UNIVERSITY OF NAIROBI

ASSESSING THE IMPACTS OF CLIMATE VARIABILITY AND CLIMATE CHANGE ON BIODIVERSITY IN LAKE NAKURU, KENYA

BY

MBOTE BETH WAMBUI
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DEPARTMENT OF METEOROLOGY
SCHOOL OF PHYSICAL SCIENCES

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Declaration

This dissertation is my original work and has not been presented for the award of a degree in the University of Nairobi or any other University

Signature………………………….. Date …………………………..

Mbote Beth Wambui
154/64201/2013
Department of Meteorology
University of Nairobi
P.O. Box 30197-00100
Nairobi, Kenya
Email: bethmbote@gmail.com

This work has been submitted with our approval as university supervisors

Signature………………………….. Date …………………………

Dr. Alfred Opere,
Department of Meteorology
University of Nairobi
P.O. Box 30197-00100
Nairobi, Kenya
Email: aopere@uonbi.ac.ke

Signature……………………………….. Date ……………………………

Dr. John M. Githaiga
School of Biological Sciences
University of Nairobi
P.O. Box 30197-00100
Nairobi, Kenya
Email: mainagithaiga@gmail.com

Signature…………………………………. Date ……………………….

Dr. Fredrick K. Karanja
Department of Meteorology
University of Nairobi
P.O. Box 30197-00100
Nairobi, Kenya
Email: fkaranja@uonbi.ac.ke

Dedication

This is dedicated to my lovely family, especially my mum, Rose Mbote, sister, Fiona Mbote and brother, Samuel Mbote.

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Abbreviations and Acronyms

CBD	Convention on Biological Biodiversity
CMIP5	Coupled Model Intercomparison Project Phase 5
GHGs	Green House Gases
IBA	Important Bird Areas
IBM – SPSS	International Business Machines - Statistical Package for Social Sciences
ICPAC	The Intergovernmental Authority on Development Climate Prediction and Applications Centre
IGAD	The Intergovernmental Authority on Development
ILEC	International Lake Environment Committee
ITCZ	Inter Tropical Convergence Zone
IUCN	The International Union for Conservation of Nature
KFS	Kenya Forest Service
KWS	Kenya Wildlife Service
LNNP	Lake Nakuru National Park
MEMR	Ministry of Environment and Mineral Resources
NCCRS	National Climate Change Response Strategy
NEMA	The National Environment Management Authority
NMK	National Museums of Kenya
RCPs	Representative Concentration Pathways
UNESCO	The United Nations Educational, Scientific and Cultural Organization
WMO	World Meteorological Organization

Abstract

Hydrological systems are potentially very sensitive to changes in climate. Recently, attention has been mainly drawn to the rising global temperatures; however, over the past century, human livelihoods have substantially been directly affected by changes in the regional hydrological balance. Lake Nakuru is one example of a hydrological system which has seen its water levels increasing since September 2010 during the beginning of the short rains making it the first lake in the Rift Valley bursting its banks, leading to decreased electrical conductivity levels as a result of water dilution. All flamingos left the lake, initially settling in the Lake Oloidien a small alkaline lake south of Lake Naivasha and Lake Bogoria. The increased water levels led to change in aquatic life and biodiversity, including submersion of habitats adjoining the lake and have therefore had major ecological implications on the lake and its environs.

This study, therefore, assesses the impacts of the increased water levels and the flooding of Lake Nakuru and its surrounding areas on biodiversity, specifically, the phytoplankton and lesser flamingo communities, owing to climate change and climate variability. The study focused on reviewing and analysing observed climatic records from 2000 to 2014, obtained from the Kenya Meteorological Department, especially temperature, precipitation and evaporation of Lake Nakuru in order to assess how climate variability and climate change has contributed to the increased lake levels, monitoring and reviewing information on the state of past and present records of the lesser flamingo and phytoplankton communities of Lake Nakuru was undertaken, with the data sets obtained from the Kenya Wildlife Service and National Museums of Kenya database. Several methods were employed in order to determine the past and current trends of climatic parameters (temperature, precipitation and evaporation), and also for the physicochemical characteristics of Lake Nakuru (conductivity, phytoplankton, lesser flamingos and the lake depth). These included time series analysis, trend analysis and the Pearson's correlation analysis was used to correlate the changes in lake conductivity to changes in population estimates of the lesser flamingos and the phytoplankton. Data set extracted from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (IPCC Fifth Assessment Report (AR5) Atlas subset) models were subjected to time series analysis method where the future climate scenarios of near surface temperature, precipitation and evaporation were plotted for the period 2017 to 2100 (projection) for RCP2.6 and RCP8.5 relative to the baseline period 1971 to

2000 in Lake Nakuru were analysed. The results were used to assess the impact of climate change on the lesser flamingos and phytoplankton abundance.

It was observed that there was an increase in the mean annual precipitation during the study period (2009 to 2014) which caused the increase in the lake's surface area from a low area of 31.8 km² in January 2010 to a high of 54.7 km² in Sept 2013, indicating an increase of 22.9 km² (71.92% surface area increase). Mean conductivity of the lake also decreased leading to the loss of phytoplankton on which flamingos feed causing them to migrate. A strong positive correlation between conductivity and the lesser flamingo population was observed implying that low conductivity affects the growth of phytoplankton and since the lesser flamingos depend on the phytoplankton for their feed, this subsequently demonstrated that the phytoplankton density could be a significant predictor of the lesser flamingo occurrence in Lake Nakuru. There was also a strong positive correlation observed between phytoplankton and the lesser flamingo population which confirms that feed availability is a key determining factor of the lesser flamingo distribution in the lake.

It is projected that there would be an increase in temperatures, precipitation and evaporation for the period 2017 to 2100 under RCP2.6 and RCP8.5 relative to the baseline period 1971 to 2000 obtained from the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model ensemble. As a result, it is expected that the lake will further increase in surface area and depth by the year 2100 due to increased precipitation thereby affecting the populations of the lesser flamingos and phytoplankton, as the physicochemical factors of the lake will change as well during the projected period.

Recommendations that can be taken to contribute to the country's biodiversity resources, specifically in Lake Nakuru through climate change mitigation and appropriate adaptations have been provided. They include: In order to assess the variability in climate, continuous monitoring and analysing meteorological parameters in the lake basin is suggested; government policy on illegal water abstractions and massive afforestation of indigenous trees need to be enforced in order to enhance precipitation regularity so as to sustainably utilize and manage Lake Nakuru's waters; Climate vulnerability assessments need to be carried out in order to come up with mitigations and adaptations measures unique to Lake Nakuru basin to inform the measures that

need to be taken in order to minimize the negative impacts of climate vulnerability/change, and exploit the beneficial ones.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background information

Africa has been recognized as one of the high risk regions in the world regarding climate change, according to the Fourth Assessment report from the Intergovernmental Panel on Climate Change (IPCC, 2007). As stated by the report, there are some areas in Africa which evidently are highly vulnerable to climate variability and change. Increased changes and variability of different climatic factors have been forecasted by Kenya’s current climate predictions. Severe challenges to sustainable development are being presented by climate change in Kenya, as it’s possibly a major environmental challenge of our time (Mutai *et al*., 2010). Addressing impacts of climate change on water resources, coastal zones, ecosystems, health, industrial activity, food and human settlements, offers opportunities for improved livelihoods, business and innovation.

Over time, changes in land use patterns and continuous droughts have caused a decline in the accessibility of water resources in Kenya. These resources will further decrease resulting from increased evaporation and precipitation variability due to increased temperatures as shown by climate scenarios. Global warming is believed to already cause the extreme declines in the glaciers and snow of Mount Kenya (Ministry of Environment and Mineral Resources, 2009). The next 15 years are projected to have these glaciers vanish and this will affect hydroelectric power production, agricultural activities, tourist activities and the availability of water for both urban and rural populations as flow systems of rivers influenced by melt water will be disrupted (Ministry of Environment and Mineral Resources, 2009).

Varying patterns of precipitation and rising temperatures have also worsened the problem of wetlands drying out, thereby threatening water availability leading to decreased agricultural production and thus increasing food insecurity due to decreasing yields in crop. Varying patterns of precipitation have posed threats to the renowned wildlife safaris in Kenya, and especially to one of the Seven Wonders of the World: The Mara River migration of wildebeests, which is common with tourists around the world (Climate Action Network, 2009). Intermittent patterns of rain affect the wildebeests as their migration is influenced by the smell of rain, since the pattern of migration is usually timed to correlate to the growth of grass and annual precipitation patterns in the North. Drawing closer to March, which is characterized by a season of short dryness, the wildebeests start migrating from Serengeti as the grass begins drying out towards the western Serengeti woodlands. By end of June when the long rains start declining in Kenya, the arrival of wildebeest from the Western Serengeti is observed in the Maasai Mara Game Reserve. Scarce feeding vegetation and the drying-up of rivers, owing to unpredictable climate, has caused huge losses in wildlife numbers (Climate Action Network, 2009).

The United Nations Convention on Biological Diversity defines biodiversity as “the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems” (CBD, 1992). The Intergovernmental Panel on Climate Change (IPCC) also emphasizes these three levels that is, genetic, species and ecosystem (IPCC, 2002).

There is an extensive variety of wildlife and ecosystems in Kenya, inhabiting in air, water and land. This biodiversity is vital to the prosperity of Kenya’s economy as sources of wood, shelter, fuel, employment, food, and foreign revenue, especially through tourism, agriculture and energy sectors. There is still a great possibility for further application of local biodiversity through industrial processes led by further research in bioprospecting. Different ecosystems and habitat types, changing climatic patterns and history which has evolved over time, are some of factors that can be attributed to Kenya’s rich biodiversity whose main concentration spots are under existing strict protected areas network (sanctuaries, national parks and reserves), which are mostly managed by the Kenya Forest Service (KFS), Kenya Wildlife Service (KWS), and individual or community land owners. Over seventy percent of Kenya’s biodiversity is conversely found outside the officially secured areas (Government of Kenya (GoK), National Environment Management Agency (NEMA), 2011). As such, conservation problems have been presented by substantial threats leading to the biodiversity status to quickly decline. Threats to biological diversity in Kenya are diverse and their spectrum encompass inadequate education and lack of community engagement, rising poverty levels, unsustainable land use practices, increase in population, conflicts, poor policies, laws, and institutional frameworks. Others arise from pollution caused by unsustainable land use practices, degradation of land and invasive species (Fourth Kenya CBD report, 2009).

Sixty one Important Bird Areas (IBAs) and five global hot spots of biodiversity importance are found in Kenya. These include: the coastal forests of Arabuko-Sokoke and the lower Tana River Basin; the Indian Ocean Islands of Lamu and Kisite; Kakamega's Guineo-Congolian equatorial forest; the Afro-montane forests of Mount Kenya, Aberdare and Mount Elgon; and the Northern dry lands that form part of the distinct Horn of Africa biodiversity region. These ecosystems collectively have a rich genetic pool and great numbers of species varieties, with some being vulnerable or threatened, seriously endangered, rare or endemic(NEMA, 2009a).

Biodiversity assets known in Kenya include 7,000 plant species, 315 mammals, 1,133 birds, 25,000 invertebrates (21,575 of which are insects), 191 reptiles, 692 marine and brackish fish, 180 freshwater fish, 88 amphibians and about 2,000 species of fungi and bacteria (NEMA, 2009a). Kenya boasts a large population of mammalian species' ranking it third in Africa, with fourteen of these species endemic to the country (IGAD, 2007). Large mammals such as the African elephant (*Loxodonta africana*), leopard (*Panthera pardus*), black rhino (*Diceros bicornis*), African lion (Panthera leo) and buffalo (*Syncerus cafer*) have made the country become popular due to their diverse nature (NEMA, 2009a). According to the IUCN Threat Criteria (2008), 146 plant species of the 7000 found in Kenya have been assessed with 103 being classified as threatened (vulnerable, endangered or seriously endangered) (Government of Kenya (GoK), National Environment Management Agency (NEMA), 2011).

Biodiversity provides opportunities such as: Employment, food, recreation, livelihoods and income, herbal and pharmaceutical products, education and knowledge, raw materials for industry, religious rites and transmission of cultural values, tourism and filming industry, research, and sustainability of gene pools and food chains. In spite of the good opportunities provided by biodiversity to mankind, in Kenya, threats to biodiversity have been on the increase over the past decades due to human-wildlife conflicts, habitat loss, population increase and infrastructure development, global climate change, pollution, biopiracy, poaching and overexploitation, invasive alien species and biosafety concerns (Government of Kenya (GoK), National Environment Management Agency (NEMA), 2011). In this regard, safeguarding these biodiversity will be critical to securing livelihoods resulting to reduced levels of poverty – reflecting a population of 46.6 percent – suggesting a nine percent change if the social equity scales are to be attained as projected by the Vision 2030's social pillar (Government of Kenya (GoK), National Environment Management Agency (NEMA), 2011).

