The Eco-hydrology of Lake Naivasha

A focus on sediment deposition and aggregation to investigate changes in water volume and methods of continual long term monitoring.

Submitted by David Walker to the University of Exeter as a thesis for the degree of Masters by Research in Geography, November 2016

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University

Signed………………………….

Photos: David Walker

Acknowledgements

I would firstly like to thank my supervisor’s Jamie Shutler and Chris Laing for their continued guidance and support throughout this MbyRes process. Also thanks to all those out in Kenya and particularly to Ed Morrison, Enoch Mobisa, Joost Hoedjes and Sarah Higgins whose contacts, local knowledge and support were invaluable during the data collection process in Naivasha. Finally, to friends and family who have helped me keep up the motivation to complete this research.

Abstract

Lake Naivasha is an important economic asset for Kenya; it currently supports a growing population, a thriving tourism industry, geothermal energy production and over 60 flower farms which predominantly export to Europe. Recent declines in lake level and water quality have led to a marked increase in scientific studies with a common goal to improve management and conservation. The lake is vulnerable to long, hot periods with low rainfall, which increases evaporation rates resulting in concentrations of pollutants in the water rising. The effect of variations in water quality and availability are both felt locally and internationally. While the flower farms and other abstractive industries are easy to blame for the lakes decline in water level, sediment deposition is, and has been, occurring since the formation of Lake Naivasha. Changes in sediment load and streamflow are indicative of the health of the upper catchment. Upstream land usage has changed from natural forests and open land to farming and anthropogenic uses and due to erosion, riverine loads have increased in recent decades. By using remote sensing and coring, this study sought to identify areas of sediment deposition and quantify recent changes in deposition rates due to upstream erosion events or changes in land-management practices. A novel low-cost and easily replicable remote sensing technique was developed successfully to quantify deposition rates. Sedimentation was found to be most prominent in the northern area of Lake Naivasha at an average of 23 mm yr^{-1}, displacing 308139 m^3 of water each year. Current management plans set abstraction quotas using lake level measured in metres above sea level. While long-term fluctuations of lake-levels are consistent or perhaps even increasing, lake volume may in fact be slowly declining. This paper recommends that regular satellite and sonar

remote sensing could be key to monitoring the health of the basin as well as effectively improving the management of Lake Naivasha which will ensure the long-term existence of the resource and the population and industry it supports.

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Author’s Declaration

This study has been carried out by myself for the fulfilment of a Master’s by Research. I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University. Chapter 4 is a paper that is pending submission to the Journal of Ecohydrology, it has been written by myself as lead author based on the research carried out for this Masters - with some additional material provided by named co-authors; Shutler JD, Morrison EHJ, Laing C.

Glossary

The following terms and abbreviations are defined for the purposes of this study.

bathymetry	the study of underwater depth of lake or ocean floors
Cyperus papyrus	Papyrus
Eichhornia crassipes	Water Hyacinth
endorheic basin	a closed drainage basin which has no visible outflows to rivers or oceans
epsilon band	a band of uncertainty between two land covers, within which the true boundary may lie
GPS	global positioning system
LaNaWRUA	Lake Naivasha Water Resource Users Association
LNGG	Lake Naivasha Growers Group
masl	metres above sea level
mya	million years ago
pXRF	portable X-ray fluorescence
QGIS	open source geographic information system software
Salvinia molesta	Floating Water Fern
Sonar	a technique for measuring distance underwater using sound propagation (origin; acronym for **SO**und **N**avigation **A**nd **R**anging)

starboard	the right side of a boat when facing forward
sustainable development	economic development that does not cause the depletion or destruction of natural resources
topographical	graphic representation of the surface features of a place or region on a map, showing relative positions and elevations
water towers	mountainous areas of high elevation (>2500 masl in Kenya) which naturally collect, store and distribute freshwater, via ground water, run-off and major rivers, to lowland regions
WAP	Water Allocation Plan
WHO	World Health Organisation
WWF	World Wide Fund for Nature

1 An introduction to water stress, the Kenyan Rift Valley and Lake Naivasha

Fresh water is essential for life and as a limited resource it is under pressure. This is due to the constant demand to grow more food and support ever increasing populations (Hoekstra *et al.,* 2012). According to the World Health Organisation (WHO, 2015), by 2025 half of the world's population will be living in a water stressed region. Water stress is split into two types; economic and physical. Economic water stress is an anthropogenic issue caused by lack of investment in infrastructure or lack of human capacity to utilise an adequate water source. Much of Africa suffers from economic water stress due to a lack of funding, as well as political and ethnic conflict resulting in an unequal distribution of resources (The Water Project, 2016). Physical water stress relates to the lack of abundance of water in the system to meet necessary demands. While arid regions are associated with natural physical water stress there are many fertile and productive areas, such as the Colorado River basin, which have been developed and abstracted to such a degree there is limited water left in the system, causing anthropogenic water stress and creating issues downstream (Castle *et al.,* 2014).

Water Stress

While developing countries tend to suffer more from economic stress, changes in streamflow, caused by increased physical water stress, still have a great impact as it compounds the pressure created by population and economic growth, made worse by land use change and rapid urbanisation (Kyambia and Mutua, 2015; Mogaka *et al.,* 2006). A healthy upper catchment should hold and release water slowly acting as a buffer for climate anomalies. As climate change is increasing so too does the intensity and frequency of fluctuations in streamflow (flow rate and erosion will increase when the upper catchment is in poor health), therefore harvesting and storing water sustainably when in surplus should be encouraged (Mogaka *et al.,* 2006). Approximately 40% of Earth's growing regions that are equipped for irrigation use groundwater as a source due to its stability and minimal requirements for infrastructure (Scanlon *et al.,* 2012). Many of the vegetable farms and flower farms in the Lake Naivasha catchment depend on the surface and groundwater flows for irrigation (van Oel *et al.,* 2013). Making a shift to modern sustainable management techniques can effectively address economic water stress and will ensure this basin retains its high yields and that the lake is preserved as a resource (The Water Project, 2016). Lessons should be learnt from other regions of the world, for example in California decades of dependency on diversion and abstraction of water for irrigating the fruit-growing Central and other valleys has left much of the state in a severe drought. Recently in 2013 and 2014 several communities were given a 90-day period before water ran out completely (Scanlon *et al.,* 2012; Swain *et al.,* 2014).

Ramsar

Wetland habitats are recognised as being central to sustainable development due to their filtration properties, which freshen water (Gaudet 1978; Ramsar 2014b). The Ramsar Convention is the oldest modern intergovernmental environmental agreement which nations can sign up to. It provides a frame work for the conservation and *wise-use* of wetland environments. These include; lakes and rivers, aquifers, swamps and marshes, wet grasslands, peatlands, oases, estuaries, deltas and tidal flats, mangroves and other coastal areas, coral reefs, and all human-made sites (Ramsar, 2014b). Ramsar's mission states that;

> *"…the conservation and wise use of all wetlands though local and national actions and internationals co-operation, as a contribution towards achieving sustainable development throughout the world."* (Ramsar, 2014a)

As is the case with many developing countries while regulation surrounding Kenyan water sources exists to reduce economic water stress, it is poorly enforced and rarely followed. However, in 1995 Lake Naivasha was designated a Ramsar site allowing Naivasha to join a list of over 2,200 sites around the world (Becht *et al.,* 2006b). The convention assists local stakeholders in conserving their asset by educating and helping to create management plans for the protection of the Lake and its wetlands (Ramsar, 2014b). An improvement in education should stop damaging attitudes to the use of water resources and in time will allow evidence based management plans to be more effective and born from more accurate data.

Monitoring and Management Plans

To balance conservation and resource use with socio-economic growth, water management plans of some kind are needed. However, any water management plan which is based on inconsistent and scarce data has the potential to be detrimental to the entire system (Hogeboom *et al.,* 2015). Now more than ever, parallels can be drawn between the over management of the Colorado basin and the future of Kenyan water sources. It has been reported by Cherono (2016) that there are plans to construct a collector tunnel in the

Abedare Mountains leading to Nairobi. While this would improve water provisioning in Nairobi and reduce the economic water stress in the region, the environmental impacts of diverting water from the Abedare's catchment straight into Nairobi could be disastrous. Removal of water, and the potential subsequent desertification, will increase suspended sediment in rivers. This, alongside an increase in physical water stress will have dire consequences for water levels and the health of the lower catchment (Scanlon *et al.,* 2012; Swain *et al.,* 2014). There have been many, sometimes conflicting, studies on groundwater flows in the rift valley (Darling *et al.,* 1990; Becht *et al.,* 2006a; Yihdego and Becht, 2013; Hogeboom *et al.,* 2015) which complicate the decision making process. It is perhaps unwise to embark on such major engineering works without being certain of what the impacts will be. This is especially important considering the lasting effect that diverting water from the Colorado River basin to the farms and Pacific coast cities has had on the entire state of California (Scanlon *et al.,* 2012; Swain *et al.,* 2014).

For Lake Naivasha, consistently in the literature and local management plans the lake level is referred to in metres above sea level (masl) (Becht and Harper, 2002; Becht *et al.,* 2006b, Hogeboom *et al.,* 2015). The lake has periods of high and low water which can mean months' pass where whole areas of the lake are completely dry (Becht *et al.,* 2006b). The lake level in masl dictates the percentage of their quota that stakeholders (people and industries) are allowed to abstract (Harper *et al.,*2013). Åse (1987) noted from a 1986 bathymetric survey that the relatively flat bottomed lake is in direct contrast with sharper and more defined topography of the region surrounding the lake, therefore making the assumption that a thick sediment layer covers the lake bed, as corroborated since by Yihdego and Becht (2013). Past studies have also shown that sediment deposition occurs at a rate of between 10 - 30 mm yr^{-1} across different parts of the lake (Verschuren, 1996; Tarras-Wahlberg *et al.,* 2002). Current management plans use lake level in masl as a guide to restrict water abstraction and ensure water security. This measurement however, does not take into account any variation in the topography of the lake bed due to continual deposition. As Lake Naivasha is an endorheic basin with no visible surface outflows the predominant movement of water leaving the lake is through evaporation, groundwater seepage and abstraction (Becht *et al.,* 2006b; Hogeboom *et al.,* 2015). Thus, it is logical to assume that sediment brought into the lake remains there. To improve management plans and the long term preservation of Lake Naivasha it is important to know whether deposition could have an effect on the recorded fluctuations in lake level data. A quantification of this deposition could also offer an insight into the changing health of the upper catchment as increased loads are symptomatic of degraded land upstream. Downstream if lake level is rising at a lesser rate than deposition is occurring, it would imply a net loss of lake volume. If this is the case stakeholders will continue to live and work in a region where water security is not perceived to be an issue, whereas the amount of water in the lake and the health of the upper catchment may in fact be decreasing.

Report Structure

This report is structured as follows. This is chapter 1. Chapter 2 goes on to introduce the formation of the Lake Naivasha basin and surrounding region, highlighting some of the complexities of the system that have made Lake Naivasha so important to Kenya. The field methods carried out for this research project can be found in chapter 3. In chapter 4 an investigation is carried out looking at rates of sediment deposition and the impact on water levels using inexpensive easily replicable remote sensing techniques. By using secondary data and collecting raw data in the field this study aimed to identify and quantify areas of deposition. in a bid to improve management plans this study also considered whether current and historical level records are valid for monitoring and whether there are implications in failing to account for deposition in long term monitoring. Chapter 5 discusses the merits of this further, looks at the limitations of this study and outlines recommendations for any future work that may replicate methods and build on the results of this study.

