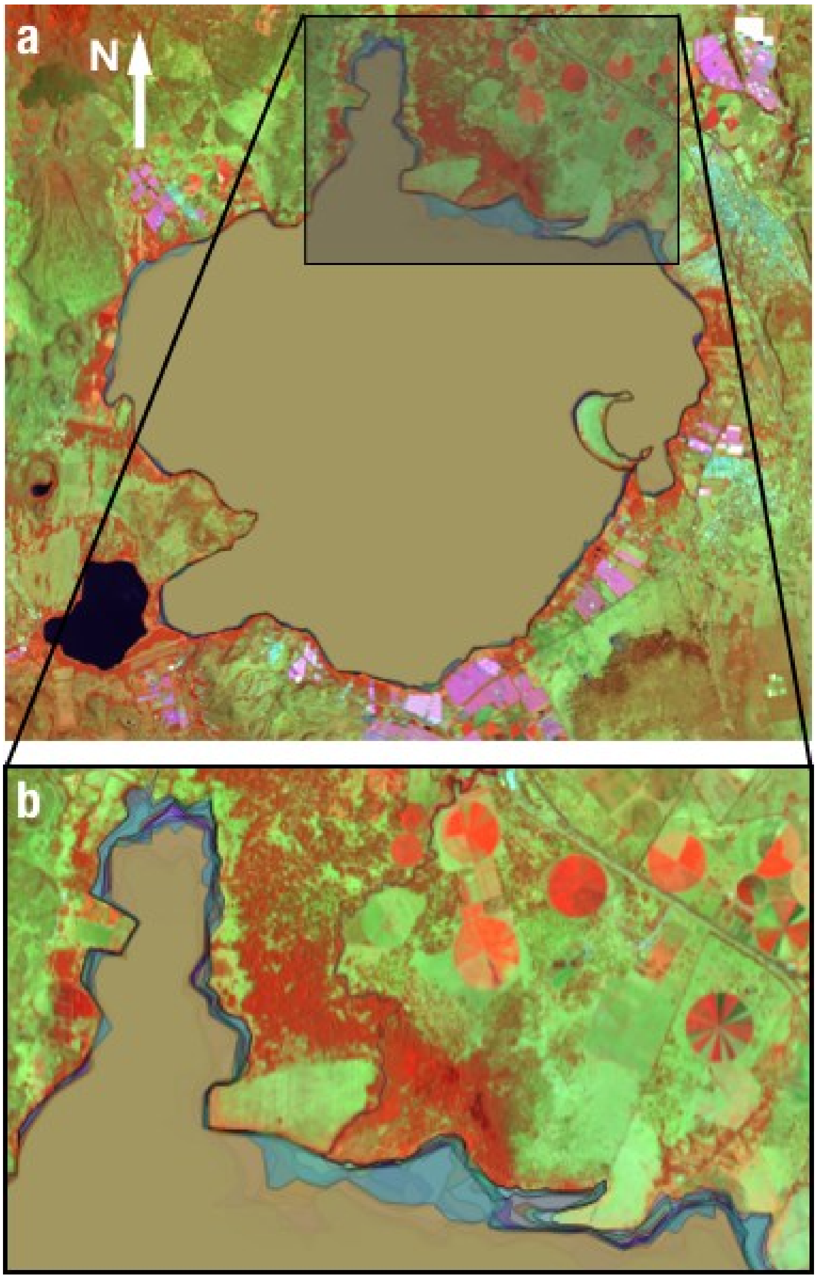

0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
Lake Level Relative to 2016 Mean
Feb
Mar
Apr
May
Jun
Jul
Month
measure
solonist
wrua

Figure 4


170
160
150
140
Lake Area (km^2)
30-May-2013
16-Sep-2013
4-Jan-2014
23-Apr-2014
11-Aug-2014
28-Nov-2014
18-Mar-2015
6-Jul-2015
23-Oct-2015
10-Feb-2016
Date