Provided crucial coping, mitigation and adaptation approaches are realized, future climate variability and climate change impacts can be avoided, delayed or reduced. About US $500 million per year was needed in Kenya to address the climate change effects by 2012 (Stockholm Environment Institute, 2009). US $1-2 billion per year was the amount this figure was forecasted to increase to by 2030 (Stockholm Environment Institute, 2009). The collective effect of impacts of climate change will limit the realization of Vision 2030 targets, unless there is an urgent institutionalization of effective adaptation and mitigation mechanisms. As such, in order to tackle climate change, a range of policy instruments need to be formulated. A national policy on climate change need to be formulated and a climate change law further enacted, recognizing that the National Climate Change Response Strategy (NCCRS) was finalized in 2010. The country will not only be economically affected by the impacts of climate change but also its biodiversity heritage.

1.2 Scope of the research

The study aimed to assess the impacts of the increased water levels and the flooding of Lake Nakuru and its surrounding areas on biodiversity, specifically, the phytoplankton and lesser flamingo communities, owing to climate variability and climate change. The study therefore focused on reviewing and analysing the past and present climatic records, especially temperature, precipitation and evaporation of Lake Nakuru in order to assess how climate variability and climate change has contributed to the increased lake levels, monitoring and reviewing information on the state of past and present records of the lesser flamingo and phytoplankton communities of Lake Nakuru. Data set extracted from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (IPCC, 2014, Fifth Assessment Report (AR5) Atlas subset) models were subjected to time series analysis method where the future climate scenarios of near surface temperature, precipitation and evaporation were plotted for the period 2017 to 2100 (projection) for RCP2.6 and RCP8.5 relative to the baseline period 1971 to 2000 in Lake Nakuru were analysed while the results were used to determine the impact of climate change on the lesser flamingos population and phytoplankton abundance. Recommendations that can be taken to contribute to the country's biodiversity resources, specifically in Lake Nakuru through climate change mitigation and appropriate adaptations have been provided.

1.3 Statement of the problem

Lake Nakuru water levels increased since the beginning of short rains of September 2010 which led to the bursting of its bank, making it the first Rift valley lake to do so. The surface area of the lake increased from a low of 31.8 Km^2 in January 2010 to a high of 54.7 km^2 in Sept 2013, an increase of 22.9 km^2 (71.92% increase in surface area) (Onywere *et al.*, 2013). The increased water levels were as a result of increased recharge from Njoro, Makalia, Larmudiak, and Enderit Rivers which led to the lake water being diluted thus decreasing its electrical conductivity levels. All the lesser flamingos left the lake, initially settling in the Lake Oloidien a small alkaline lake south of Lake Naivasha and Lake Bogoria. This led to change in aquatic life and biodiversity, including destruction of habitats and has therefore had major ecological implications on the lake and its environs. The increase in the surface area and depth of the lake has been attributed to the seasonal changes in precipitation due to climate variability.

Challenges facing the lake and its catchment include: Destruction of catchment areas, pollution - both liquid and solid wastes, excessive water abstraction in the catchment, siltation, climate change impacts, invasive plant species (*Solanum incanum, Lantana camara, Tarchonanthus camphoratus, Datura stramenium, Opuntia spp*. etc), urban expansion and poor urban planning and lack of wildlife dispersal areas.

As such, this research project sought to assess the impacts of the increased water levels and the flooding of Lake Nakuru and its surrounding areas on biodiversity, due to climate variability. While climate variability and climate change have both been examined in this study, climate variability describes the way climate fluctuates yearly above or below a long term average value, usually, for a short term period such as a month, a season or a year whereas climate change refers to the long term continuous change to average weather conditions typically over decades or longer.

Plate 1: Loss of Acacia trees and other vegetation due to submergence from the rising level of the lake

1.4 Justification of the study

One of the most exciting wildlife concentrations in the county is found in Lake Nakuru National Park. Covering an area of 188 square kilometres, the park boasts rich habitats, which represents eleven major ecological habitats, each with its distinctive flora and fauna, varying from mud flats, salt marshes, the lake, open and wooded, bush, dense forest and cliff habitats.

Water-related birds and waterfowl of over seventy species are supported by the lake and its littoral area. It is Africa's first bird sanctuary, a World Heritage Site designated by UNESCO and Kenya's first Ramsar site. Through curio sales, food, tourism development, hotel accommodation and other entrepreneurial activities, a contribution to the socio-economic development of Nakuru town and its neighbourhood is made by the park. In addition, it generates revenue for the country. A study to assess the impacts of climate variability on Lake Nakuru's biodiversity and especially the lesser flamingos and phytoplankton communities is thus necessary.

1.5 Objectives of the research

The main objective of the research was to assess the impacts of climate variability and climate change on Lake Nakuru's biodiversity.

1.5.1 Specific objectives

The specific objectives were to:

1. Estimate the trends of past and present climatic records, and especially the temperature, precipitation and evaporation, of Lake Nakuru basin in order to understand the causes of increased lake levels.
2. Correlate changes in lake conductivity to changes in population estimates of aquatic species especially the phytoplankton and the lesser flamingos of Lake Nakuru basin
3. Assess in light of future climate projections, especially temperature, precipitation, and evaporation, the likely impacts of climate change on Kenya's biodiversity especially the lesser flamingos and phytoplankton in Lake Nakuru basin.

1.6 Research questions

1. How has the climate of Lake Nakuru basin varied in the past years?
2. How have the changes in the lake's conductivity affected phytoplankton species population and the lesser flamingos of Lake Nakuru basin?
3. What are the likely impacts of climate change, especially the temperature, precipitation, and evaporation, in light of future climate projections on Kenya's biodiversity particularly the lesser flamingo and phytoplankton in Lake Nakuru basin?

1.7 Area of Study

1.7.1 Location and characteristics

The study site was Lake Nakuru. It was chosen because it is one of the most important habitats for the flamingo species and also one of the important tourist destinations in Kenya.

Lake Nakuru National Park is located between 0°19'- 0°24' S and 36°04'-36°07 E, approximately 3km South of Nakuru town, Kenya. It lies in a graben between Lion Hill fracture zone in the east and a series of east downthrown step-fault scarps leading to the Mau Escarpment to the west.

Lake Nakuru extends in the N-S direction in the trend of the axial rift faults as shown by Figure 1. It includes other chains of alkaline-saline lakes in the eastern arm of the Rift Valley, Kenya. Existing more than twelve million years, one of the earth's spectacular geological formations was formed by the catchment and its landforms which included rifts, cliffs, mountains, volcanoes and lakes (Odada *et al*., 2006). Progressions of characteristics and features that describe Lake Nakuru have been influenced by climate, evolutionary history and Geography. Levels of productivity and successful establishment of species have been determined by these features which set in motion the chemistry of the lakes' water. The ecosystem of the lake is made unique by the chemistry of the alkaline water which depends on the larger catchment for sustenance and independent of its immediate environment for it functions. White salt filets swirling with dust devils are sometimes created when there are enormous water body reductions resulting from changes in the surface area of the lake.

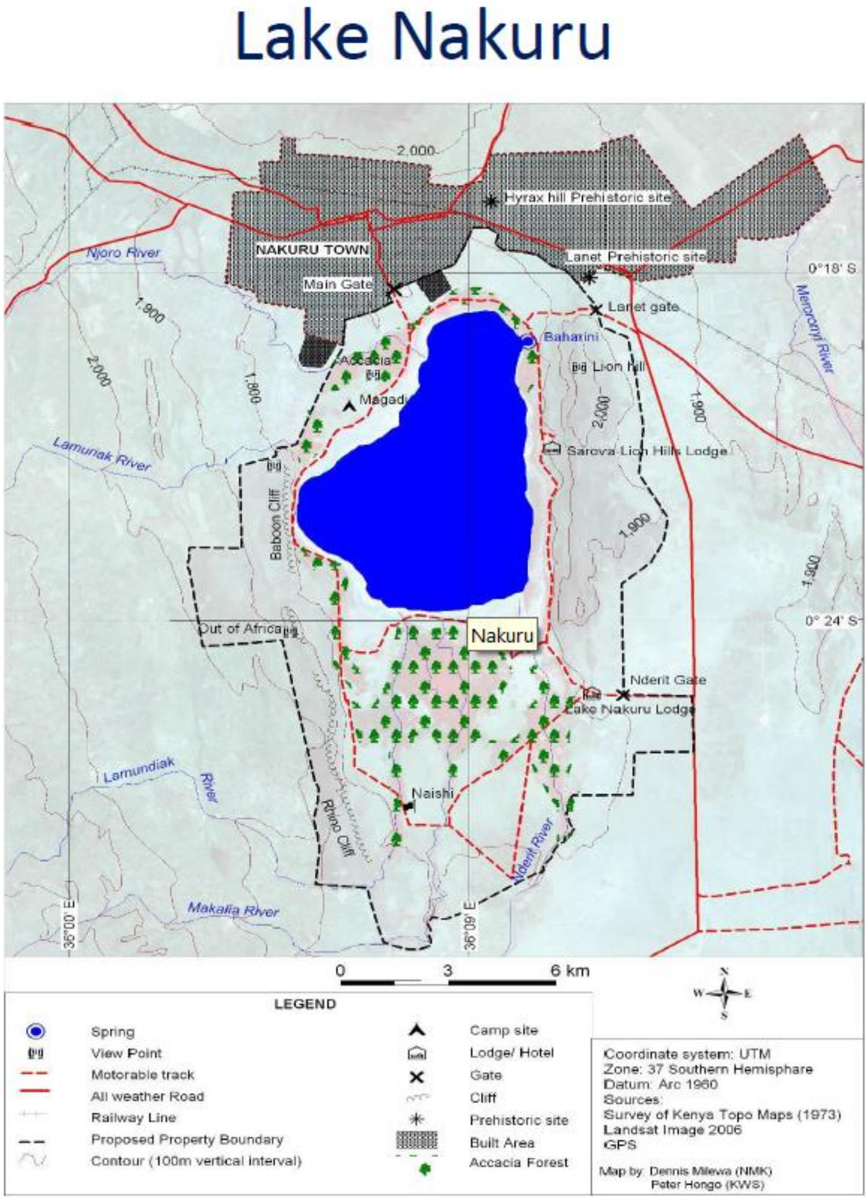

Figure 1*:* Map of Lake Nakuru showing detailed geographic features

1.7.2 Biophysical Features

Lake Nakuru lies at a longitude of 0°19'- 0°24' S and latitude of 36°04'-36°07 E. Lying at an elevation of 1,759 metres above sea level, the lake has an estimated surface area of 44 square kilometres (Odada *et al*., 2006). The lake is shallow with a bottom that is almost flat, gentle slopes and a regular-shaped basin. The lake has an estimated water volume of 92 x 106 cubic metres, a maximum depth of 4.5 metres and an average depth of 2.5 metres. Lake Nakuru is recharged mainly through direct precipitation. Surface run-off through Makalia, Larmudiac, Njoro, which drain the Mau escarpment, and Enderit Rivers arising from the Eburu Hills also contribute to the recharge. In some exceptional conditions of precipitation, the rivers reach the lake through surface runoff. Drainages from Bahati, Eburru, and the other areas of the Mau escarpment, only carry run-off when precipitation is prolonged, but do not reach the lake through surface recharge. These drainages are short and quickly taper off as they approach Naishi, Bahati and Kiwi plains along the Rift Valley axis.

The Rift Valley over the years has had volcanic and tectonic activities which also include climatic changes which have caused the lake to evolve over time. In the past, approximately 1000 years, Lakes Naivasha, Nakuru and Elementeita made one fresh water lake of about 700km^2 and 180m deep which later dried up due to drought causing separation of the three lakes (Odada *et al*., 2006). Stress extremes are occasionally experienced by the shallow, Polymictic Lake (ILEC, 1995).

Lake Nakuru is characterized by a catchment of about 1800 km^2 drainage which is a closed system, where to the West, lies the Mau Escarpment (3000m a.s.l.), Eburru Hills lies to the South, Menengai Crater lies to the North (8060m-2040m a.s.l), the gentle grasslands between Lake Elementeita and Lake Nakuru basins lie to the East and to the North East lies the Bahati Highlands. Lake Nakuru National Park rests itself at the depression of this catchment basin that acts as a buffer area between the lake and human activities. Influenced by a faulting chain, the lake's geology and its catchment is largely comprised of rocks which are volcanic in nature (pyroclastics and flows of lava) found during the Tertiary-Quaternary era. Volcanic soil found here is characterized by a structure which is loose, highly permeable and porous exposing it to sinking land, agents of erosion and fractures, after or during intense rains (Odada *et al*., 2006).

1.7.2.1 Biodiversity

The lake's catchment basin is comprised of two major biological resources areas which include the LNPP and the forests extending the upper catchment. Human areas of habitation, with little biodiversity, are interposed between the two biodiversity ones (LNPP and the forests). These areas depend either directly or indirectly on the high biodiversity zones for ecological services.

The high biodiversity areas' ecological stability has equally been influenced directly and indirectly by the human habitation areas.