2 The formation and current understanding of the dynamics of the Lake Naivasha basin and surrounding region

Formation of the Rift Valley and Lake Naivasha

Lake Naivasha is one of many lakes found in the Kenyan Rift Valley, which in turn is part of the East African Rift System, that stretches north from Tanzania towards the Red Sea and Gulf of Aden Rifts (Baker and Wohlenberg, 1971). From between 30 and 15 million years ago (mya), volcanic activity and tectonic development began to occur with a gentle downwarping and subsequent flooding with lava. Phases of faulting created step-fault platforms and towards the Naivasha - Nakuru region voluminous trachytic volcanism filled the rift depression (Baker, 1986). Large-scale volcanic damming, has sub-divided the East African Rift into several sedimentary basins (Baker, 1986; Becht et al., 2006a). Drainage from the rift flanks has filled these basins and created a chain of freshwater and saline lakes with no surface outflows, all of which are affected by high evaporation rates and low rainfall (figure 2.1) (Eugster, 1980; Nyingi et al., 2013). In a lacustrine environment high levels of salinity can be caused by an arid climate, eruption of sodium carbonate rich ash and the recirculation of alkaline groundwater (Baker, 1986; Jiang et al., 2004; Melack, 1983). There are seven major lakes in the Kenyan section of the Rift Valley; Lake Naivasha (fresh), Lakes Turkana and Baringo (moderately saline), Lakes Bogoria, Nakuru and Elementaita (saline) and Lake Magadi (hyper saline), as well as 7 minor lakes. By altitude Lake Naivasha sits at the highest elevation, 1890 masl (figure 2.2) (Becht *et al.,* 2006b).

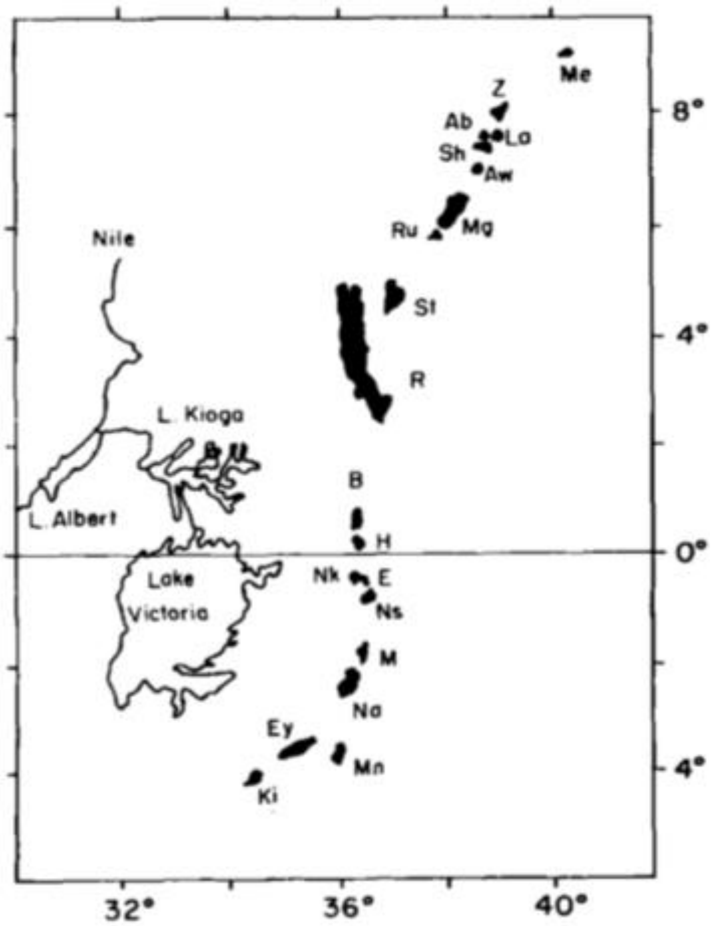

Figure 2.1 Closed basins of the Eastern Rift Valley. North to South: Me - Metahara, Z - Zwei, Ab - Ablata, La - Langano, Sh - Shala, Aw - Awassa, Mg - Margherita, Ru - Ruspoli, St - Stephanie, R - Turkana, Ba - Baringo, H - Bogoria, Nk - Nakuru, E - Elmenteita, Ns - Naivasha, M - Magadi, Na - Natron, Mn - Manyara, Ey - Eyasi, Ki - Kitangiri. Lake Victoria is given for reference. (Eugster, 1980).

Basin Dynamics and Groundwater Characteristics

Despite the arid climate and surrounding geology being conducive to the creation of saline bodies of water, Lake Naivasha is able to maintain it's freshness and support an incredibly biodiverse system. Water replenishes the lake via the Malewa and Gilgil rivers which provide 80% and 20% respectively of the total inflow into the north of the lake (Becht *et al.,* 2006b). Due to their respective sources being at altitude in two of Kenya's five 'water towers' (>2500 masl) there is a near constant influx of water (Becht and Harper, 2002). As well as water, the rivers transport sediment down from the upper catchment and both vegetation and sediment at the mouth of the river play an important part in revitalising the water quality (Morrison and Harper, 2009; Tarras-Wahlberg *et al.,* 2002). Despite more than 60 years of study into the water balance of the lake no obvious surface outflow has been ascertained, it is thought groundwater must play a vital role in the hydrology and freshening of Lake Naivasha (Becht *et al.,* 2006a; Becht *et al.,* 2006b; Darling *et al.,* 1990; Hogeboom *et al.,* 2015). Since Thompson *et al.* (1958) there have been many attempts to map the groundwater flow from Lake Naivasha (Becht and Harper, 2002; Yihdego and Becht 2013). These studies have culminated in the assertion that 40% of Lake Naivasha's subterranean outflows flow into and freshen other lakes in the Rift Valley (Becht *et al.,* 2006a). With Lake Naivasha being at the highest altitude of all the Kenya Rift Valley Lakes, it is logical that this would be the case (figure 2.2).

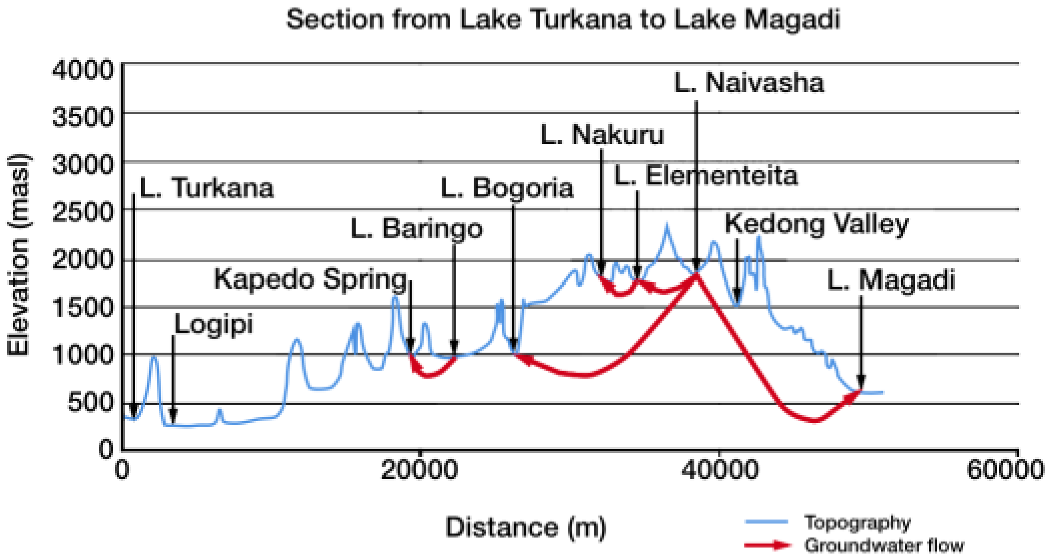

Figure 2.2 Cross section from Lake Turkana to Lake Magadi. Water

balances show groundwater outflows out from Lake Naivasha (at the highest elevation) and Lake Baringo to a number of the other lakes in the Rift Valley. Particularly to the north to Lakes Nakuru, Elementeita and Bogoria. (remastered from Becht *et al.,* 2006a)

Groundwater is vital for understanding lake systems as it regulates a lake's water and nutrient budget (Becht and Nyaoro, 2006). There is an assumption that the northern part of the lake has higher levels of pollution due to the Malewa and Gilgil Rivers bringing sediment and pollutants from upstream (Becht *et al.,* 2006b) while the south and eastern areas of the lake have a superior water quality (Ndungu, 2014). It has been shown that ground water originating from the lake flows both northerly towards the hot springs of Lake Elementia and southerly towards the Olkaria well-fields (Becht and Harper, 2002). Groundwater extraction to the north of the lake tends to be used for irrigation in the same area, creating a groundwater depression. As water is re-circulated around the system the levels of pollutants increase in concentration, reducing water quality in the area (figure 2.3) (Becht and Nyaoro, 2006).

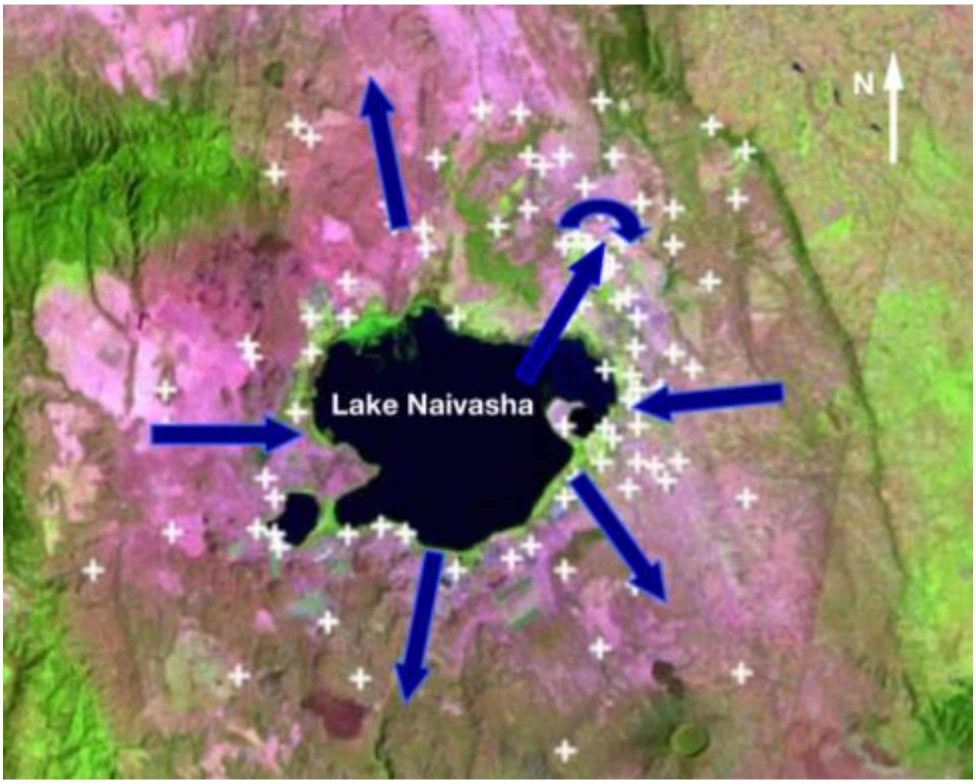

Figure 2.3 Lake Naivasha with wells (+) showing the direction of groundwater flows (arrows) into and away from the lake. Most water flows north and south along the length of the Rift Valley, with replenishment flowing from the elevated eastern and western flanks. (adapted from Becht and Nyaoro, 2006).

Productivity and Biodiversity

In the Rift Valley, primary productivity of the saline lakes can be attributed to floating algae and phytoplankton, whereas the freshwater biodiversity of Lake Naivasha is predominantly built on freshwater algal blooms, phytoplankton and large beds of wetland vegetation (Nyingi *et al.,* 2013). The wetlands carry local, national and international importance, however due to the unceasing pressure for social and economic development the biodiversity is constantly under threat (Otiang'a-Owiti and Oswe, 2010). Through the introduction of invasive species, an abundance of alien aquatic fauna has been developed over the last century, drastically reducing the biomass of native species (Becht *et al.,* 2006b), in some cases to the point of extinction. For example *Procambarus clarkii* (Louisiana red swamp crayfish), introduced in the 1970s, is suspected to have caused the complete decimation of native plant species, evidenced by periods of recovery of the native flora occurring alongside declines in *P. clarkii* (Smart *et al.,* 2002). Lake Naivasha is not only under pressure from the biodiverse ecosystem of competing native and invasive flora and fauna, but also from the large floriculture and tourism industries (and increasing populations) that require freshwater and further strain the resource (Becht *et al.,* 2006b; Mogaka *et al.,* 2006; Otiang'a-Owiti and Oswe, 2010).