518 **Figure 5**

519 

520

Figure 6

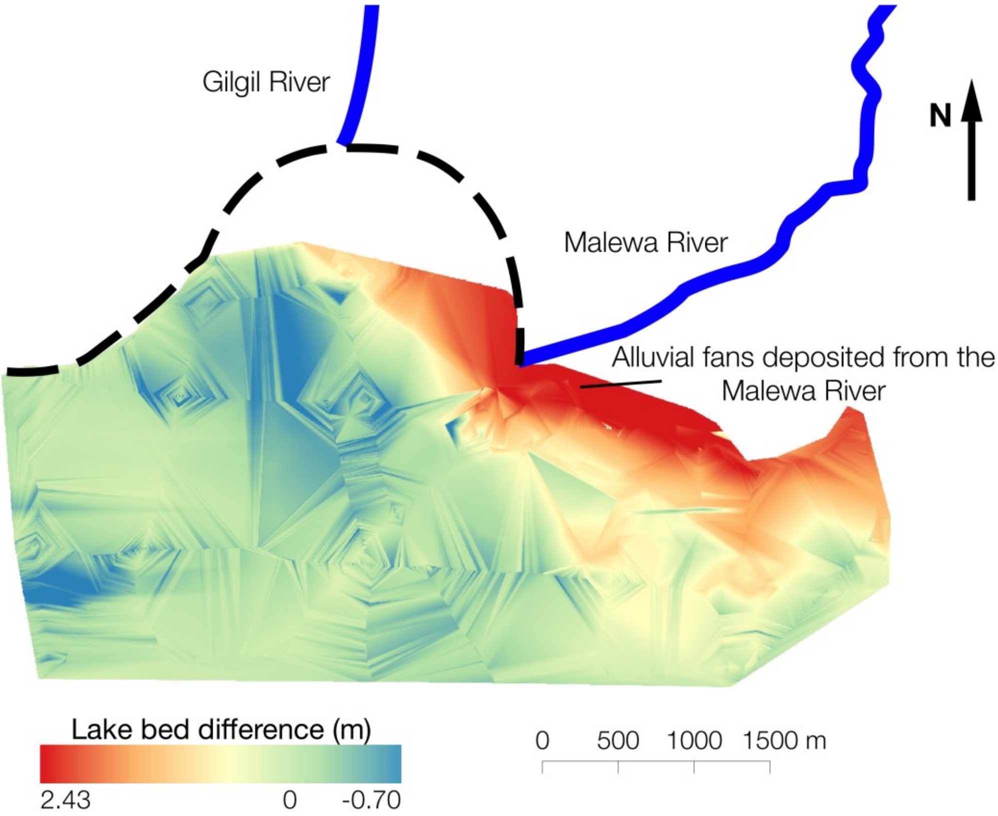

Gilgil River
Malewa River
N
Alluvial fans deposited from the Malewa River
Lake bed difference (m)
2.43
0
-0.70
0
500
1000
1500 m

Figure captions

Figure 1. A map of Lake Naivasha showing the principle road network and major areas of anthropogenic land-use. Most industrial and agricultural complexes are located to the north and south with Naivasha town and other residential areas concentrated to the east where the main arterial roads link Naivasha to the rest of Kenya. Information gathered and mapped by the authors during fieldwork in 2016.

Figure 2. The northern third of Lake Naivasha with the north lake study site highlighted in green. The sonar survey route are shown in black illustrating the variations in transects due, due to the boat having to navigate around floating vegetation.

Figure 3. Lake level as recorded by the Solinst level logger compared to the secondary data acquired from the LaNaWRUA over the period 23 January 2016 to 30 June 2016.

Figure 4. Monthly lake area derived from the Landsat data for the period May 2013 to March 2016. The linear regression result suggests that the lake area steadily reduced from May 2013 until March 2016. The vertical error bars show the estimated uncertainty in lake extent of ±1.5%.

Figure 5. False colour satellite images from 19 March 2016 overlaid with 33 polygons (from the monthly Landsat satellite passes) illustrating the variation in lake area from May 2013 to March 2016. Dark blue/black indicates water and healthy green vegetation is clearly visible as red with shades of purple indicating buildings. **a** The complete lake. **b** A magnified region of the North Lake region highlights the variations in the lake perimeter.

Figure 6. Topographical map of the North Lake Study Site showing evidence of positive (up to 2.43 m) and pockets of negative (less than 0.70 m) change in the height of the lakebed in metres over the 15 year period, 2001-2016, indicating deposition is occurring at a rate of 23 mm yr^{-1} which has likely displaced more than 40192 m^3 of water. Also shown are the two rivers that flow into Lake Naivasha. The gap between the Gilgil and the study area represents a region of the study site for which there was no historical data for comparison, likely due to obstructive vegetation.