A very rich concentration of wildlife is found in Lake Nakuru National Park which comprises of two hundred plant species, four hundred bird species and seventy mammal species. Forming the heart of the park, Lake Nakuru has an international recognition for the large numbers of lesser flamingos that that use it as an irregular breeding, display and feeding ground. Cyanobacterium, *Arthrospira fusiformis*, the major primary producer within the lake, not only makes the preferred diet of the lesser flamingo but also has unique bio-molecules which are in high content. Yearly, a manifestation of numerous species of Palearctic waders is observed, enhancing the local population of birds in the park, since the lake acts as their staging ground in their winter migration down the Rift Valley fly way.

1.7.2.2 Economics

At fairly low costs of management, and thereby creating significant income for the government, Lake Nakuru National Park ranks second as the most regularly visited park in Kenya. Due to its popularity with international and domestic tourists, who yearly reflect a number of 200,000 earns around over US$ 4.5 million annually, from gate collections alone (Odada *et al*., 2006). Through curio sales, food, tourism development, hotel accommodation and other entrepreneurial activities, a contribution to the socio-economic development of Nakuru town and its neighbourhood is made by the park, which additionally generates revenue for the country.

1.7.3 Climate

Contingent on the topography and altitude, climate in Lake Nakuru's basin varies significantly from arid and semi-arid to humid and cold that is characteristically of the Rift Valley floor. The mean annual precipitation, affected by the Inter Tropical Convergence Zone (ITCZ), is positioned at 750mm with the peaks months being between April and May and, November and December. Mean annual evaporation is 1800mm. From the catchment's crest, located in the lake shadow and close to Lake Nakuru, an overall reduction in precipitation is observed using Isohyetal examinations. Conventional precipitation falling in the afternoons is characterized by erosive, strong storms lasting between ten minutes to one hour. A range of 6,000 and 10,000 Joules/sq./yr is the variability of the rainstorms' erosivity (Odada *et al*., 2006), making it among the highest energy ranges in Kenya. The catchment's north-western part is rampant with gully erosion, including the newly opened forest zones seriously experiencing erosion. Annually, more than 80,000 tons of total soil is lost from the whole catchment, reflecting an annual 17 tons for each hectare (Odada *et al*., 2006).

1.7.4 Hydrology

Beside the rivers' upstream parts for factory, domestic and irrigation use, water abstraction has been on the increase. Streams in the catchment have over 350 unregulated and registered water intakes. Alteration of an area's hydrological regime is caused by exertion of pressure collectively and individually from urbanization, deforestation and cultivation. Biodiversity supported by forests, is presented with serious consequences resulting from deforestation, while major and collective impacts are reflected on the hydrology of the catchment. There has been drying up of springs that have supported humans over past three decades since their arrival in the area. Major reduction in the steady yields of boreholes and wells, more destructive and increased peak discharges of rivers and other water courses, higher rates of run-off and marked seasonality in stream flow, demonstrate some of the hydrological impacts. The ability of the catchment to hold and harvest rainwater seems to be on the decline due to the increased rate in abstraction and growing water demand (Odada *et al*., 2006).

CHAPTER TWO

2.0 LITERATURE REVIEW

This chapter reviews the literature relevant to this study.

2.1 Impacts of climate change and climate variability on the hydrological systems

Climate change causes variations in evaporation, precipitation and runoff which in turn affect the water variability and availability globally. Considerable changes in global climatic patterns are resulting from growing levels of atmospheric greenhouse gases (GHGs), causing global warming (IPCC, 2007; Xu *et al*., 2011). Communities whose livelihoods are heavily dependent on agriculture, forestry and water resources are harshly influenced by climate change impacts as these sectors are climate-sensitive (Xu *et al*., 2013). Shifts in the availability of water resources are expected to be among the most significant consequences of projected climate changes (IPCC, 2007; Kingston & Taylor, 2010). Perturbations to the hydrological system will have implications on runoff volume and timing, ecosystem dynamics, social and economic systems. The intensity of the impacts at local level and the vulnerability of communities and ecosystems to these impacts are highly contingent on the particular characteristics of the area, as well as the magnitude and spatial distribution of the changes that will be experienced (Hagg *et al*., 2007; Matondo *et al*., 2004).

Major challenges for water resource planning and management are posed by possible hydrological climate change impacts, considering the crucial role of water resources in socio-economic development. With regular additive effects, all components of the water cycle are nearly affected by human and natural activities. Anthropogenic activities including agriculture, afforestation and deforestation have disrupting influences on the water cycle over time, which also affects flow regimes, sea level, evapotranspiration, and groundwater table. Cloud formation is also being influenced by human activities through aerosol emissions and their gaseous compounds. Atmospheric levels of greenhouse gases are being increased by human activities leading to the warming of the atmosphere, whereas in certain regions aerosols concentrations are also increased, tending to cool the atmosphere. Collectively, the increases in the levels of aerosols and greenhouse gases are estimated to amount to global and regional variations in climate-related and climate factors including precipitation, temperature and sea level (IPCC, 1995). While agriculture mainly causes global increased concentrations of nitrous oxide and methane, changes in land and fossil fuel use largely result to increasing global carbon dioxide levels (IPPC, 2007). The timing and magnitude of groundwater recharge and surface run-off is influenced by varying precipitation, which also affects the intensity and frequency of droughts and floods. Variations in temperature cause effects on infiltration conditions, evapotranspiration and soil moisture successively leading to variabilities in vegetation, surface wetness and reflectivity influencing formation of clouds and evaporation, including precipitation and the surface net radiation (IPCC, 1995). Potentially, hydrological systems are very sensitive to climate changes, which are demonstrated in varying key hydro-climatic elements of the hydrological cycle and vice-versa (IPCC, 1995). Recently, attention has been drawn mainly to the rising global temperatures; however, over the past century, a more direct and substantial effect on the livelihoods of humans has been impacted by fluctuations in the regional hydrological balance.

The arid and semi-arid lands are environments mostly affected by the variability of weather elements as they already have limited water resources. Possible climate change effects on the hydrological systems have raised questions which are currently been debated upon. Most parts of the Rift Valley in Kenya, where most lake are located, experience an arid and semi-arid climate. Apart from Lake Naivasha and Lake Baringo which are fresh water lakes, most of the lakes located in the Rift valley are tectonic in origin; they are long, deep, narrow, salty and deep.

In Lake Nakuru and its ecosystem, climate variability and climate change has caused both direct and indirect impacts. Conductivity, fluctuation of lake levels, and aquatic life disturbance are some of the direct impacts of extreme climate events (droughts and floods). Striking changes related to climatic variations have been documented in intensive limnological studies of Kenya’s soda lakes conducted in the 1970s (Melack, 1996). Strong diel cycles of mixing and stratification have been as a result of the daily changes in cooling and heating (Melack & Kilham, 1974). A considerate number of phytoplankton is usually supported by adequate supply of nutrients and high insolation (Vareschi, 1982). During the day, high rates of photosynthesis causes the upper waters to super saturated dissolved oxygen (Melack & Kilham, 1974; Vareschi, 1982). According to Melack (1988), phytoplankton cannot tolerate a changing conductivity rate greater than 5 mmho's cm-1 per month and a conductivity beyond 25 mmho's cm as this will result to the lake changing the composition of its biota.

A period that displayed rapid increases in salinity (6 mmhos cm-1per 40days) and reduced precipitation was documented in Lake Nakuru by intensive limnological studies on soda lakes of Kenya, showed a drop in the abundance of phytoplankton (Melack, 1988; Vareschi & Vareschi, 1984). Moreover, the dominant species *Spirulina platensis* (revised to *Athrospira fusiformis*) was replaced by much smaller phytoplankton like *A. arnoldii* and picoplanktonic cyanobacteria. In response to this, the abundance of lesser flamingos decreased markedly (Vareschi, 1982).

2.2 Impacts of climate variability and climate change on biodiversity

Impacts of climate change on biodiversity include: migratory timings and routes of species that use both track seasonal changes in vegetation and seasonal wetlands being altered by changes in climate. Consequently, this has heightened conflicts involving mammals such as elephants and human beings in areas with decreased precipitation levels (Thirgood *et al*., 2004); varying climatic conditions causes increased adaptivity of exotic species other species with high reproductive and dispersion abilities (Malcolm *et al*., 2002); alteration of the composition and structure of biological resources as species make an effort to familiarize to varying conditions (Lovett *et al*., 2005); populations' genetic structure change could be resulted from changed related breeding rates caused by changes in the duration or intensity of the rainy versus dry seasons (Poole, 1989; Rubenstein, 1992); The biome sensitivity assessments in Africa suggest that small decreases in precipitation during the growing season effects changes to the semi-deciduous and deciduous closed-canopy forests. This demonstrates that grasslands or savannahs are less sensitive to changing precipitation than deciduous forests (Hély *et al*., 2006); Responding to the changing climate, species ranges will not shift in intact and cohesive units and will also become more fragmented as they shift (Channel & Lomolino, 2000); Regional changes in climate will cause huge variations in ecosystem function and composition resulting to spill over impacts on the biodiversity of species (Sykes & Prentice, 1996; Solomon & Kirilenko, 1997; Kirilenko & Solomon, 1998). During already dry month, the resilience of plants will be reduced due to less precipitation experienced as suggested by climate projections (Vanacker *et al*., 2005). A new and growing threat is being presented by changing climate in the savannahs of East Africa, sub-Saharan Africa. Modification in growth of vegetation will cause a corresponding impact on food availability for migrating animals, which will be as a result of an occurrence of increased severity and frequency of floods and droughts (IPCC, 2012). More than 85% of wildebeest population crashed in 2009, caused by a severe drought in the ecosystem of Amboseli. Before the drought, there were over 15,000 animals which afterwards reduced to 3,000 animals in 2010, making it the lowest observed population number in over 30 years (MEMR, 2012; Ogutu *et al.*, 2012). Many ecosystems, especially sub-Saharan Africa, also comprising East Africa parts, are demonstrated to be impacted by variability in climate, resulting from short-term water availability (Vanacker *et al*., 2005).

2.3 Effects of lake levels on the lesser flamingo and phytoplankton communities in Lake Nakuru

Globally, Lake Nakuru is believed to be one of the most productive ecosystems (Warren, 2011) caused by the rich populations of halotolerant cyanobacteria, especially *Arthrospira sp,* which regularly blooms reaching its peak growth in the waters yet at other times its productivity crashes. The significant source of food for the large flocks of the Lesser Flamingos, *Phoenicanaias minor* Geoffroy, that inhabit Lake Nakuru is *Arthrospira fusiformis.* About 72 g dry weights (DW) of cyanobacteria are estimated to be consumed per day mostly, by an adult Lesser Flamingo in shallow lake areas (Vareschi, 1978; Owino *et al*., 2001). Lesser Flamingos constitute the biggest part of the lake's bird population that are a world-famous tourist attraction contributing greatly to the much needed revenue to the countries that are home to the soda lakes. However, great numbers of *Arthrospira* operate best at preferred optimum temperatures and conductivity. As such, populations tend to irregularly collapse unpredictably in Lake Nakuru, leading to highly-stressed malnourished flocks of lesser flamingos subject to mass deaths (Vareschi, 1978; Kreinitz & Kotut, 2010).

Due to its saline nature, Lake Nakuru is highly prone to changes in water levels and even dries up completely from time to time displaying its ability to rapidly and considerably respond to even small climatic changes (Williams, 1981; Padisák, 1998). This is because small changes in evaporation, rainfall and temperature will result to large changes to its natural salty character. Time to time variation of Lake Nakuru water levels is largely dependent on the vagaries of annual rainfall inflow/runoff. Lake Nakuru mostly dried up in 1962, resulting to only a few tens of centimetres remaining, thereby increasing the conductivity levels of the lake. This was recently observed in 2008. In 1972 to 1974, Lake Nakuru had an abrupt biomass change related to increased lake conductivity levels as a result of low lake levels. This abrupt change affected the species of birds at the lake resulting to the lesser flamingos' emigration in hundreds of thousands (Tuite, 2000). Low populations of lesser flamingos' were once again observed in 1993, 1995 1998, 2006 and 2012, and the remaining populations were stressed and exposed to mass deaths. The lesser flamingos' die-offs of 1993 started in August and resolved by mid-November of the same year with arrival of the rains (Kock *et al*., 1999; Motelin *et al*., 2000). Occurrence of deaths took place during a drought period when ambient temperatures were high and the lake levels were low, and a similar episode occurred in 1995. Unlike 1974, the declining lesser flamingo population in 1998 was related to the increasing lake levels resulting to the reduction in *Arthrospira* biomass, due to decreased conductivity levels. This phenomenon was observed after the *El Niño* rains.

By 2000, previous low conductivity levels had increased, occasioning the return of huge numbers of feeding lesser flamingos, as a result of a suitable environment for another extensive *Arthrospira* bloom being created, an occurrence which continued until 2006. In Lake Nakuru, the most dramatic deaths of the lesser flamingos in the last two decades were when 30,000 died in August 2006 coinciding with the low lake levels. The lake levels then increased at the beginning of the short rains in September 2010, which led to the lesser flamingo population fleeing to Lake Bogoria to feed.