The formation of the East African Rift Valley and subsequent hydro-dynamics have left Lake Naivasha to be a freshwater anomaly in an otherwise saline hydrological system. This fact alone has meant it is put under a lot of strain by people and industry concentrating themselves around the shore (Nyingi *et al.,* 2013). As it is only two hours from Nairobi a vast number of export industries also rely on the water and fertile riparian land surrounding the lake (Mogaka *et al.,* 2006; Otiang'a-Owiti and Oswe, 2010). Should the lake dry up completely, or a reduction in water quality render it un-usable, people would lose jobs and livelihoods as the industries that depend upon the plentiful lake would decline and move away. At a national level the economy would suffer a blow as the large foreign businesses and investors, of which the floriculture alone makes up 75% of all Kenya's floral exports (Kyambia and Mutua, 2014) would also move their business elsewhere. Most crops (flowers, fruit and vegetables) grown on commercial farms around Lake Naivasha are exported to Europe, therefore short term repercussions of drought and reduced yields are not only felt locally but internationally as consumers would see prices increase and certain products become less widely available.

In a region which has been shaped by multiple periods of tectonic activity, creating several closed hydrological basins. It is the very specific set of local geological and hydrological characteristics that have created only one fresh water resource. Due it’s rarity it is a key resource for the ecosystem and developing human population, leading to its heavy exploitation. Growing industry is potentially damaging and the larger populations which are reliant on the freshwater are extremely vulnerable to any changes in the lakes volume and concentration of pollutants.

3 Field methods and techniques

To quantify areas and volumes of deposition time was spent in the field at the study site - Lake Naivasha, Kenya - to collect data. Two elements of data were collected in the field between 20/01/2016 and 10/02/2016; lake depth and sediment samples. The methods employed were conducting some bathymetric surveys and taking sediment cores. All quantitative field data collection was performed from a boat on the lake. Field work was restricted to week days as boats were not available at the weekends. Sonar was used to map changes in lake depth and sediment samples were taken with a kayak corer (Kvernevik *et al.,* 2002, Tarras-Wahlberg *et al.,* 2002). Secondary data was also key to this study; historical lake level data was provided by the Lake Naivasha Water Resource Users Association (LaNaWRUA) and bathymetric data was collected by Rupasingha (2002) and is available at *Naivasha Research* (2010).

Bathymetric Surveys

Using sonar is the most efficient way to comprehensively measure the changes in depth across a large body of water. For this study the method was derived from a study by Kvernevik *et al.* (2002) which evaluated low cost procedures for mapping the seabed. Kvernevik *et al.'s* (2002) system was portable but required a battery and a laptop sealed in a box, wired up to the sonar in the boat to constantly collect data. This study used a consumer grade Deeper Fishfinder (Deeper, 2016) which records data directly to a smartphone via a wireless Bluetooth connection. The internal batteries and wireless nature of this system allowed it to be easily deployed and meant a waterproof case was sufficient to protect the phone from water damage (figure 3.1). The sonar operates at both wide and narrow beam frequencies (90kHz and 290kHz). While the system was derived from Kvernevik *et al.'s* (2002) the procedure for data collection was developed to be comparable to the data collected in 2001 by Rupasingha's (2002) study to ensure that the results could be compared. Rupasingha (2002) used a Garmin Fishfinder 100 for collecting bathymetric data and this sonar operates dual beams at similar frequencies (50kHz and 200kHz). The method of data collection was otherwise identical. Alongside the sonar and smartphone, a Garmin eTrex 10 global positioning system (GPS) was used to navigate around the study site. Open-source software, QGIS, was used to create a sampling grid with optimal survey routes that could then be loaded onto the GPS. From initial field testing it was found that the speed needed to efficiently record data while maintaining repeatable results was between 8 and 10 km hr^{-1} depending on conditions. While out on the water the readings needed to be constantly monitored to ensure speed was maintained in changing wind and chop directions. The survey routes occasionally had to be modified while on the water due to the constantly shifting abundance of hydrophytic species; *Salvinia molesta* (Floating Water Fern), *Eichhornia crassipes* (Water Hyacinth) and *Cyperus papyrus* (Papyrus) (Harper *et al.,* 1995; Mavuti and Harper, 2006; Onywere *et al.,* 2012), which tessellate and interweave to create vast impassable floating mats of vegetation (figure 3.2). Initially a low resolution survey was undertaken of the whole lake before going back to undertake a higher resolution survey of the area deemed most promising for further depositional study. After looking at previous studies and assessing the low resolution survey it was decided to focus on the northern area of the lake, colloquially known as North Lake because the lake bed topography suggested there to be potential fluvial features. This study site was

13.2 km² and sits to the south of an area of former swampland (Morrison and Harper, 2009).

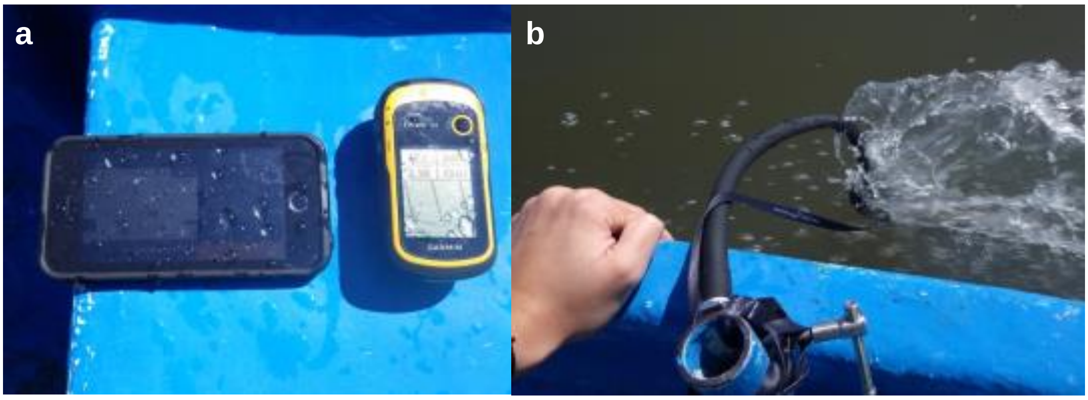

Figure 3.1 a Smartphone in waterproof case running the Deeper Fishfinder app and the Garmin eTrex 10 GPS with waypoints and routes marked. **b** Deeper Fishfinder, attached to the starboard (right) side of the boat, in the water constantly measuring lake depth.

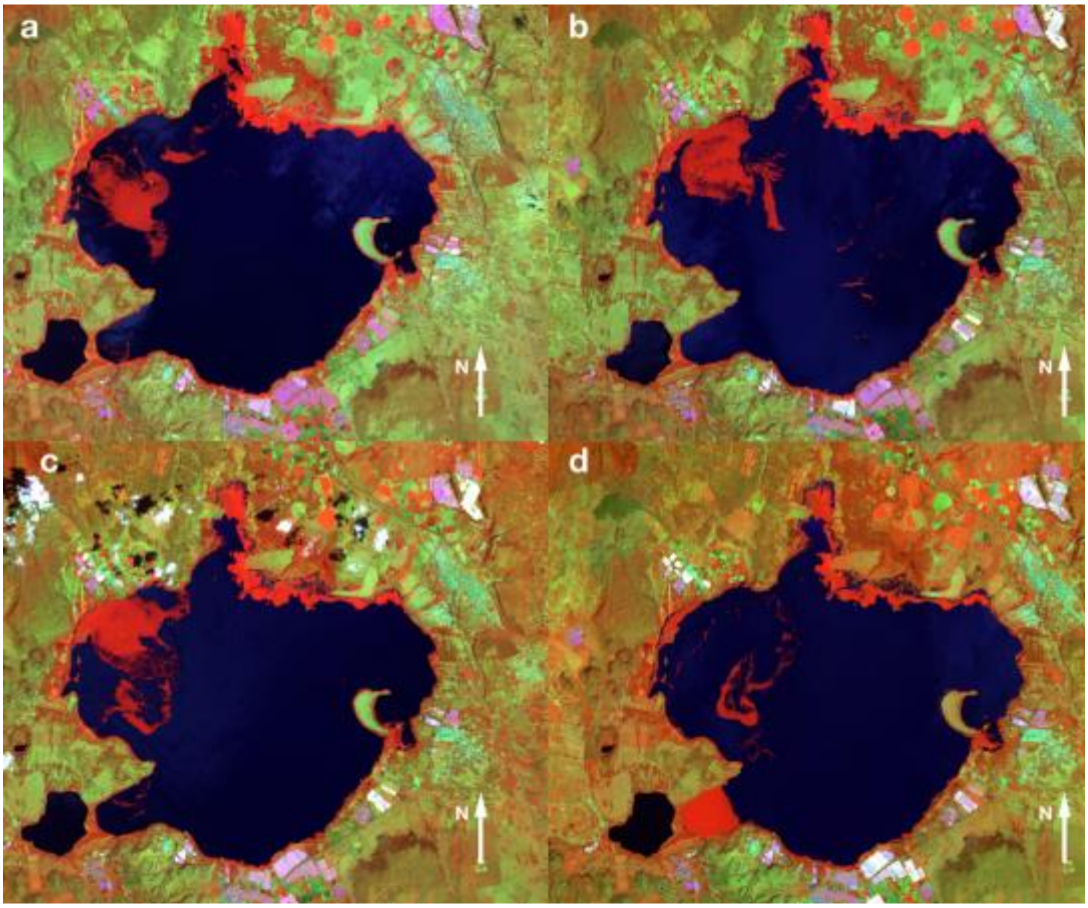

Figure 3.2 These 4 false-colour LandSat 8 images are from consecutive passes of the sensor over Lake Naivasha. **a** 19/3/16, **b** 16/2/16, **c** 31/1/16, **d** 30/12/15. The dark blue is open water and it is clear to see the movements of floating vegetation (red) covering swathes of the lake. The light pink areas around the lake shore are flower farms, greenhouses and other commercial facilities, with greens and browns indicating vegetation and scrubland (Astro Digital, 2016).

Sediment Coring

Despite scientific concerns that sediment layers at the bottom of a shallow lake may not be well preserved, coring has been shown to be a sound method of extracting sediment without disturbing layers of deposition (Kenney *et al.,* 2016). After mapping the study site, initial analysis showed a feature that looked to be an alluvial fan from the Malewa River. This northern edge of the study site was where the coring was focused, with one deeper site to the west. The sediment corer used was a weighted model from UWITEC (UWITEC, 2016). The sediment corer was dropped from the boat vertically into the sediment. One operator held the corer rope, keeping it vertical while the other used the hammer action to drive the corer further into the sediment. This process of driving the corer into the lake bed continued until it could not be driven any further (UWITEC, 2016). As the corer was pulled up the end of the tube was capped before it broke the surface of the lake - ensuring no sediment was lost from the bottom of the core. In total seven cores were taken with lengths ranging from 350 mm and 550 mm (figure 3.3). To transport the cores back to the UK labs for analysis they had to be prepared in the field, this occurred after being left vertically for between 3 and 5 days to allow the sediment to settle (Frew, 2014). The preparation followed Stoof-Leischsenring *et al's* (2011) method; using a piston extruder and core cutter. Each core was cut into 10 mm slices and each slice sealed in zip-lock freezer bags and then double boxed ready for transport. The bags follow the numbering system - C# - ##. The first number represents the core identification and the second the position along the core the slice. While these samples were sealed and packed ready for transport, unforeseen circumstances meant they were not able to be analysed due to transportation issues. This is addressed further in chapter 5.