As observed above, huge numbers in migration of the lesser flamingos to feed in Lake Nakuru occurs when the optimum conductivity conditions are present to facilitate an *Arthrospira* bloom. In October 1997 and April 1998, during the *El Niño* period, it was observed that the lake levels significantly rose due to the heavy rains causing low conductivity. This occurrence also recurred in 2013. Once the lake levels start decreasing, conductivity levels also start increasing creating an optimum condition for *Arthrospira* bloom.

However, there are some unresearched arguments that in the 1990s and 2000s, the mass deaths and low population of Lake Nakuru's flamingos were signs of heightened levels of sewerage discharges encouraging eutrophication and increased heavy metals from increasing pollutants from industries, uncontrolled deforestation, the drastic increase in local human population in Nakuru town, along with general stress on the population of birds from tourists.

CHAPTER THREE

3.0 DATA AND METHODOLOGY

This chapter presents the data and methods that were used for the analysis of the objectives of the study to obtain the results.

3.1 Data type and sources

3.1.1 Data type

Data used in this study included climatic data comprising of mean annual temperature, mean annual precipitation mean annual evaporation and the Coupled Model Intercomparison Project Phase 5 (CMIP5) Representative Concentration Pathways (RCP2.6 and RCP8.5) near surface temperature, precipitation and evaporation data. Lake data comprised of conductivity, lake levels, surface area and depth. Flamingo data comprised of the lesser flamingo population. Below is a detailed description of the data types and their sources.

3.2 Methodology

In this section, the methods that were used in the study for data collection, organization and analysis based on the specific objectives of the study are presented.

3.2.1 Study design and sample size determination

Sample and sample size identification was purposive and quantitative. Four sites Nderit, Makalia, Baboon Cliff and Lion Hill, were selected as sampling sites/stations for the collection of water samples which were used to determine the levels of phytoplankton population densities, species composition and conductivity measurements in the lake in 2014. The sampling sites were largely determined by their accessibility as the lake was quite flooded at the time leading to the loss/damage of the road infrastructure which limited access to other sites. Water samples from the lake were collected in four replicates, fortnightly, in August 2014 and the first half of September 2014. The study sought to investigate the impact of climate variability and climate change on Lake Nakuru's biodiversity on the following indicators:

- Lake levels (surface area and depth)
- Conductivity levels

- Change in species populations of the phytoplankton and the lesser flamingos.

3.2.2 Data Sources

3.2.2.1 Field visits and preliminary assessments

The water samples collected were used to determine the levels of phytoplankton population densities, species composition and conductivity measurements in the lake in 2014. These measurements were compared with data acquired from the Kenya Wildlife Service database for the period 2009 to 2014.

Samples were collected in sterile bottles and transported in a cool box to the laboratory at the School of Biological Sciences, Chiromo Campus, University of Nairobi, where ex situ measurements of conductivity and phytoplankton concentration were conducted. Before analysis, the samples were stored in a fridge in the laboratory.

A Hanna Multi-parameter Water Analyzer Model HI 9828 was used to measure the conductivity of the water samples collected. The mean value of the four replicates was determined for each sampling site which was used to compute the mean conductivity of the lake.

To determine the phytoplankton cells concentration and species identification one replicate from each site was randomly selected. 1 µl was taken from the bottle and suspended and centrifuged in 100 µl sterilized water. 1 µl of this suspension was placed on a glass slide and observed under a LEICA DM500 microscope where the number of individuals in the field of view (quadrant) were counted and identified. This process was replicated for the other samples.

3.2.2.2 Populations of lesser flamingos

Data on population estimates of the lesser flamingos in the lake for the period 2009 to 2014 was collected from the KWS *Bi-annual Waterfowl Count Report- Kenya Rift Valley Lakes* determined using a modification of a method as described by (Pomeroy & Dranzoa, 1997). The information was used to determine the recent population trends and movement patterns of lesser flamingo in the context of flooding and the extensive dilution of the lake and correlate the changes in lake conductivity to changes in the population estimates of the phytoplankton and lesser flamingo for the period 2009 to 2014.The data was based on records of the January water bird counts that are conducted jointly by the National Museums of Kenya and Kenya Wildlife Service.

3.2.2.3 Changes in the lake levels

Data to determine the changes in the lake surface area and depth was obtained from (Onywere *et al.*, 2013) and the Kenya Wildlife Service records respectively. Documentation of the changes in the lake surface area was made using Geographic Information System (GIS) digital techniques and information extraction and representation from Landsat satellite image data for January 2010, May 2013 and September 2013 and October 2013 (Onywere *et al*., 2013), whereas monthly measurements of the depth of the lake was collected from KWS. This had been determined from the readings of a staff gauge located at the lake centre.

3.2.2.4 Physicochemical characteristics of water (phytoplankton concentration and conductivity)

The physicochemical qualities of water (phytoplankton concentration and conductivity) for the period 2009-2013 were obtained from the Kenya Wildlife Service (KWS) database.

Monthly measurements of conductivity and concentration of phytoplankton in lake water had been determined based on monthly analysis of water taken from the lake centre. Conductivity had been determined using a pH meter. The concentration of phytoplankton had been determined using the Sedgewick-Rafter counting chamber as described by Kimberly (1999).

3.2.2.5 Observed climate data

The climatic data (Precipitation, temperature, evaporation) for the period 2009 to 2014 was collected from the Kenya Meteorological Department, based on monthly data from the Nakuru Meteorological Station – 9036261(0.28^{o}S, 36.1^{o}E), located 3km north of the lake at the Nakuru Agricultural show grounds.

3.2.2.6 Climate projection data sets

In this study, the projected changes in near surface temperature, precipitation and evaporation for Lake Nakuru were extracted from the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble (IPCC Fifth Assessment Report (AR5) Atlas subset) models. The output data were extracted as a relative change from 1971 to 2000 (baseline) to, 2017 to 2100 (projection) under two scenarios, namely, the RCP2.6 and RCP8.5 scenarios (Taylor *et al*., 2012). The RCP2.6 and RCP8.5 represent ‘low’ (RCP2.6) and ‘high’ (RCP8.5) scenarios featured by the radiative forcings of 2.6 and 8.5 Wm−2 by 2100, respectively. The CO2 equivalent concentrations in the year 2100 for RCP 2.6 and RCP 8.5 are 490 ppm and 1370 ppm, respectively (Moss *et al*., 2010). RCP2.6 and RCP8.5 were chosen for this study as RCP2.6 describes an all-out effort to limit global warming to below 2°C with emissions decreasing sharply after 2020 and zero from 2080 onward, whereas RCP8.5 describes a business-as-usual scenario with increasing greenhouse gas emissions over time, leading to high greenhouse gas concentration levels.

These Representative Concentration Pathways (RCPs) are among four new GHG concentration developed scenarios set containing emission, concentration and land-use trajectories which have been adopted by the IPCC Fifth Assessment Report (AR5) (Moss *et al.*, 2010; Van Vuuren *et al*., 2011; IPCC, 2014). They describe possible climate futures explaining the possible range of forcing values up to the year 2100, with respect to the situation before industrialization. RCP2.6 and RCP8.5 were chosen for this study as they

3.2.3 Data quality control

Data quality control was done to ensure that the data sets were devoid of missing values, consistent, uniformly entered and arranged to facilitate further processing. The data was then subjected to various statistical computations.

3.2.3.1 Homogeneity Test

Most long-term climatological data records have been affected by a number of non-climatic factors that make these records unsuitable for comparison over long time periods and between different stations. These relate to alterations that can affect instruments, site, or procedures and methods in the observations and data processing. These factors are caused by changes in: instrumentation, observation practices, location of station, and formulae used for means calculation, and changing the environment of the station. While some changes cause critical discontinuities, others, particularly changes around station environment, due for example to, urbanisation, causes data biases which are gradual leading to time series biases and studied climate misinterpretations. In this study, the cumulative mass curve technique described in the subsection below was used to test for data homogeneity.

3.2.3.1.1 Mass curve

Mass curve analysis entails plotting of cumulative climatological data records against time to depict the homogeneity. The patterns of these graphs can be used to test for the quality of the records. A single straight line indicates a homogeneous record whereas heterogeneity tendency is indicated by existence of more than one line fitted to the graphical plots of the cumulative data. For the heterogeneous records, correcting the heterogeneity would be the next step. Double mass curves are commonly used to adjust heterogeneous records whose principles are similar to those of mass curves.

In this study, the single mass curve technique was used to test the data consistence where cumulative precipitation and temperature data was plotted against time to depict the homogeneity. A straight line graph depicted homogeneous data.

3.2.4 Time series analysis

Time series is the organization of statistical data in chronological order; in order with its time of occurrence. In this study a plotting of the annual means of precipitation, temperature and evaporation data for the period 2000 to 2014 using graphical method was undertaken. In addition, annual data means for lake depth, lesser flamingo population, conductivity, and phytoplankton levels for the period 2009 to 2014 were also plotted.

In order to determine the projected changes in near surface temperature, precipitation and evaporation for Lake Nakuru, data extracted from the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble (IPCC Fifth Assessment Report (AR5) Atlas subset) models were plotted using the *KNMI Climate Change Atlas* to analyse the data for the period 2017 to 2100 for RCP2.6 and RCP8.5 relative to the baseline period 1971-2000.

3.2.4.1 Trend analysis

The trend is characterized by the long term movement that is either represented by a growth or decline in a time series through a lengthy period of time. The trend in time series in this study, graphical method was used to determine the past and current trends of climatic parameters (temperature, precipitation and evaporation), and also for the physicochemical characteristics of Lake Nakuru (conductivity, phytoplankton, lesser flamingos and the lake depth).

Standard error of the mean was used to provide information about the distribution of the values within the trends as shown by Equation (1) below.

$$\sigma_M = \frac{\sigma}{\sqrt{N}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (1)$$

Where, σM is the standard error of the mean, σ is the standard deviation of the original distribution and N is the sample size (the number of counts each mean is based upon). Specifically in this study, the error bars were fitted graphically to assess whether there was a significant difference between the data sets. While a larger sample size suggests a smaller standard error of the mean, overlapping error bars implies that the difference is usually not significant. However, when the error bars do not overlap, it suggests that the difference is significant.

3.2.5 Correlation analysis

The Pearson Correlation coefficient (r), given in equation (2) below, was used to quantify the degree of relations between pairs of study variables. It is used extensively as a measure of the degree of linear dependence among two variables. If two variables 'x' and 'y' are so related, where, 'x' is the conductivity of the lake and where, 'y' is represented by either the phytoplankton or the lesser flamingos, the variables in the magnitude of one variable tend to be accompanied by variations in the magnitude of the other variable, they are said to be correlated. Therefore, correlation as a statistical tool helps to determine whether or not two or more variables correlate and if they are correlated, the degree and direction of their correlation.

$$r = \frac{n\,(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n(\sum x^2) - (\sum x)^2]\,[n(\sum y^2) - (\sum y)^2]}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \; (2)$$

Where, r is the Pearson correlation coefficient, N is the sample size, ∑xy is the sum of the products of paired scores, ∑x is the sum of x scores, ∑y is the sum of y scores, and $\sum x^2$ is the sum of squared x scores

The student T-test was used to test for the significance of the correlation coefficient. The computed t-statistic derived from Equation (3) below, was compared with the tabulated t-value of the student t-distribution at the $n-2$ degrees of freedom and 5% significance level.

$$t_{n-2} = r\sqrt{\frac{(n-2)}{1-r^2}} \quad \text{……………………………………………………………… (3)}$$

Where, n represents the length of the data that were used, $n-2$ is the degree of the freedom, t_{n-2} is the computed t-statistic and r is the Pearson correlation coefficient.

Correlation coefficient was considered to be significant if the computed value of t was greater than the tabulated value at the 5% significance level. This is usually done to determine whether the linear relationship in the sample data is strong enough to use to model the relationship in the population.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results related to the study objectives and the methods of analyses. The results of the study are presented in the following sections:

4.2 Data quality control

In this section, results of data quality control are presented and their suitability for the study established. Specifically this section presents results of the homogeneity test. The Figures 2 and 3 below show simple mass curves for precipitation and temperature respectively.

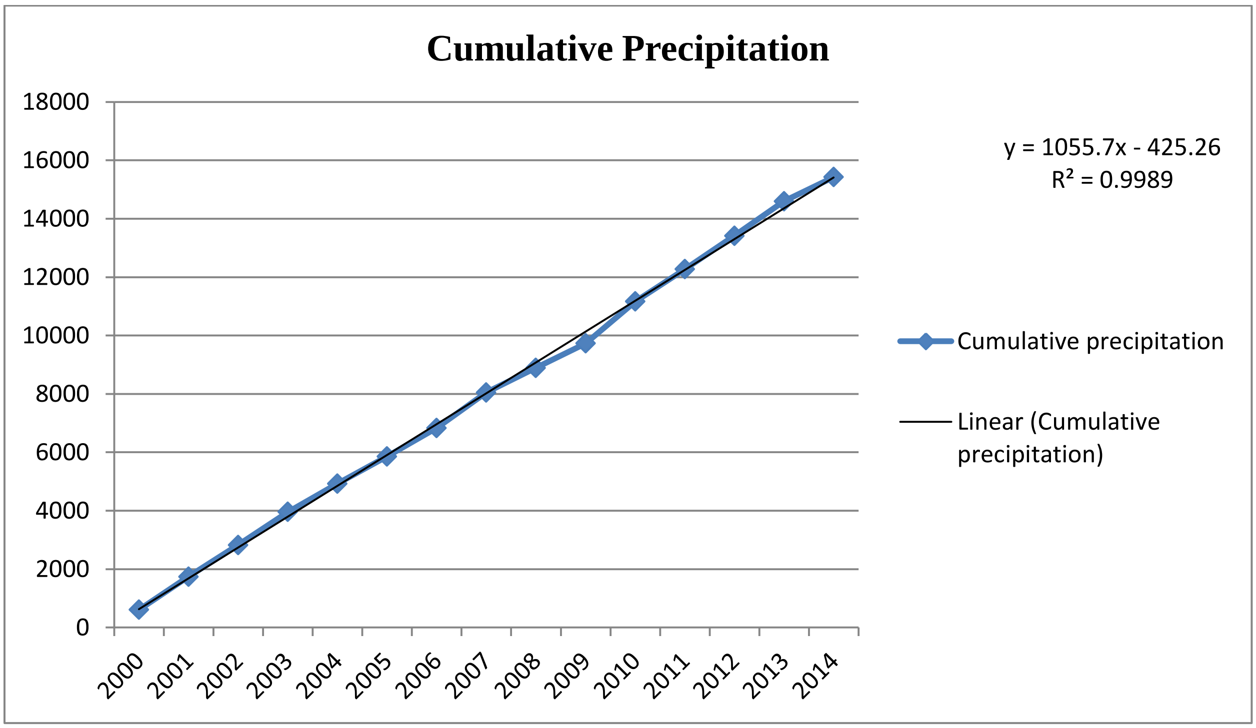

Figure 2: Single mass curve, cumulative annual precipitation

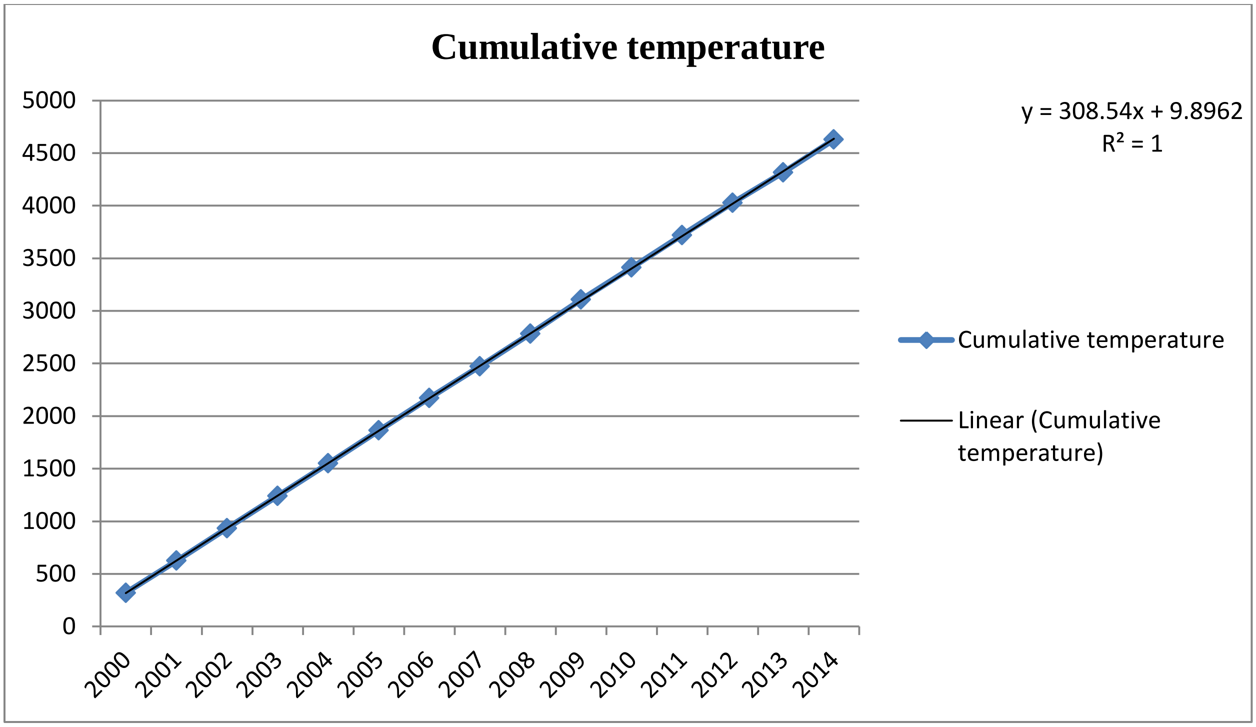

Figure 3: Single mass curve, cumulative annual temperature

It can be observed from Figures 2 and 3 that the precipitation and temperature data sets were homogeneous, owing to the resistant straight line plots.

4.3 Past and present climatic record of Lake Nakuru from 2000 to 2014

4.3.1 Trend analysis of climatic data

4.3.1.1 Trends in precipitation patterns from 2000 to 2014

There has been marked variability of the mean annual precipitation patterns of Lake Nakuru basin with major precipitation intensification in the years 2000 to 2001 and 2009 to 2010, with the highest (120mm) being recorded in 2010 (Figure 4).

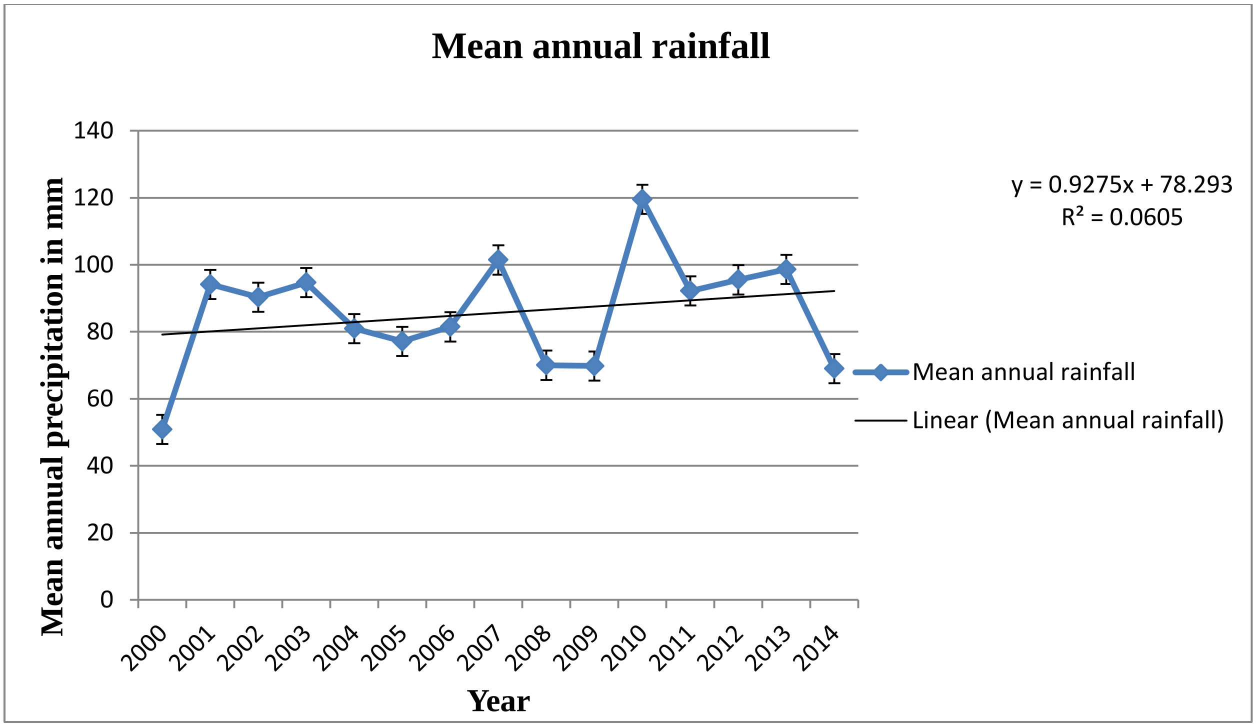

Figure 4: Mean annual precipitation patterns for the period 2000 to 2014

It can be noted that generally the precipitation has been gradually increasing leading to an increase in the surface runoff, most of which subsequently ended up in the lake.

4.3.1.2 Trends in temperature patterns from 2000 to 2014

Mean annual temperatures has been on a decreasing trend during the period 2000 to 2014, with the highest temperatures being recorded in 2000 (26.6 ºC) and in 2009 (27 ºC) (Figure 5).