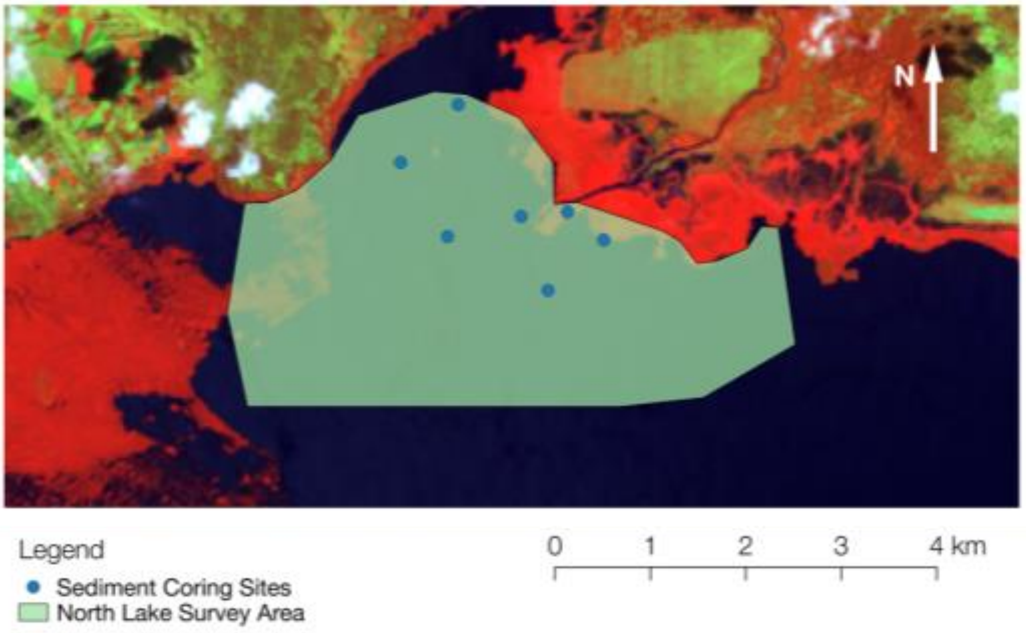

Figure 3.3 The North Lake Survey Area with sites of all seven cores marked. The dark blue is the Lake and the red is the floating vegetation mats. These moved around the western half of the survey area – slowing progress. The floating mats to the northeast did not move but constricted the size of the survey area.

4 Lake Naivasha sedimentation, extent and water levels from bathymetry surveys and satellite remote sensing: recommendations for future lake management

Walker D, Shutler JD, Morrison EHJ, Laing C

This paper is pending submission to the Journal of Ecohydrology.

keywords: *lake, remote sensing, bathymetry, sedimentation, land-use management*

Abstract

Lake Naivasha currently supports >60 different farms and industries, along with a growing population. Due to the large volume of exports it helps to produce and the large population and local industry that rely on it as a source of fresh water, the lake can be viewed as an economic asset to Kenya. The highly complex system within which the lake is located has seen a decline in health and has become particularly vulnerable to long dry periods. These drastically reduce the water level of the lake, causing an increase in concentrations of pollutants and levels of invasive species. Current rhetoric firmly places much of the responsibility for the lakes health at the door of the flower farms and other industry that extract water from the lake. However, sediment deposition is indicative of upper catchment health and has been occurring since the Lake's creation. In recent decades this has likely increased due to upstream land-use change from natural forests and open land to agricultural land. This study sought to identify and quantify sediment deposition

rates and their impact on water levels using inexpensive remote sensing techniques that could be easily replicated for future monitoring. We found sedimentation has been increasing in a specified northern area of the Lake at an average of 23 mm yr^{-1}, displacing 308139 m^3 of water each year. This means measuring the lake health and guiding management plans and abstraction using metres above sea level (masl) alone is erroneous and perhaps detrimental to the long term health of the lake. While long-term fluctuations of lake-levels are consistent or perhaps even increasing, lake volume and the health of the 'water tower' that feeds it may in fact be slowly declining.

Introduction

Kenya's sources of fresh water are found in 5 'water towers' at varying levels of altitude between above 2500 metres above sea level (masl), and the drainage of these systems is dictated by the underlying strata, the Kenya Rift Valley, with the rivers flowing into the Indian Ocean, swamps or simply evaporating (Nyingi *et-al.,* 2013). Lake Naivasha sits at the bottom of a shallow endorheic basin with no surface outflows, 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, 1890 masl (Becht *et al.,* 2006b). All the open bodies of water in the 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 unpredictability of the inflows, in turn resulting in the lake level fluctuating by multiple metres within just a few years (Kuhn *et al.,* 2016; Verschuren *et al.,* 2000). Becht *et al.* (2006a) have shown that there are subterranean flows in the Kenya Rift Valley, predominantly dispersing from Lake Naivasha and acting as a freshening system. Lake levels across the region are also considered in part to fluctuate due to short term changes in groundwater levels.

Naivasha is the only freshwater lake in the Kenyan Rift Valley and supports over 60 floriculture and vegetable farms, artisanal fisheries and an expanding local population (Becht *et al.,* 2006b). Its existence forms a key component of the Kenyan economy with the farms exploiting the fertile lands for growing and then exporting flowers and vegetables to European markets; a market in which 38% of all cut flower imports come from Kenya. The floriculture industry in total brought KES 62.92 billion (~£472 milllion) to the Kenyan economy in 2015 (Kenya Flower Council, 2016). As thriving industry requires increased labour, the town of Naivasha itself has expanded from 160,000 in 1999 to 380,000 people by the 2009 census (Onywere *et al.,* 2012), with workers bringing families from the rural communities to work at one of the large farms or the tertiary and quaternary industries that are a bi-product of a growing industrial town. The World Health Organisation (WHO) recommends 1000 m^3 of water available per capita with a prediction that due to population growth and the current levels of degradation and environmental change water availability in Naivasha could drop from 647 m^3 to 235 m^3 per capita (Kyambia and Mutua, 2015; WHO, 2006). The Lake Naivasha basin is a fragile eco-system which is both vital for, and increasingly at risk from, those that live and work around the lake and the upper catchment (Onywere *et al.,* 2012). The large regulated commercial farms and industry are found in the lower catchment, whereas further upstream in the middle and upper catchments there is a vast amount of unregulated subsistence based land-use including logging, agriculture and charcoal production (Naliaka, 2011). While the lake levels have always historically fluctuated (Becht and Harper, 2002) the demands on the lake and its need to remain a stable source of fresh water are continuing to increase.

Local tradition suggests that a short while before European discovery in the late 19th century the lake was dry (Åse *et al.,* 1986). From this dry basin the lake level is considered to have risen until the end of the 19th century when a maximum level of 1896 masl was recorded, after which the level has then declined throughout the early 20th century (Tarras-Wahlberg *et al.,* 2002). The lowest recorded level was in 1946 (1882 masl) and since then the lake level has fluctuated greatly, with notable high level periods in 1988 and 1997 after heavy rains linked to El Niño events (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 levels. However, anthropogenic activity and abstraction have driven negative change in long term average lake level (Becht and Harper, 2002; Kuhn *et al.,* 2016; Van Oel *et al.,* 2013). Current management guidelines and community plans aim to curb the levels of abstraction through licensing and water quotas and attempts to discourage wastage. For example, towers surrounding the lake display the current water level and what that means in terms of the Water Allocation Plan (WAP) and accompanying abstraction regulations (LaNaWRUA, 2016b). This is based on a traffic light system where red means 'cease all abstraction', amber means 'reduce abstraction' and green means 'continue abstraction to the level of your licence'. It is only recently that these licences and abstractions have been strictly policed alongside the WAP. Between 2007 and 2009 there was a significant ~3 metre drop in lake level, (akin to the 1946 low) which prompted international concern and many Non-Governmental Organisations (NGO's) attempted to identify the issues involved and potential new solutions to the regulation of the water extraction. For example, one report that the World Wide Fund for Nature (WWF) and Lake Naivasha Growers Group (LNGG) funded, found 97% of water extractors were unlicensed or their licenses had expired (Harper *et al.,* 2013). This has created a renaissance of lake research at Naivasha and has spawned many studies into the practices of water extraction and problems of land-use change in the area with the aim to identify potential management solutions (Van Oel et al.*,* 2013; Kuhn *et al.,* 2016).

There are two river inflows and these naturally bring sediment down from the upper catchment and the lack of a significant natural outflow infers that the sediment brought into the lake must accumulate there. Åse (1987), from the 1986 bathymetric survey and Yihdego and Becht (2013) have 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. Suggesting that over time sediment deposition may have 'filled in' the rough topography of the lake bed. Degradation of the upper catchment affects the rates of streamflow and will therefore increase erosion and sediment load being transported downstream.

Following the severe fluctuations of the late 2000s and the more recent dry periods, stakeholders realize the need to maintain the level and health of the lake and catchment to ensure a sustainable future for themselves and their businesses. However, there appears to be a significant oversight in the current monitoring and management plans, as lake level recorded in masl is unable to account for a changing, and potentially rising, lake bed. Nor does it consider the health of the upper catchment which dictates the rates of replenishment after a dry period. For example, a constant lake level (currently assumed to be stable enough to allow sustainable abstraction) may in fact be a function of a raised lake bed combined with a reduced volume of water. Not only does a lesser volume of water reduce the size of the population and industry that the lake can support, so too does a shallower lake with an expanding surface area and stable volume. In this latter instance evaporation cause the body of water to be more susceptible to drought and the exacerbation of the problems caused by higher concentrations of pollutants.

This paper aims to explore the levels of lake bed sedimentation in Naivasha and hence determine the efficacy of the current basin management plans, abstraction licensing and quotas that are based on daily lake water level measurements. We quantify the effect of sedimentation on the upper portion of the lake as this region is most likely to be impacted by riverine sediment inputs from the rivers Gilgil and Malewa. The results from the bathymetric surveys and satellite remote sensing observations demonstrate the influence that this sedimentation has had on lake level and volume. Conclusions are then drawn regarding future management approaches towards ensuring the sustainability of the lake as a source of fresh water.

Methods

Study Site

Lake Naivasha is located in the Kenyan Rift Valley, itself a section of the East African Rift. Within the Rift, volcanic and tectonic activity has created large sedimentary basins that have been subdivided into closed local basins by volcanic damming (Baker, 1986; Becht et al., 2006a). Drainage from the rift flanks runs into the basins, creating a chain of lakes with no surface outflows (Eugster, 1980; Nyingi et al., 2013). Lake Naivasha is 80 km to the North West of Nairobi (Becht et al., 2006b) with a contemporary average area of 154 km^2, the basin receives an average annual rainfall of 610 mm yr^{-1} (Kyambia and Mutua, 2015). There are two rivers, the Malewa and Gilgil which refresh the lake with water from the upper catchment to the North in the Aberdares. The rapidly expanding commercial activity around the lake shore and the population of the catchment rely on the continued functioning of Lake Naivasha as a hydrological system (figure 4.1).

The bathymetry study site was a 13.2 km^2 portion of the northern part of the lake, commonly known as North Lake (figure 4.1). This area sits to the south of the former North Lake swamp and was chosen after carrying out a low-resolution survey of the lake to identify possible large-scale sediment deposition features. Here the shape of the bathymetry suggested there to be features associated with sediment deposition from riverine inputs. The area is fed directly by the Malewa and Gilgil rivers which flow into the lake from the upper Aberdares catchment, with maximum discharge normally occurring between September-October (Åse et al., 1986; Becht *et al.,* 2006b). The Northern bounds of the survey area were constricted by the shore to the West and the abundance of *S. molesta, E. crassipes* and *C. papyrus* to the East. The moving vegetation being an issue for previous bathymetric studies on the lake (Rupasingha, 2002).