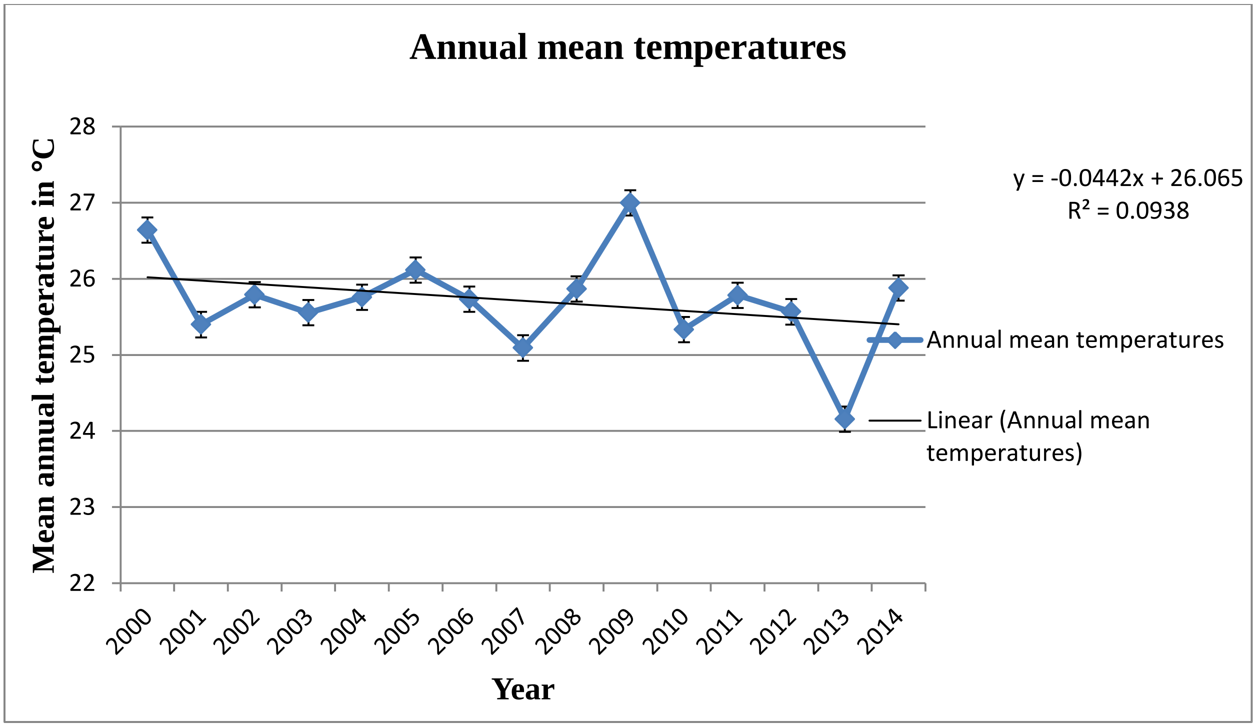

Figure 5: Mean annual temperatures from the year 2000 to 2014

4.3.1.3 Trends in evaporation patterns from 2000 to 2014

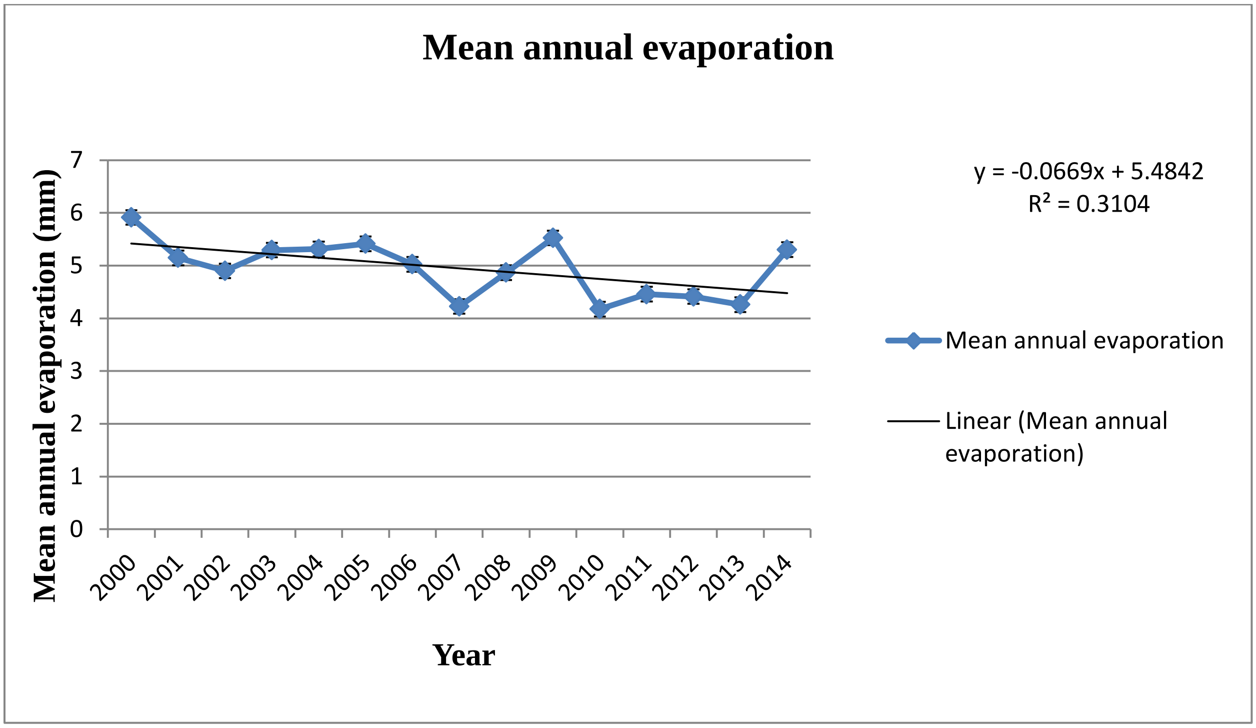

Figure 6: Mean annual evaporation patterns for the year 2000 to 2014

Evaporation in the Lake Nakuru basin shows a declining trend over the study period. However, the observed decrease in evaporation from the year 2009 is consistent with the increase in precipitation observed in Figure 4 and temperature decrease observed in Figure 5 above.

4.4 Changes in the lake levels (depth and surface area) 2009 to 2014

4.4.1 Time series of Lake Nakuru levels (depth)

Lake Nakuru levels have been rising over the years 2009 to 2014 (Figure 7).

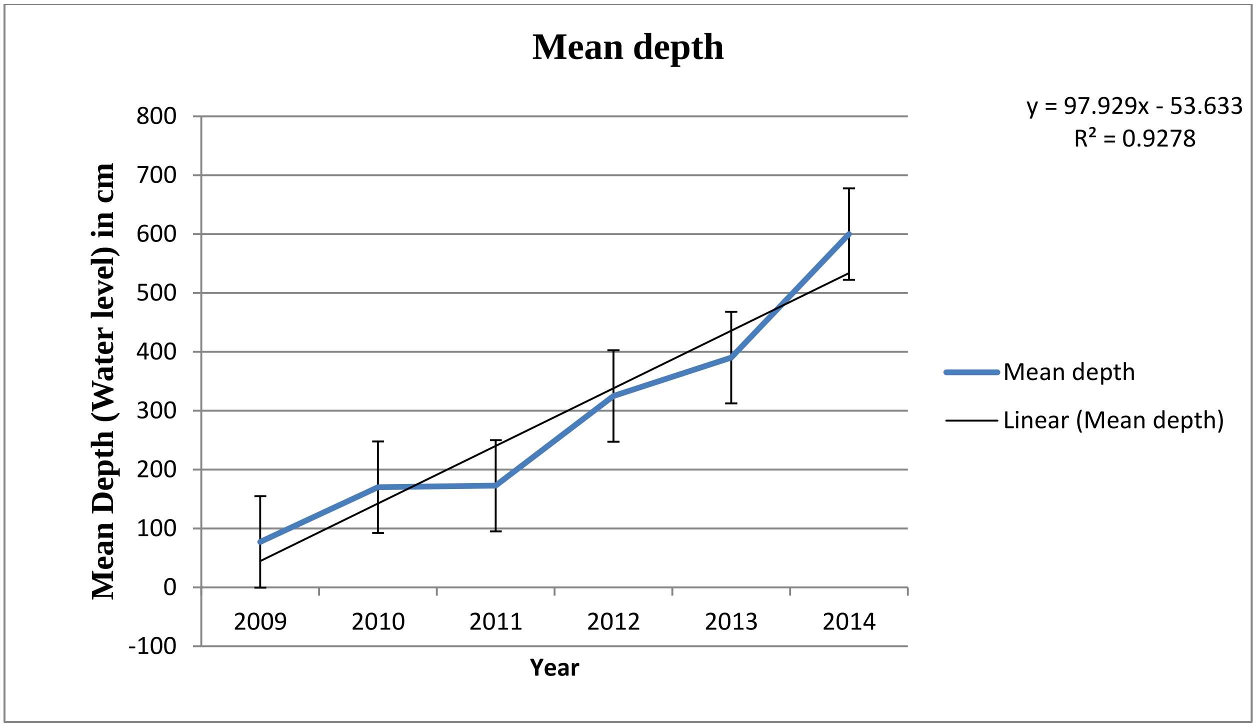

Figure 7: Changes in the mean depth of Lake Nakuru from 2009 to 2014

As seen in Figure 7, the mean depth of the lake rapidly increased during the study period (2009 to 2014). This could have been caused by increased precipitation during the study period which led to increased surface runoff and direct precipitation into the lake. The increased water levels led to the flooding of the lake which further lowered the conductivity of the lake as more fresh water was added into it.

4.4.2 Changes in the lake surface area

Lake Nakuru's surface area increased from an area of 31.8 km^2 in January 2010 to a high of 54.7 km^2 in Sept 2013 (Figure 8 and 9), an increase of 22.9 km^2 (71.9%). This led to the submergence of 60% of the transport infrastructure in Lake Nakuru Nationa Park and the park's main gate, during this period, thereby displacing wildlife.

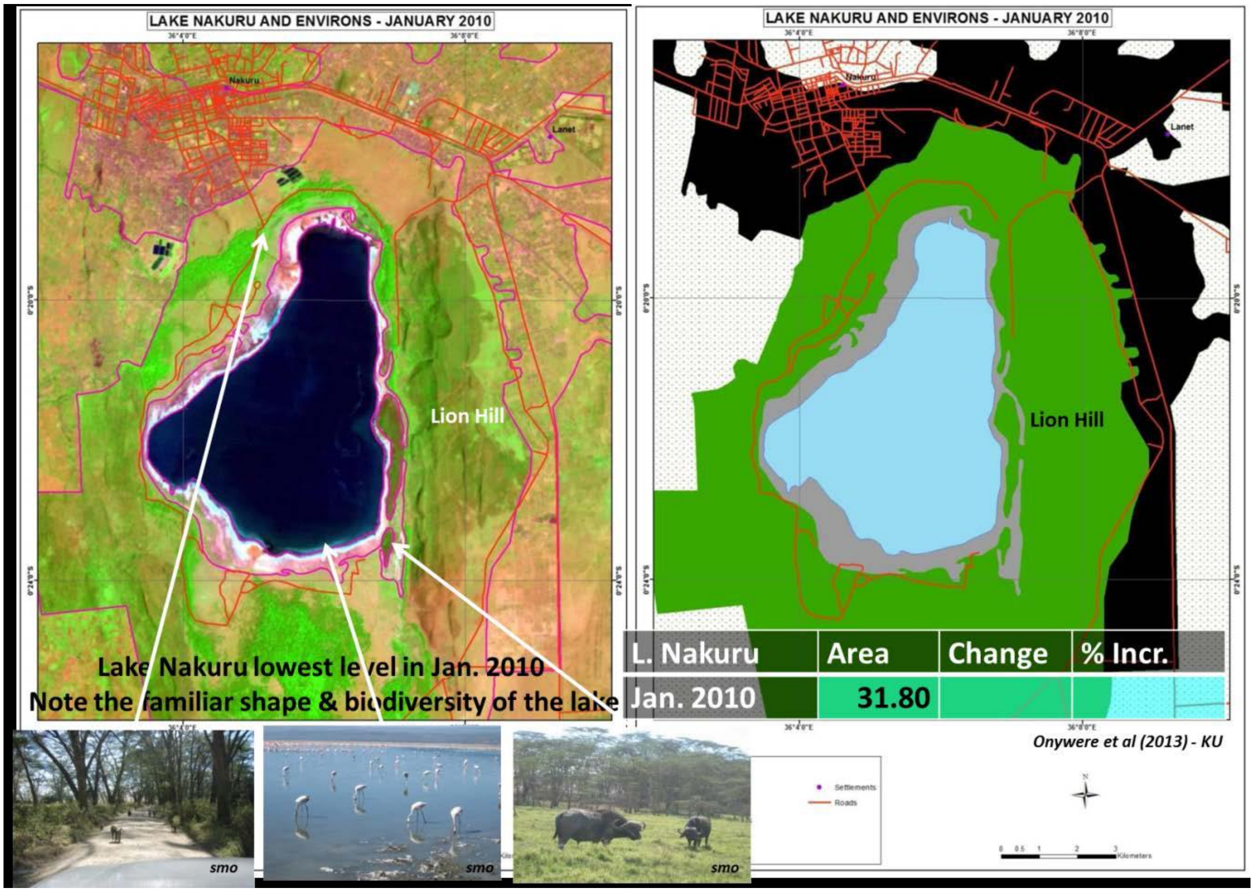

Figure 8: Changes in the surface are of Lake Nakuru between January 2010 and 2013 *(*Source*:* Onywere *et al.*, 2013*)*

At the highest level, the lake expanded and submerged areas that have never been recorded in the last 100 years (Figure 9).

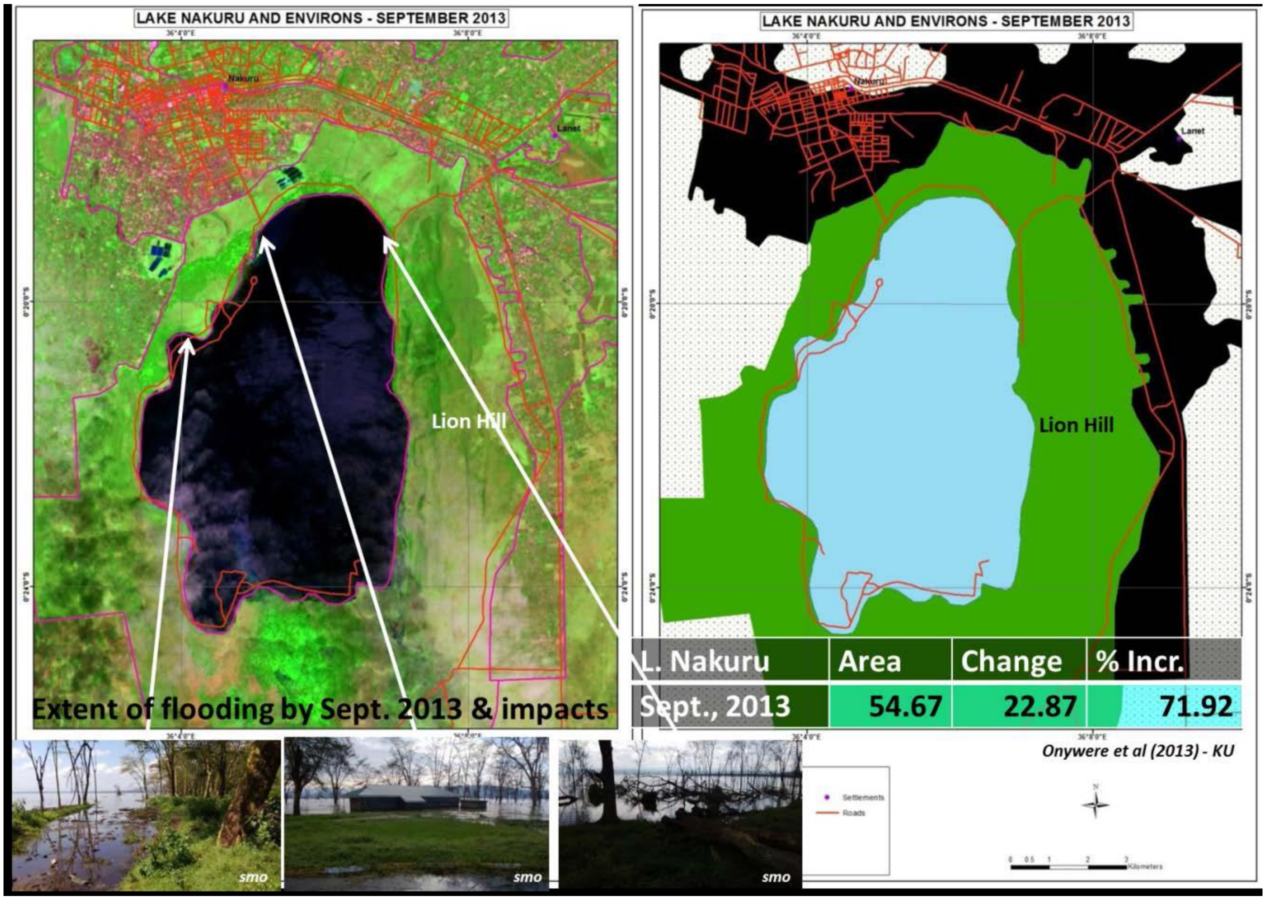

Figure 9: Lake Nakuru highest water level in September 2013

*(*Source*:* Onywere *et al.*, 2013*)*

The extent of the flooded area and the impacts are illustrated in the image data and digitized maps shown in Figure 10, and also in Plate 5 below

Lake Nakuru time series extent

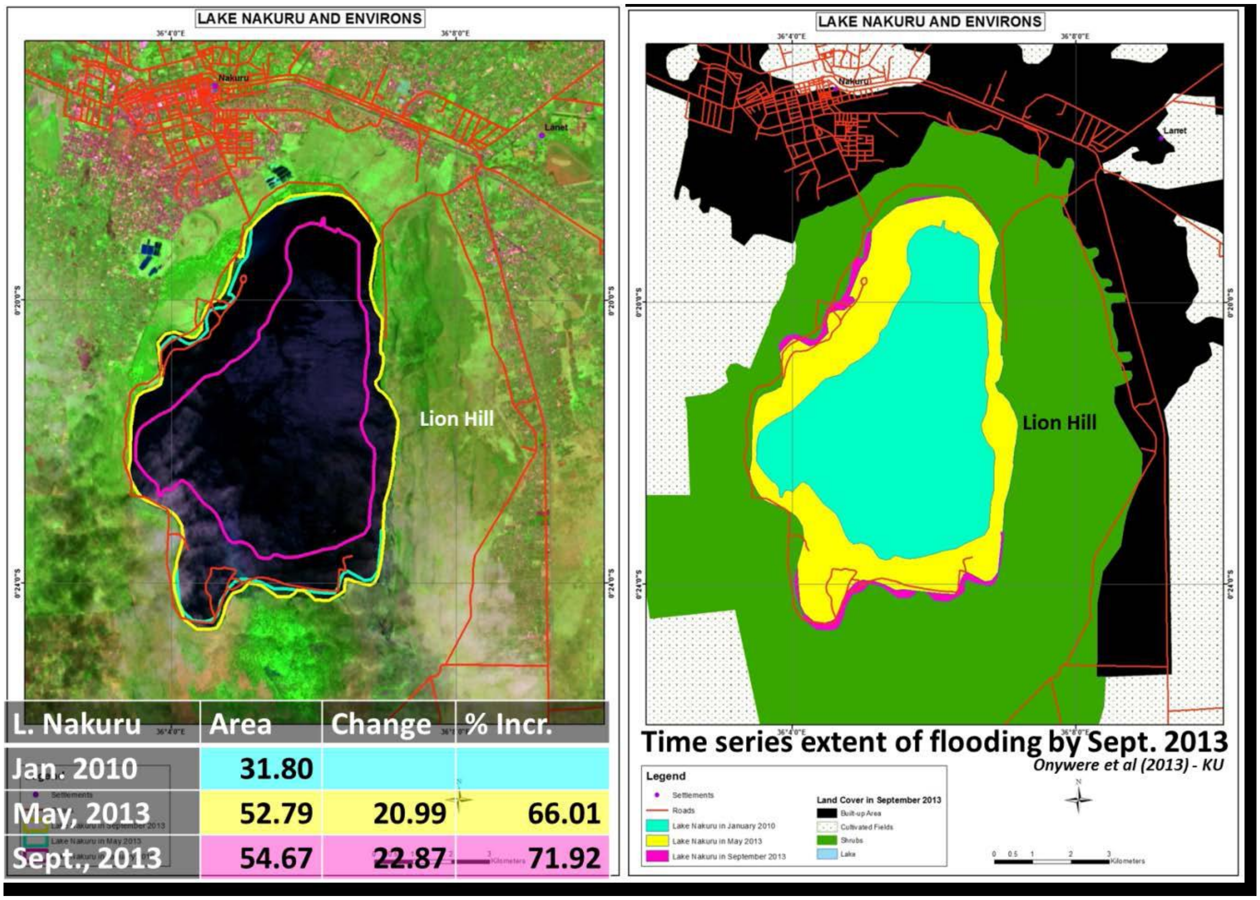

Figure 10: Time series extent of flooding in Lake Nakuru from a low area of 31.8 km² in January 2010 to a high of 54.7 km² in Sept 2013, a total increase of 22.9 km² (71.9%)

*(*Source*:* Onywere *et al.*, 2013*)*

Plate 2: Current surface area (April 2016) of Lake Nakuru (54.8 km^2) as observed from Google maps area calculator tool from the internet

*(*Source: *Adapted from Google maps*, April 2016)

4.5 Conductivity, phytoplankton levels and the lesser flamingos populations

4.5.1 Conductivity levels

The mean conductivity of Lake Nakuru decreased from the period 2009 to 2014 (Figure 11).

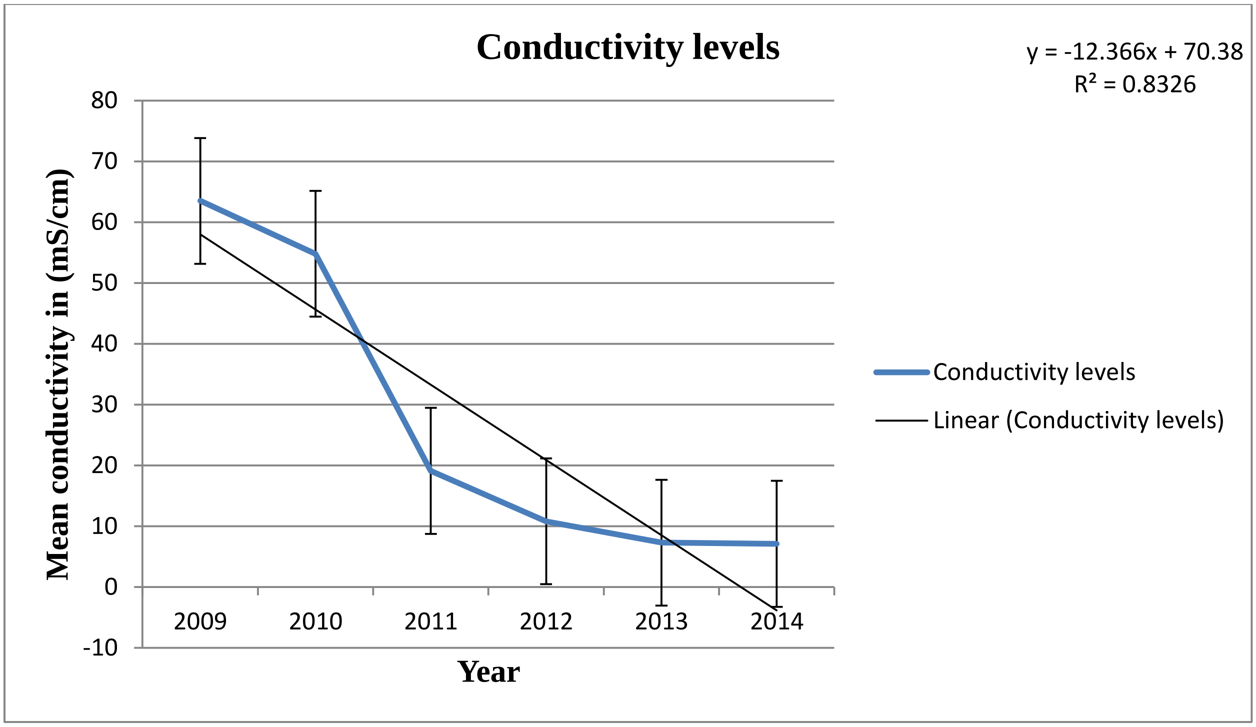

Figure 11: Trend in mean conductivity levels from 2009 to 2014 in Lake Nakuru

This coincided with the beginning of the rains from the year 2010 as shown in Figure 4. The declining conductivity of the lake could result into loss of phytoplankton (reduction in food supply) upon which the lesser flamingos feed. This could eventually lead to the migration of the lesser flamingos from the lake. This is due to the fact that as more fresh water was added in to the lake, it lowered the conductivity of the lake because fresh water has low conductivity and the increase in water levels dilutes mineral concentrations.

4.5.2 Phytoplankton levels

The phytoplankton levels in Lake Nakuru were quite variable for the years 2009 to 2014 as shown by Figure 12.

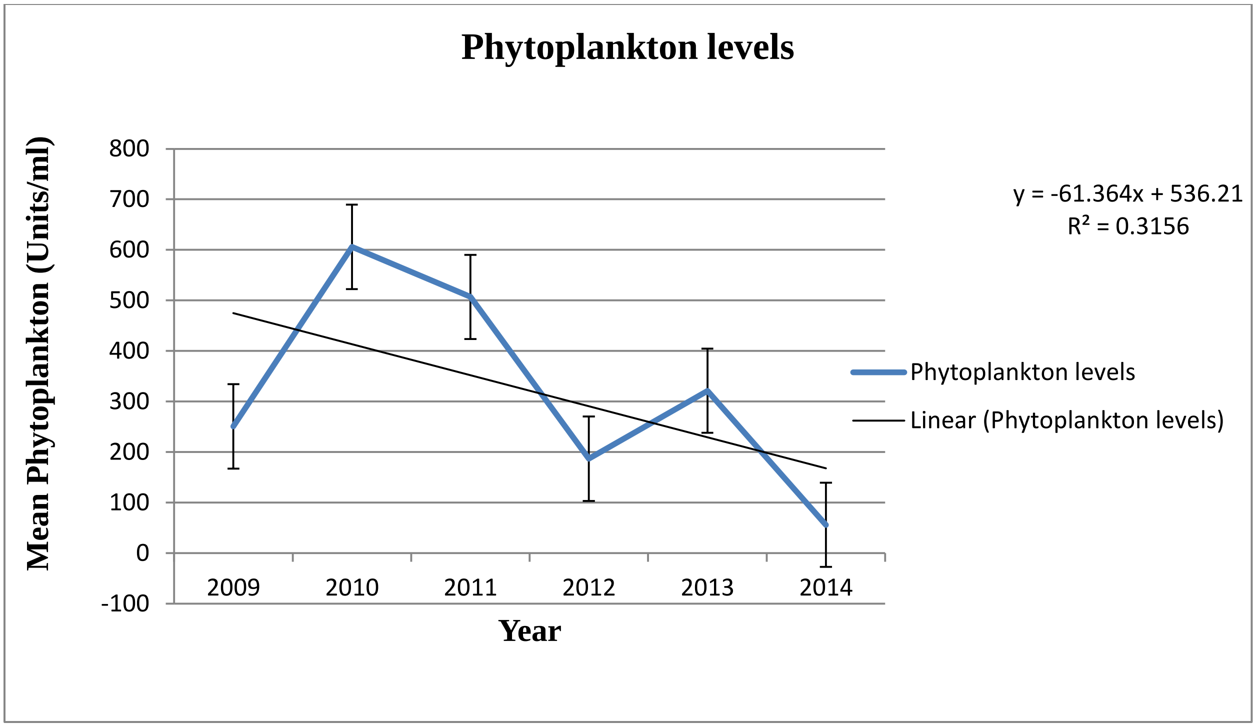

Figure 12: Trend in mean phytoplankton levels in Lake Nakuru from 2009 to 2014

Notably, however, there was a general reduction in the phytoplankton levels which coincided with the onset of the rains from the year 2010 as shown in Figure 4. Phytoplankton levels decreased from 606 Units/ml in 2010 to 187 Units/ml in 2012. However, there was an increase in the phytoplankton levels to 321 Units/ml in 2013 which could have been caused by changes in phytoplankton species composition and diversity that in turn affected their abundance due to changes in the chemical and physical properties of the water (Kihwele., *et al* 2014).