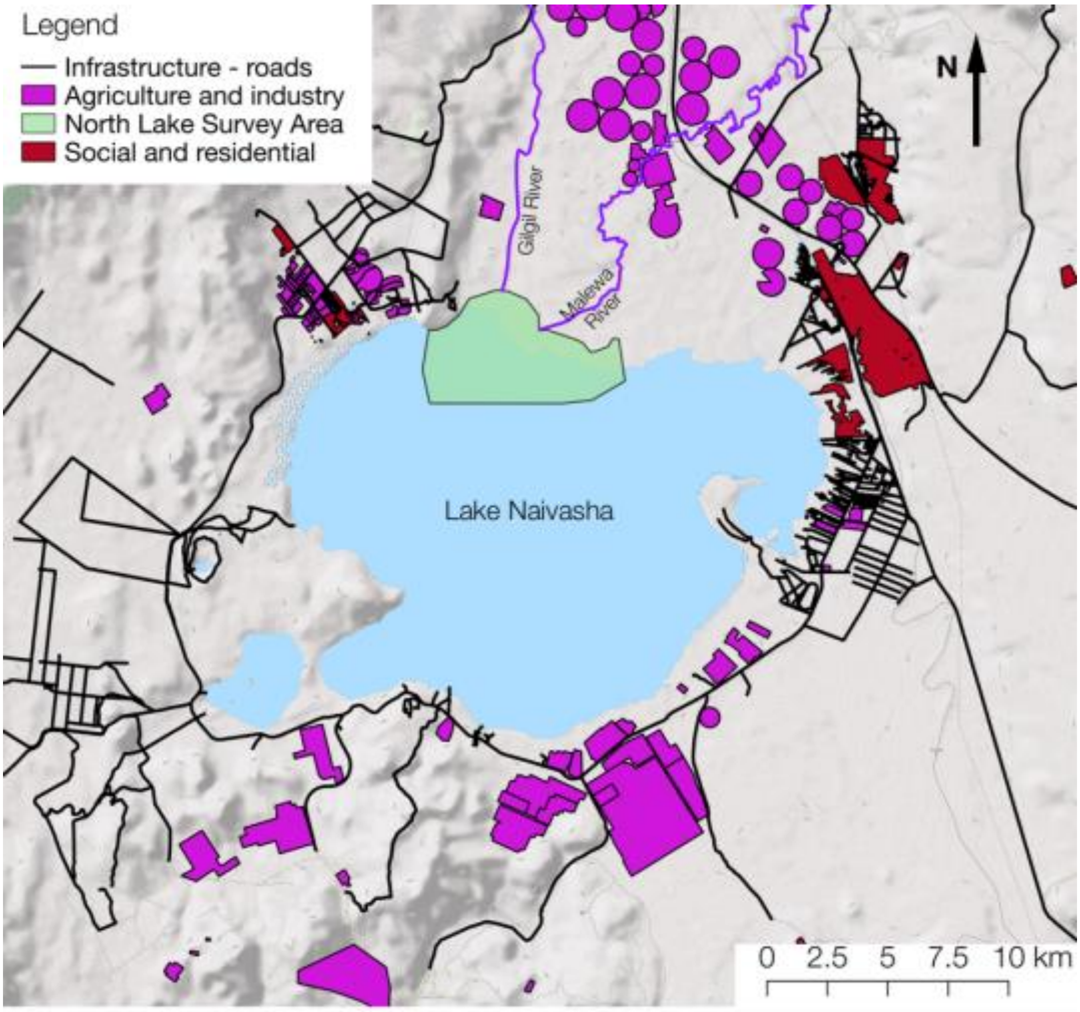

Figure 4.1 Lake Naivasha and its surroundings showing; the principle road network and major areas of anthropogenic land-use cover. Most industrial and agricultural complexes are located to the north and south. Naivasha town and the other residential areas are concentrated to the east where the main arterial roads link Naivasha to the rest of Kenya. However, there are many small social and residential areas dotted all around the lake following the road network.

Lake Level Measurement

Lake level measurements were taken to validate an extensive secondary dataset of lake levels (LaNaWRUA, 2016a). This ensured accurate calculations of lake bed topography could be made. Lake levels were measured between January to June 2016 using a Solinst Levelogger Edge [Model 3001-M5] and a Barologger Edge (Solinst, 2013). The Levelogger and Barologger were installed along the easily accessible southern bank of the lake, hanging inside a PVC pipe hammered into the lake bed to protect the instrument from damage and interference. The Levelogger is accurate to ± 0.003 m and records absolute pressure (water pressure + atmospheric pressure). The Barologger is accurate to ± 0.05 kPa and records fluctuating atmospheric pressure to provide accurate barometric compensation (Solinst, 2013). Data were collected on an hourly basis. Secondary lake level data were provided by the Lake Naivasha Water Resource Users Association (LaNaWRUA). This secondary dataset runs from the late 19th century to present day, with monthly lake levels, and also daily data since July 2003 (LaNaWRUA, 2016a). In this study the Levelogger data were used to verify the quality of the secondary long term LaNaWRUA data. This was achieved by analyzing both datasets with respect to lake level around the mean, reviewing any visual trends within these data and statistically testing the correlation, accuracy and bias of the secondary data (which assumes that the more accurate Levelogger data are truth).

Lake Area

Remote sensing techniques offer methods of low cost monitoring. Being able to freely compare historical lake level data and satellite imagery allowed an exploration of the potential of satellite imagery for long term monitoring. Freely available LandSat satellite imagery were acquired from two sources, Astro Digital (LandSat 8) for the period 10/05/2013 - 19/03/2016 (Astro Digital, 2016) and Earth Explorer for pre 2013 (LandSat 7) satellite imagery (USGS, 2016). The data were used to create a false colour image using bands 5-7-2 (5 – 0.85

- 0.88 μm; 7 – 2.11 - 2.29 μm; 2 – 0.45 - 0.51 μm), which enables the distinction between water, terrestrial vegetation and floating vegetation to be easily identified. From these false colour images it was possible to visually identify the lake boundary and therefore create polygons of the lake extent and area. LandSat spatial resolution is 30 m at nadir therefore an epsilon band (a band of width epsilon centred on the boundary) was calculated along the lake periphery (Blakemore, 1984). This band was 60 m wide and represents the positional uncertainty in where the true boundary lay between the lake and land.

Bathymetric Surveys

Bathymetric surveys constantly measure point depths along a trolled route to create a topographical map of the lake bed. Different surveys can then be compared spatially to calculate a change in lake bed levels.. This study used a sonar system purchased for the study, the cost-effective Deeper Fishfinder sonar (Deeper, 2016). This is a portable device that runs off an internal battery and measurements are logged via Bluetooth and a smartphone running the accompanying phone application. 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 navigation on the water. Data were collected for this study between January and February 2016. The device was clamped to the side of the boat to keep it at a set depth whilst moving. The system was continually monitored alongside the depth read out, to adjust for wind chop and wake which affected the surface of the lake potentially forcing the device to sit too low or too high in the water which can cause it to cease taking measurements. Expanses of hydrophytic species; *S. molesta, E. crassipes* and *C. papyrus* (Harper *et al.,* 1995; Mavuti and Harper, 2006; Onywere *et al.,* 2012) proved to be problematic and dictated regions where the sampling boat was able to progress resulting in a modified sampling grid whilst still ensuring good coverage of the study area (figure 4.2).

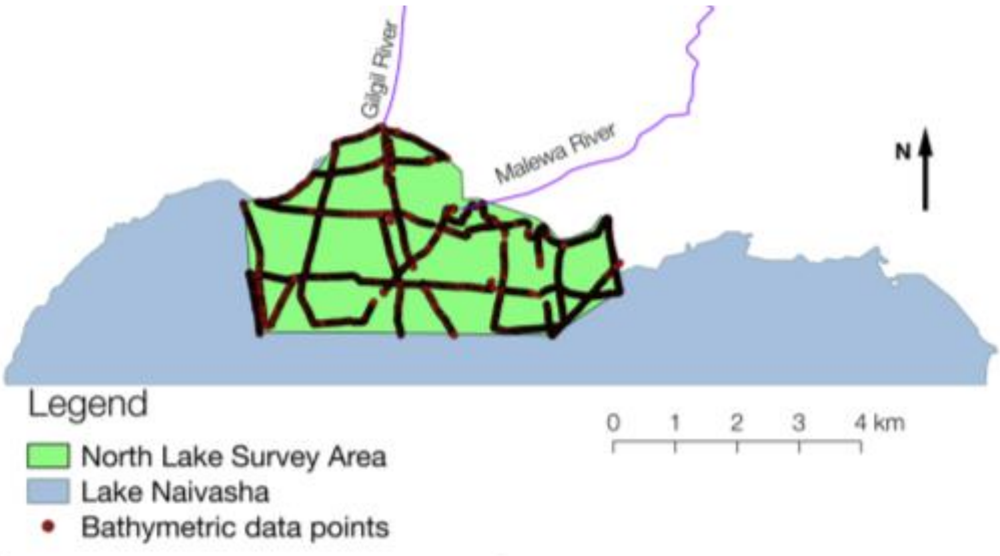

Figure 4.2 The northern third of Lake Naivasha with the North Lake Study Site highlighted. The depth points are marked however due to the frequency of data collection the individual points appear as survey routes within the North Lake Study Site.

The 2016 data collected for this study were then compared with data from 2001 collected by Rupasingha (2002), which were also collected using a sonar (Garmin Fishfinder 100), to calculate the change in lake bed levels. The method used with the Garmin Fishfinder 100 is identical to that of the Deeper Fishfinder. Both devices operate at a wide beam frequency (Deeper – 90kHz, Garmin – 50kHz) and a narrow beam frequency (Deeper – 290kHz, Garmin – 200kHz). The data collected by Rupasingha (2002) is available at *Naivasha Research* (2010). Both sets of Sonar bathymetric data were interpolated using the Triangular Irregular Network (TIN) method to create *n* 5×5 m (P) grid-based depth charts for the North Lake study site (*n*=2647690). Depth values (*d*) were subtracted from the average lake level (*l*) at the time of data collection to create comparable topographical maps of lake bed level (*b)* (masl) (l - d = b). These topographical maps of lake bed levels were subtracted from each other (2001 - 2016) so that a positive difference shows accumulation and a negative difference shows erosion. By using equation (1) an estimate of the volume of water (*v*) displaced (due to change in the topography) can then be calculated.

$$v = \sum_{i=0}^{n=2647690} (b_{2001} - b_{2016})P_i \qquad (1)$$

Results

Lake Levels

To verify the quality and accuracy of the LaNaWRUA secondary data, we evaluated the trends against the higher temporal resolution Levelogger data. During the period of Levelogger deployment changes of half a metre were recorded in lake levels as rainfall in the catchment decreased from February to May in 2016, reflecting the expected seasonality of the catchment that is driven by a hot and dry climate at the beginning of the year, followed by a longer period of rainfall replenishing the lake. Both datasets recorded a similar change in levels (Levelogger – 0.46 m, LaNaWRUA – 0.52 m). Assuming the recording instruments were calibrated to two differing ranges, both datasets were normalized about their mean to show lake level change in metres. The trends in the data were found to be in good agreement (P < 0.001, r^2 = 0.900, n = 160) (figure 4.3). The LaNaWRUA data have normalized mean squared error = 0.021, standard error = 0.014, n=160 with zero average bias (bias range=-0.03 – 0.07) when compared with the Levelogger data, indicating that the LaNaWRUA lake level data are suitable to use for studying the longer term variations in lake and lake bed level.

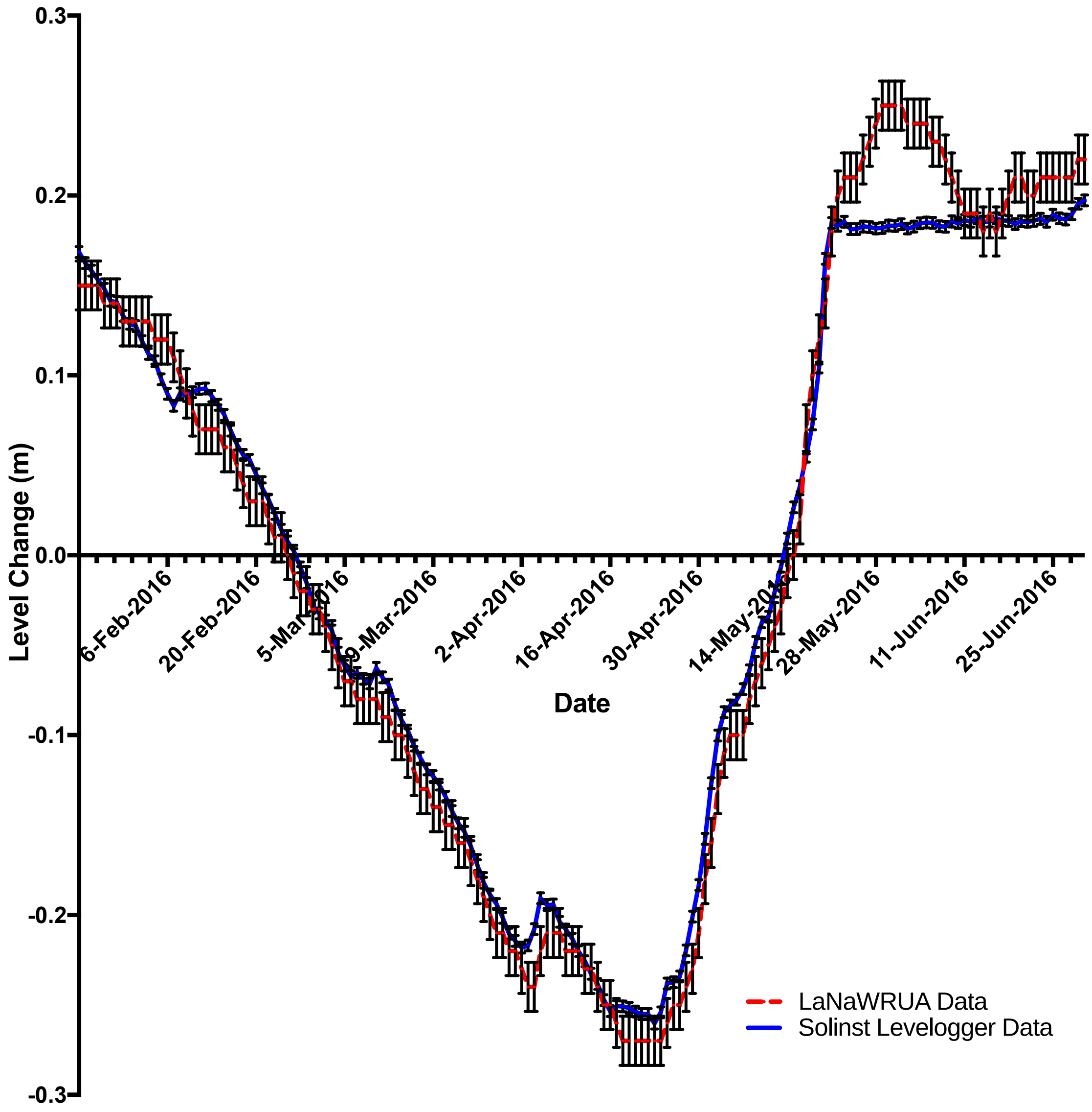

Figure 4.3 Changes in lake level as recorded by our Solinst Levelogger compared to the secondary data passed on to us from the LaNaWRUA. The agreement of trends demonstrates the suitability for the data to be used to study longer term fluctuations in lake level (P < 0.001, r^2 = 0.900, n = 160). LaNaWRUA data error bars represent standard error, Solinst Levelogger Data error bars represent instrument error.

Lake Area

The epsilon band of uncertainty in lake area was ~±1.5% and figure 4.4 shows that despite the LandSat resolution being approximately 1 pixel = 30 m (at nadir) this method of data collection shows acute monthly fluctuations greater than the error. As was to be expected when evaluating a basin lake, we found there was a strong positive correlation between the fluctuations in lake area calculated from our satellite polygon calculation and lake level for the period of May 2013 to March 2016 ($P < 0.001$, $r^2 = 0.979$, n = 29) (figure 4.5). With no data points falling significantly outside the trend we show that this method has not indicated any major deposition events which have altered the riparian topography within this period. It is important to note that the trend shown in 4.5 while valid for the period shown is not indicative of the relationship between level and area for all periods in time.

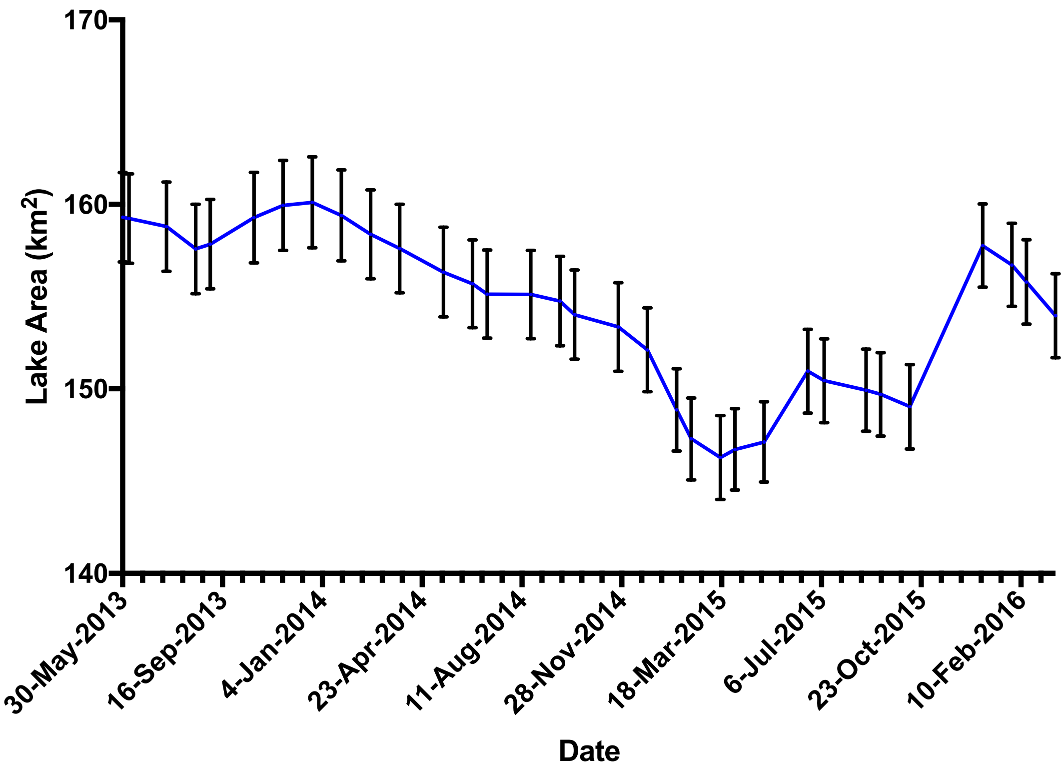

Figure 4.4 Monthly lake area fluctuations for the period May 2013 to March 2016 show that the lake shrunk significantly until mid 2015 before beginning to recover. The vertical error bars account for the uncertainty in knowing where the precise location of the lake boundary was due to the pixel size of satellite imagery.

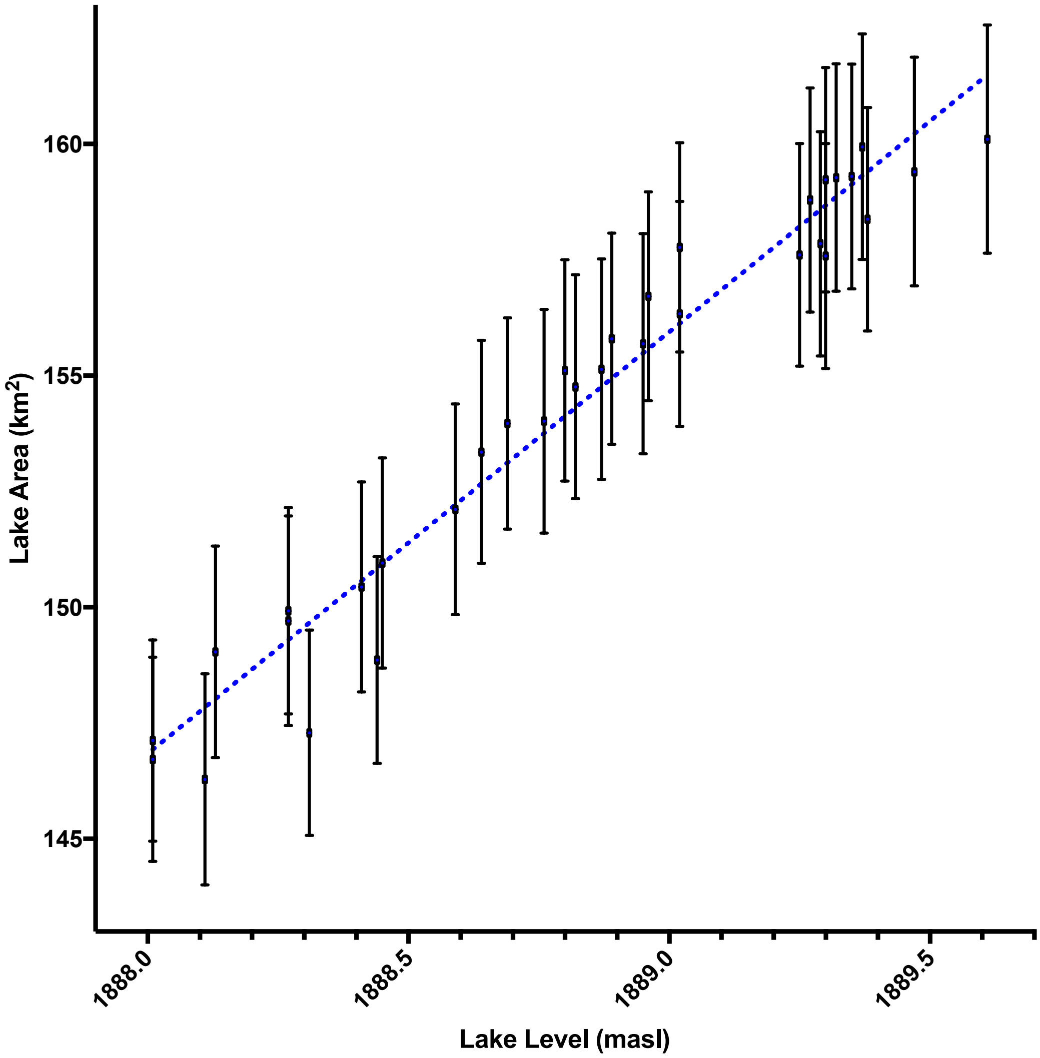

Figure 4.5 Correlation between Lake Level and Lake Area for the period May 2013 to March 2016. The trend line (dotted) falls within the calculated bars of uncertainty of the true lake area at every lake level, showing that an increase in lake level drives an increase in lake area. The vertical error bars account for the uncertainty in knowing where the precise location of the lake boundary was due to the pixel size of satellite imagery. The horizontal bars represent the standard error of the lake level dataset.

When the calculated polygon lake extents from 2013 – 2016 were overlain it was obvious that the region most affected by fluctuations in level in the entire lake was confined to the north. This portion of the lake is where the Malewa and Gilgil Rivers flow into the system and where the detailed bathymetric survey was focused (Figure 4.6).

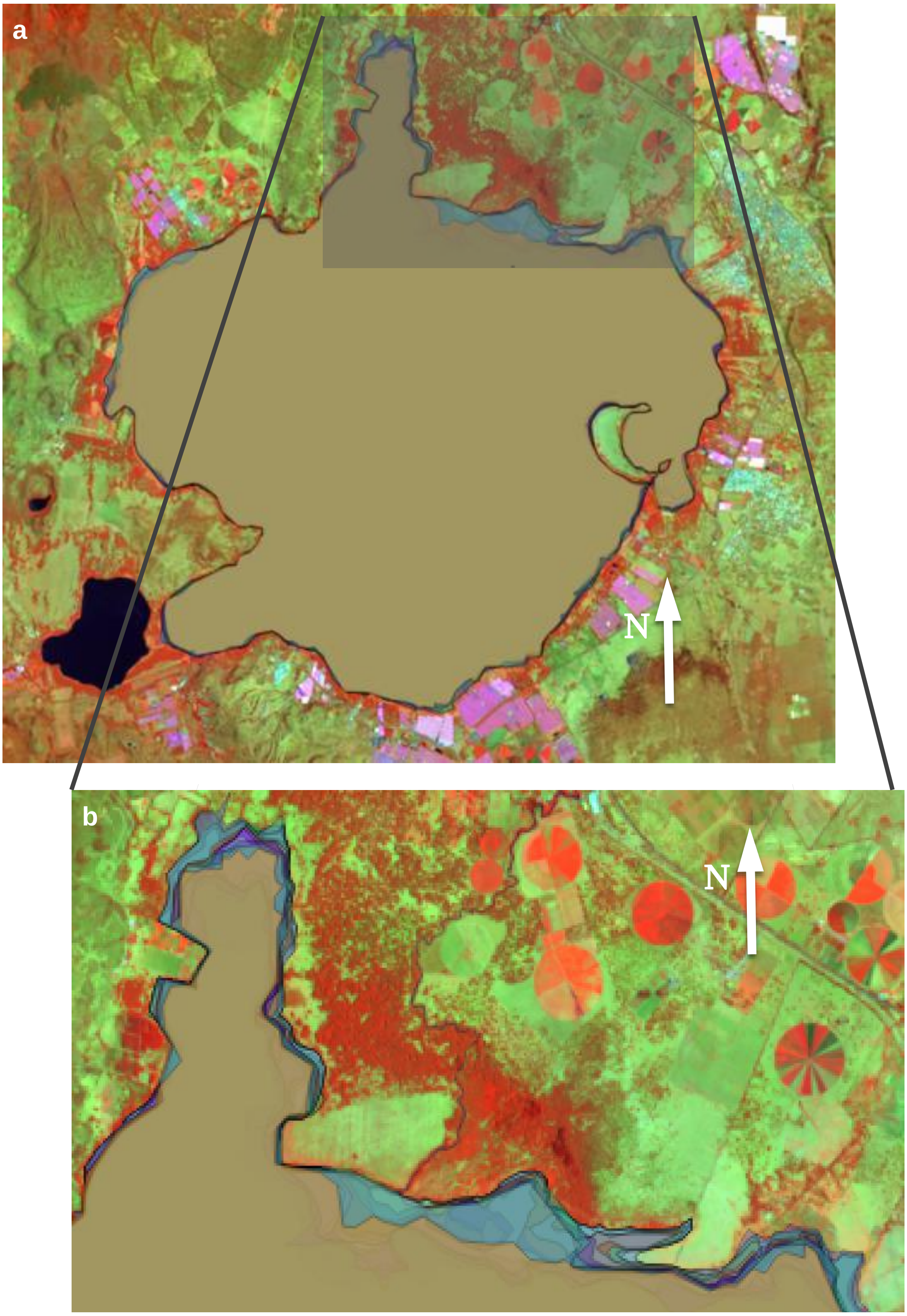

Figure 4.6 False colour satellite images from 19/03/2016 overlaid with 33 polygons (from monthly satellite passes) showing Lake Area from May 2013 to March 2016.These images incorporate floating vegetation to the lake boundary., **a** The areas of the lake which experience change in spatial extent

are highlighted for the entire lake. **b** Magnified North Lake region demonstrates the significant change in spatial extent of the lake. Expansive mats of vegetation restricted the survey boat from accessing the cove leading to the mouth of the Gil Gil River, hence the reduced survey area when compared to figure 4.2.

Bathymetric Surveys

The topographical maps of the lake bed, produced from the data collected by bathymetric surveys were subtracted to show the change in profile of the north lake bed between 2001 and 2016 (figure 4.7), where the high levels of fluctuation of the lake shoreline has also been demonstrated. There is a clear encroachment of sediment from the north east of the study site where the Malewa flows into the lake. From the bathymetric survey data collected in the north lake area clear alluvial fans could be visualised at the mouth of the Malewa River. Comparison of the average lake bed level data derived from Rupasingha (2002) and the data collected for this study showed a net positive change of bed height in the north lake over the past 15 years. This movement equates to an incremental increase of sediment at an average rate of 23 mm yr^{-1} across the north lake study site. Within the bounds of just the north lake study area (which makes up only 8.5 % of the total area) for which we have measured, we estimate that the overall volume of sediment deposited over the period between 2001 to 2016 has displaced 308139 m^3 of water per annum.

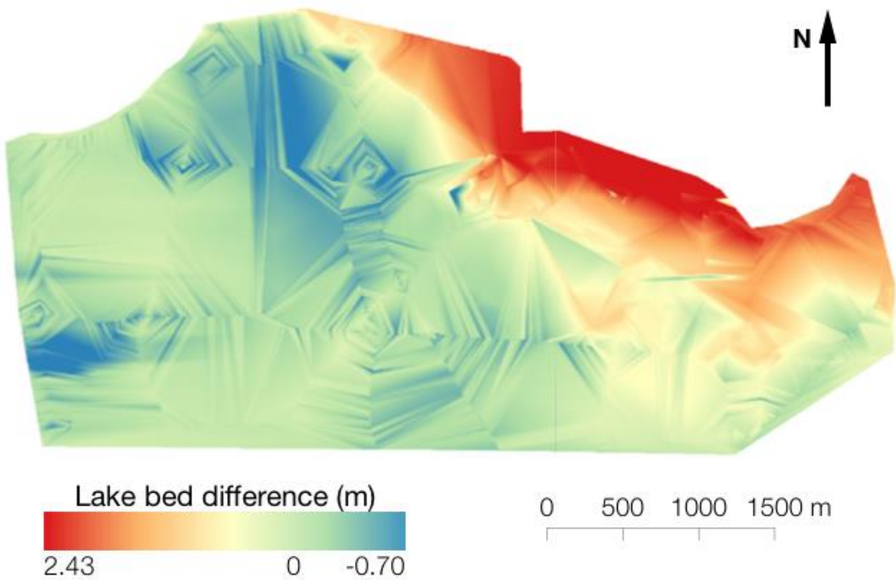

Figure 4.7 Topographical map of the North Lake Study Site showing clear evidence of positive (up to 2.43 m) and pockets of negative (less than 0.70 m) change in the height of the lake bed in metres over the 15 year period, 2001-2016. Indicating deposition is occurring at a rate of 23 mm yr^{-1} displacing 308139 m^3 of water.

Discussion

Comparing topographic maps of the lake bed we find there is a clear positive change in lake bed level, which we suggest is caused by sediment deposition. Previous estimates of sediment deposition by the Malewa are in the region of 7 million tonnes yr^{-1} (Rupasingha, 2002) but this has not been deemed significant enough to impact the Naivasha system. Our finding of sedimentation occurring at 23 mm yr^{-1} is in keeping with studies that used coring as their primary methodology which recorded between 10 and 30 mm yr^{-1} of deposition in different areas of the lake (Verschuren, 1996; Tarras-Wahlberg *et al.,* 2002). Our estimates also suggest that 23 mm yr^{-1} of sediment deposited in the north lake area have displaced 308139 m^3 yr^{-1} of water leading to expanding lake shores and predisposing this area to increased risk of drought if water influx decreases to 2009 levels. Our displacement estimates are equivalent to water for ~500 people at the WHO's current per capita estimations or ~1300 by the WHO's 2025 per capita estimations of 235 m^3 of water available per person (Kyambia and Mutua, 2015; WHO, 2006).

In 2009 the lake shrunk significantly, dry beds encroached deep into the North Lake study site and from our results we can infer an average depth across the site would have been less than 0.5 m (figure 4.8). All industry that relied on the lake was affected, including the artisanal fishermen who struggled to access the remaining fish stocks. 4.8 also shows how in the year following there is greater variation in lake levels as the basin recovered. Replenishment from a healthy upper catchment should be slow and gradual, stabilising the system. The high fluctuations in 4.8 with an overall increase in average lake level indicate that while the lake may have looked healthier the 'water tower' feeding it may not have been. If lake bed deposition continues, it is expected that the lake level (masl) would increase – assuming the volume remains constant. However, should input to the lake level drop in the future, displacement will ensure that lake level and area do not decrease as expected, the lake will for a short while appear to remain plentiful. Abstraction would likely continue and the subsequent effects on local water provisioning and agriculture would be considerable. A decreasing volume or a stable volume spread over a shallower wider area with increased evaporation, will cause an increase in the concentration of pollutants and eutrophy is likely to reduce the health of the system. For example, this may be the reason why significant increases in the levels of N and P have already been recorded (Otiang'a-Owiti and Oswe, 2010) which is thought to have led to further expansion of the invasive *E. crassipes* (Gaudiet and Falconer, 1982).

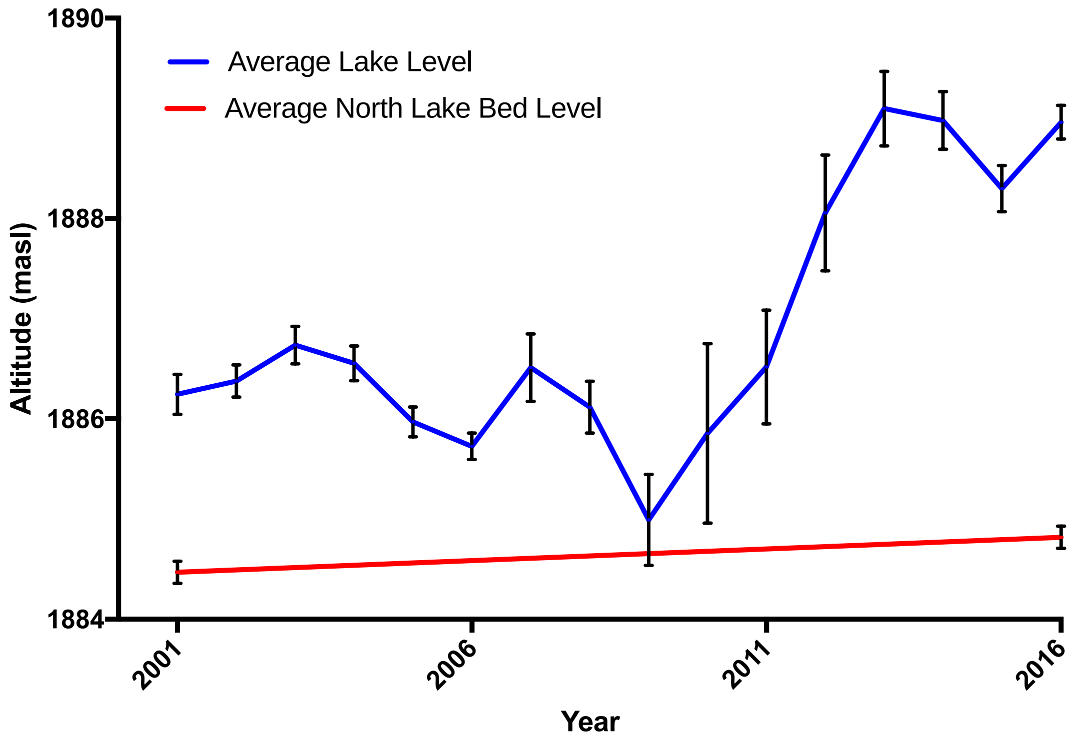

Figure 4.8 Average Lake Level plotted with average North Lake Bed Level change over 15 years. 2009 shows a period where much of the North Lake

Survey Area would have been under less than 0.5 m of water for large parts of the drier seasons. For both datasets, the error bars represent 1 standard deviation above and below the average.

The upper and middle catchment land use ranges from protected forest, moor and bamboo zones to subsistence farming, illegal deforestation practices and legal quarrying and livestock grazing (Naliaka, 2011; Nyingi *et al.,* 2013). The latter, anthropogenic land uses, increase erosion and therefore the amount of sediment carried in suspension down to Lake Naivasha. Throughout Kenya subsistent communities find it increasingly necessary to encroach onto protected land for herding and arable farming (Campbell *et al.,* 2000). This movement compounds the problem by removing further vegetation and increasing severe land cover change and erosion, usually in areas where improved land management techniques could actually allow agricultural expansion to be minimized whilst retaining yields (Onywere *et al.,* 2012). This is also a social issue due to generational land subdivision through inheritance (a father will split his land between his sons when he dies). Land packets then get smaller with every generation and less able to support herding, so farmers move to crop farming on small plots of land and require chemicals to boost yields and in turn affecting water quality downsteeam.

Illegal logging occurs extensively on the western and particularly southern slopes of the Abedares for timber and charcoal. 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). To reduce sediment and agrochemical load entering the lake, the Lake Naivasha Riparian Association (LNRA) has been informing the inhabitants of the upper catchment about good practice. However, whilst beneficial, low funding and support from the relevant government authorities reduced 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 Abedares 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). In finding increased sediment deposition around the mouth of the Malewa suggests that improved efforts to manage and monitor the levels of sediment entering the river would assist in improving the health and holding capacity of the lake downstream.

Whilst we appreciate that the LandSat imagery used for this study has a spatial resolution of approximately 1 pixel = 30 m (at nadir), the overall trend of the monthly fluctuations recorded over the past 3 years is still greater than our calculated ~±1.5% uncertainty for polygon creation. While our results identify the expected basin dynamics from the analysis of satellite imagery, the spatial resolution was still not high enough to identify any subtle changes in the relationship between lake area and level that could be driven by a deposition event. Other satellite platforms and sensors are available that can provide higher temporal and spatial resolution observations, but unfortunately they do not offer the historical record that LandSat can provide. Nonetheless, this relatively simple approach utilizing entirely open source data and software has great potential for the future monitoring of Lake Naivasha. The deployment of Sentinels 1A, 1B, 2A, 2B and 3A by the European Space Agency (ESA) have the potential to record lake area in Naivasha every 3-9 days and facilitate high spatial resolution long-term monitoring. As the programme under which they are operated (Copernicus) is funded for the next 15 years (ESA, 2016). Therefore, we suggest that future lake Navaisha management and abstraction plans and monitoring should include the use of high quality satellite remotely sensed data.

Should the lake level remain above 1881 masl, management plans and the traffic light system permit abstraction to continue at the current rate (LaNaWRUA, 2016b). Our data however demonstrates that this measure is an inaccurate record of the total amount of water in Lake Naivasha and thus, needs adjustment. In this case, a false sense of security is potentially highly damaging to the surrounding community of local people and businesses. Should sedimentation continue in this area at the rate of 23 mm yr^{-1}, and the lake volume continue fluctuating, the severity of the droughts will become greater and more regular, like 2009 (figure 4.7). Perceived lake volume by measure of an acceptable lake level will allow abstraction to continue when it should otherwise be restricted to preserve the lake's health.

Our findings imply that lake management plans should not focus solely on water extraction by the commercial growers around the shores of Lake Naivasha. It appears that water security over the next 10 years may well be determined by the management and practices upstream that are responsible for sediment deposition in the rivers that feed the lake. As soon as the health of the water towers deteriorate their capacity to hold and gradually release water decreases. Improved regulation and upstream land management practices of farming and deforestation are needed alongside improved regulation of extraction. As shown in this study, at lake level increased sediment loads have an impact on lake volume and quality however at a catchment level increasing loads are an indicator of the overall health of the system. With the climate changing and more extreme events expected regular remotely sensed bathymetric and satellite data could and should be used to aid and inform policy, to ensure the longevity of a healthy Naivasha. There have been assessments on upstream land-use and the results of these are informing initiatives that are being deployed in an attempt to minimize the effects of poor practice (Becht *et al.,* 2006b; Nyingi *et al.,* 2013). There is growing engagement between the LNGG and commercial businesses driven by an understanding that excessive abstraction is causing some damage to Lake Naivasha. In fact, it is more economically efficient to re-use water and modify farming practices than it is to extract, treat, and use water of poor quality (Ed Morrison pers comm., 2016). While it is likely that the economics are an important driving force behind this shift in practice, the potential for reduced environmental impact on the lake shores cannot be overlooked.

Conclusion

This study set out to explore in greater detail the dynamics of the surface and bed levels of Lake Naivasha. Using a combination of hydrological measurements and historical data we have quantified the change in the topography of the north lake bed of Lake Naivasha that has occurred over the last 15 years. We have also discussed how this net increase in average lake bed level is likely driven by the accumulation of sediment from the Aberdares catchment, brought in by the Malewa River. Our Levelogger recorded short-term changes in lake level of up to 0.52 m which is in agreement with the LaNaWRUA secondary data, this change is likely driven by seasonal rainfall patterns. Our findings show that positive changes in bed sediment levels may be distorting the truth about Lake Naivasha as a secure resource. This sediment displaces water and maintains lake levels and area despite the fact that water volume may be decreasing. While fluctuating lake-levels may be deemed healthy enough for water to be extracted, a decline in volume also affects a decline in freshness and an increase in concentration of pollutants.

Current management plans, for example the water allocation plan - which while informed by river flow, groundwater and predominantly lake level - could be improved to account for sediment deposition and some estimation of the variation in the lake bed. This would begin to enable abstraction limits to be set based on the volume of water in the upper and lower catchment stream flow and overall health of the basin. Here we have shown regular (satellite and sonar) remote sensing could be key to effectively improving the management of Lake Naivasha and doing so is likely to be vital to ensure the long-term existence of the resource and the population and industry it supports. The latter of which forms a vital part of the Kenyan economy through tourism and international exports.

5 Further discussion, limitations and future work

With water and food security becoming increasingly important, it is vital that wetlands and freshwater resources are protected and used efficiently and sustainably. This study has shown that there is a potential for sediment deposition to be disguising damaging reductions in the water volume of Lake Naivasha. A net increase in the height of the lake bed and the changing lake bed topography has been found and mapped in the North Lake by using affordable and portable remote sensing techniques. The method can be easily replicated in the future by local stakeholders to easily monitor the changing topography of the lake bed. Sediment samples collected whilst in the field will allow this study to be extended, to further identify key periods of increased deposition. By dating specific deposition events it may be possible to identify the causes of increased riverine loads and improve upper catchment evidence based land management techniques to enable the long term health of Lake Naivasha.

Upper catchment industry and land cover has been shown to be constantly changing with anthropogenic land use encroaching on protected forestry and 'wild' areas (Naliaka, 2011; Nyingi *et al.,* 2013). This shift in land use is driven by competition between wildlife and ever increasing human populations. Across Kenya people struggle to live sustainably off the land and alongside the flora and fauna that draws tourists from all over the world (Campbell *et al.,* 2000; Defersha and Melesse, 2012). In arid environments, land that is used for arable farming and grazing can very quickly suffer from desertification as nutrients and water are removed from the ground. This can create increased erosion and ultimately, after rainfall, the airborne dust and particles will become riverine suspended sediment being transported downstream. At the head of the Malewa, in the Abedares, shifting land use is not the only issue. Charcoal is needed to heat homes, burn rubbish and cook food. To fulfil the increasing demand for charcoal and timber, illegal loggers regularly trespass into the protected forested zones on the western and southern slopes to fell trees. Using aerial photography and other remote sensing techniques, conservation trust Rhino Ark have counted over 10,000 charcoal kilns in the region, and these kilns compound the problem of sediment entering the hydrological system (Nyingi *et al.,* 2013). The severe deforestation of the Mau forest (in the upper Mara River basin), subsequent settlement and ineffective water and soil conservation practices have caused high levels of erosion and water quality deterioration (Defersha and Melesse, 2012). This is very similar to the Malewa upper catchment. Studies have shown the northern area of the lake, where the rivers flow into Lake Naivasha, to have poorer water quality than the southern regions of the lake (Becht *et al.,* 2006b; Ndungu, 2014). Whilst carrying out field work for this study, observations made at the mouth of the Malewa River show the water quality to the north to be visually poor, muddy brown in colour and clearly laden with suspended sediment. To the north of the study site is a degraded 11.7 km^2 area of former swampland (Morrison and Harper, 2009). The Malewa River now flows through this area whereas it previously branched out into the swamp and under the mats of floating *C. papyrus* (Gaudet 1978; Gaudet 1979). There is the possibility that as the swamp and mats degrade, organic matter (peat) deposited to the bottom of the lake causing a build-up of detritus on the lake bed (Gaudet 1978; Morrison and Harper, 2009). A full investigation of the sediment cores taken while in the field could confirm how much this process plays a part in altering the lake bed topography. Regardless, the lake bed is still undergoing change and influencing lake levels, either from sediment transported from upstream or the organic sludge and sediment from the swamp.

As well as undertaking a comprehensive bathymetric survey of the North Lake seven sediment cores were taken at various points across the alluvial fan of the Malewa River to identify specific periods of significant deposition. Unfortunately, two of these cores were compromised in the field, the 5 remaining cores were left to settle for up to 5 days before being prepared for export (Frew, 2014). Due to unforeseen circumstances the samples were not able to be transported back to the UK for analysis, therefore this avenue of study remains unexplored. Studying and dating the collected sediment samples will build a more complete picture of deposition in the North Lake Survey Area. Cores allow a determination of both deposition rates and flow direction using isotope dating and gamma spectrometry is the preferred method for dating recently deposited sediment (Appleby, 2001). As well as dating the sediment cores, the samples could also be analysed using x-ray fluorescence (Peinado *et al.,* 2010). This technique measures the mineral composition of a sediment sample. By ascertaining the source of pollutants, evidence based management plans could then be created to reduce pollutants entering the water and improve the relatively poor water quality in the North Lake (Becht *et al.,* 2006b). Considering the large amount of paperwork needed to export lacustrine sediment from Kenya and the problems imposed by laboratory methods future studies should use a portable x-ray fluorescence (pXRF) machine which can provide in-situ analysis in the field quickly and accurately with little or no sample preparation (Peinado *et al.,* 2010; Sharma *et al.,* 2015).

Aside from the sediment sampling this study suffered from a number of other limitations. While the highly portable sonar worked well, the battery life reduced the capacity for data collection in the time available. A portable power bank was in the boat at all times which could charge the devices. However, valuable time on the water was lost waiting for a full charge. This could be solved by either planning to spend more time in the field with another task to do while the devices charged or simply by just taking a number of sonar devices that could be rotated to fill a 6 - 10 hour day on the water. Another obstacle that only became apparent during data collection were the floating mats of vegetation which move around the lake (figure 3.2). This again was an issue of time management, it would have been pragmatic to spend more time taking into consideration the prevailing wind and where mats were likely to be blown by assessing the North Lake Survey Area at speed before going back to troll with the sonar. These solutions would have ensured more regular survey routes and improved the quality of the data collected.

Differentiating between the detritus from the floating mats and that which is deposition of the load carried by the rivers from upstream can be achieved by analysing the sediment cores taken while in the field. Initial in situ colour observations were difficult to make, however there were definitive horizons in clast size and density. The loads of the Malewa and Gilgil are symptomatic of the health of the Aberdares' catchment with large loads indicating rapid streamflow and high levels of erosion. This is compounded by the land use and land division practices which increase erosion further. Increased streamflow means that the lower catchment is flashy and likely to recover quickly from dry periods but will be further susceptible to climatic events. Better management upstream aimed at reducing the land degradation and improving the health of the upper catchment would reduce the streamflow, erosion levels and stabilise the hydrological system making it more likely to survive future, potentially frequent due to climate change, climate events.

This study has highlighted the influence that upstream practices can have on the lake and the basin. While speaking to stakeholders around the lake who had an opinion and knowledge of what was occurring upstream was beneficial, personally travelling to the upper catchment would have produced more reliable data. It would have also given the opportunity to see whether there are differences of opinion between upstream and downstream stakeholders. Alongside this it would allow primary observations and measurements of changing land-use, erosion and flow to be collected. Demonstrating a relationship between stream flow, sediment loads and precipitation will be a good extension to this work and allow the focus to be shifted from ensuring the longevity of the lake to the health of the overall catchment.

With the data collected, this study found sediment aggregation to be occurring in the North Lake at 23 mm yr^{-1}, averaged over the last 15 years. This measurement is in keeping with studies that used coring as their primary methodology which recorded between 10 and 30 mm yr^{-1} of deposition in different areas of the lake (Verschuren, 1996; Tarras-Wahlberg *et al.,* 2002). This study's results were found used remote sensing methods alone which, due to the cost and portability of the equipment, lends itself to citizen science and more regular monitoring. By involving local fishermen, boat-owners and other stakeholders it may be possible to create continually updating topographical maps at little cost, building up a database of bathymetric change. Future studies will also be able to make use of the latest satellite technology; the ESA's Copernicus program is and will continue to launch Sentinel missions over the next few years which will mean eventually the revisit time will be reduced to only 3 days (ESA, 2016). By allowing more data to be collected at ever higher temporal and spatial resolutions it may also be possible to pick up subtle changes in the relationship between lake level and expected lake area which were not found using the methods in chapter 3.

As it is, current management plans rely on daily updates of lake level in masl, the towers surrounding the lake display the current water level and what level of abstraction is permitted according to your permit and quota (LaNaWRUA, 2016b). Despite the LaNaWRUA also incorporating river flow and ground water level as part of the WAP there is no incorporation of changing lake volume. While deposited riverine sediment rather than degrading flora sinking to the lake bed is more likely to be causing significant change to the lake bed topography, the lake bed is changing regardless. This is damaging as the monitoring and management that is carried out relies heavily on lake level recorded in masl to indicate decline or increase in lake health. This study has successfully used methods which, by recording changes in lake bed topography, can improve the monitoring of the volume of water and provide indicative data of the health of the upper catchment. Ensuring future evidence based management plans can help improve the long-term water quality and health of the ecosystem in the Lake Naivasha Basin.

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