4.5.3 Lesser flamingos population

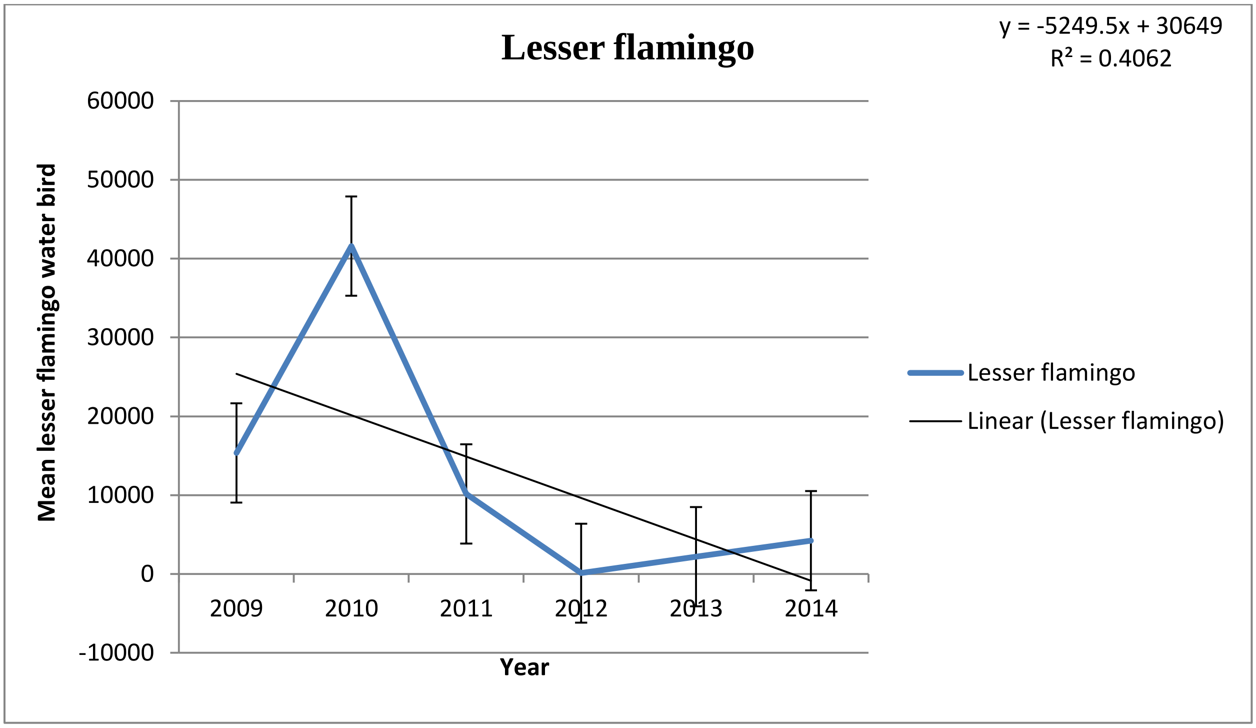

Figure 13: Trend in the number of lesser flamingos for the period 2009 to 2014

The number of lesser flamingos drastically decreased from the beginning of the rains in 2010 (Figure 13) from 41,592 in 2010 to 10,168 in 2011 and further decreased to 110 in 2012. This pattern follows that of decreasing phytoplankton levels shown in Figure 12.

4.6 Correlation between changes in lake conductivity and changes in population estimates of the phytoplankton and the lesser flamingo

Table 1: Correlation of changes in lake conductivity to changes in population estimates of the phytoplankton in Lake Nakuru during the study period (2009 to 2014)

		Conductivity in (mS/cm)	Phytoplankton (Units/ml)
Conductivity in (mS/cm)	Pearson Correlation	1	.437
	Sig. (2-tailed)		.386
	N	6	6

The findings showed that there was a nonsignificant positive correlation between conductivity and phytoplankton, (r=0.437, p=0.386).

Table 2: Correlation of the changes in electrical conductivity to changes in population estimates of the lesser flamingo in Lake Nakuru from 2009 to 2014

		Conductivity in (mS/cm)	lesser flamingo water bird
Conductivity in (mS/cm)	Pearson Correlation	1	.767
	Sig. (2-tailed)		.075
	N	6	6

The findings showed that there was a significant positive correlation between conductivity and the lesser flamingo, (r=0.767, p=0.075).

Table 3: Correlation of the changes in the population estimates of the lesser flamingo in Lake Nakuru to changes in the population estimates of the phytoplankton from 2009 to 2014

		lesser flamingo water bird	Phytoplankton (Units/ml)
lesser flamingo water bird	Pearson Correlation	1	.731
	Sig. (2-tailed)		.099
	N	6	6

The findings also showed that there was a significant positive correlation between phytoplankton and the lesser flamingo (r=0.731, p=0.099).

4.7 Projections of the climatic data (temperatures, evaporation and precipitation) for the period 2017-2100

Future climate scenarios of Lake Nakuru comprising near surface temperature, precipitation and evaporation were plotted for the period 2017 to 2100 (projection) for RCP2.6 and RCP8.5 relative to the baseline period 1971 to 2000. The results obtained are sequentially presented in the subsections that follow.

4.7.1 Near surface temperature projections

Future changes in annual temperature for Lake Nakuru under RCP2.6 and RCP8.5 for the period 2017 to 2100 relative to baseline period 1971 to 2000 are presented in Figure 14 and 15 respectively.

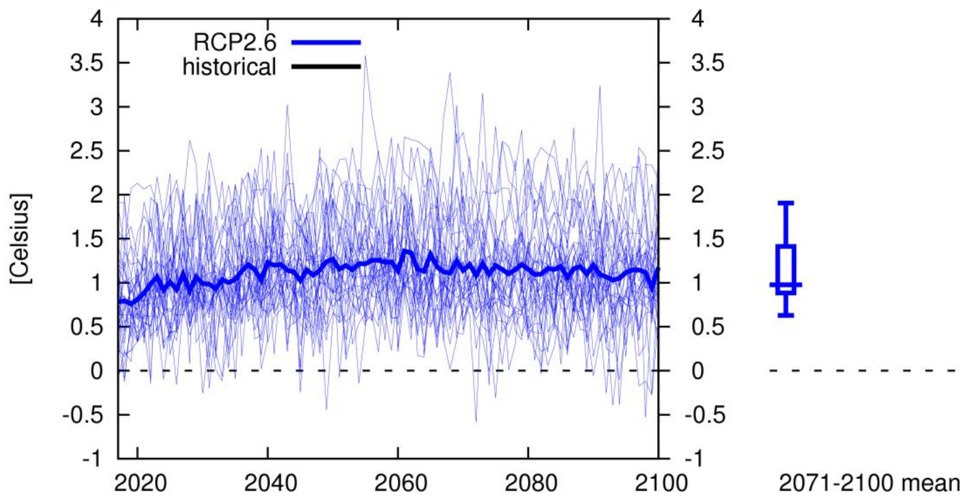

Figure 14: Near surface temperature projection for RCP2.6 for the Lake Nakuru area from 2017 to 2100 shows a 1.2°C increase for the 2071 to 2100 mean changes

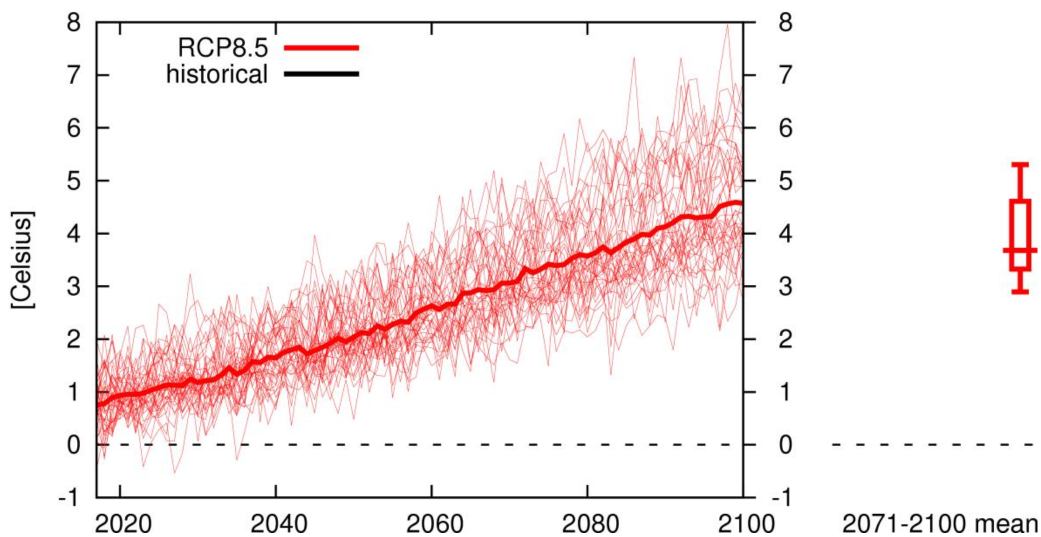

Figure 15: Near surface temperature projection for RCP8.5 for the Lake Nakuru area from 2017 to 2100 shows a 4.8°C increase for the 2071 to 2100 mean changes

Temperature projections indicate an increasing trend with a 1.2°C increase for the 2071 to 2100 mean changes for RCP2.6 (Figure 14) whereas there is a 4.8°C increase for the 2071 to 2100 mean changes for RCP8.5 (Figure 15). The likely causes of the increasing trend of temperature under both RCP2.6 and RCP8.5 could be due to increasing levels of greenhouse gas concentrations in the atmosphere during the projected period. Notably however, the rate of temperature increase in RCP2.6 is lower than that of RCP8.5.

4.7.2 Precipitation projections

Future changes in precipitation for Lake Nakuru under RCP2.6 and RCP8.5 were plotted for the period 2017 to 2100 relative to baseline period 1971 to 2000 are shown in Figures a6 and 17 respectively.

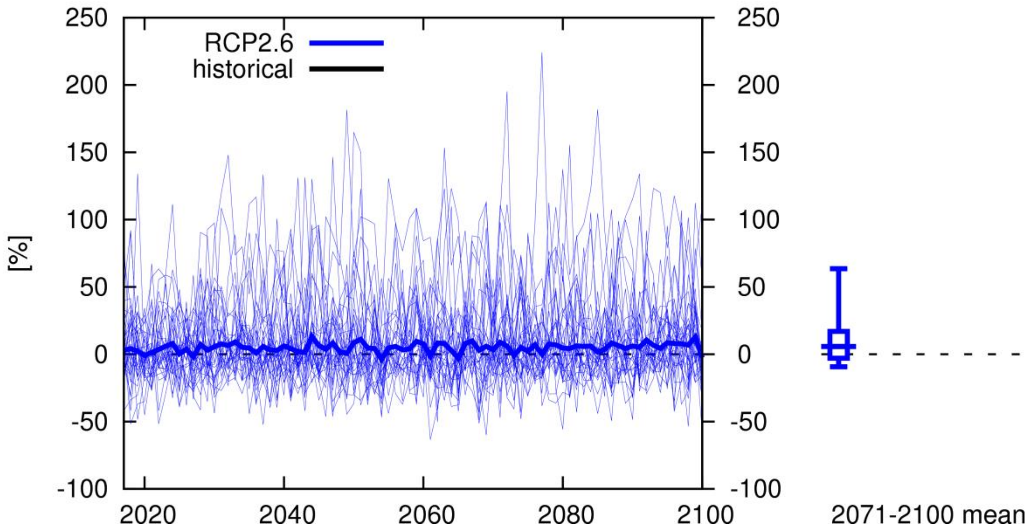

Figure 16*:* Precipitation projections for RCP2.6 for Lake Nakuru

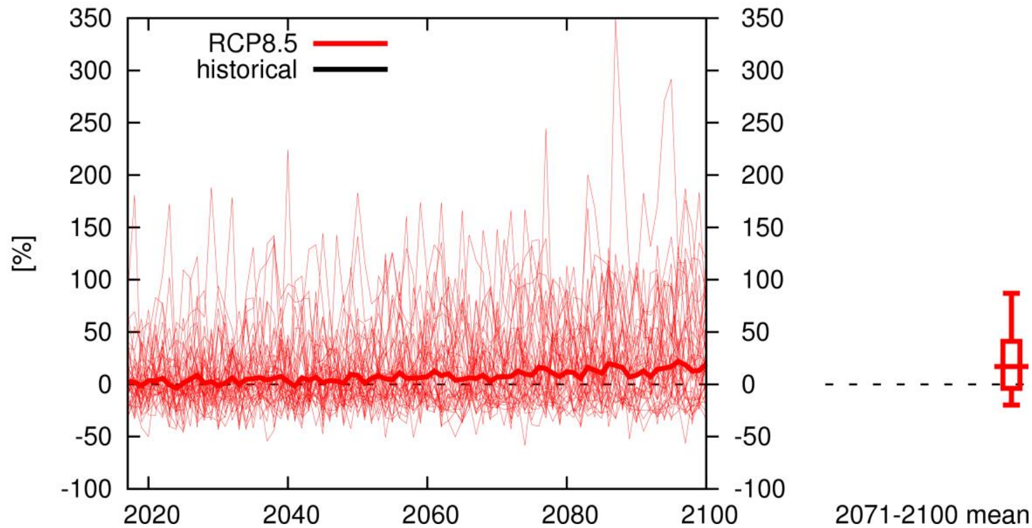

Figure 17: Precipitation projections for RCP8.5 show a 20% increase in precipitation in Lake Nakuru area for the 2071 to 2100 mean changes

The precipitation projection from RCP2.6 and RCP8.5 show a 10% and 20 % increase in precipitation for the 2071 to 2100

4.7.3 Evaporation projections

Future changes in evaporation for Lake Nakuru under RCP2.6 and RCP8.5 for the period 2017 to 2100 relative to baseline period 1971 to 2000 are shown in Figures 18 and 19.

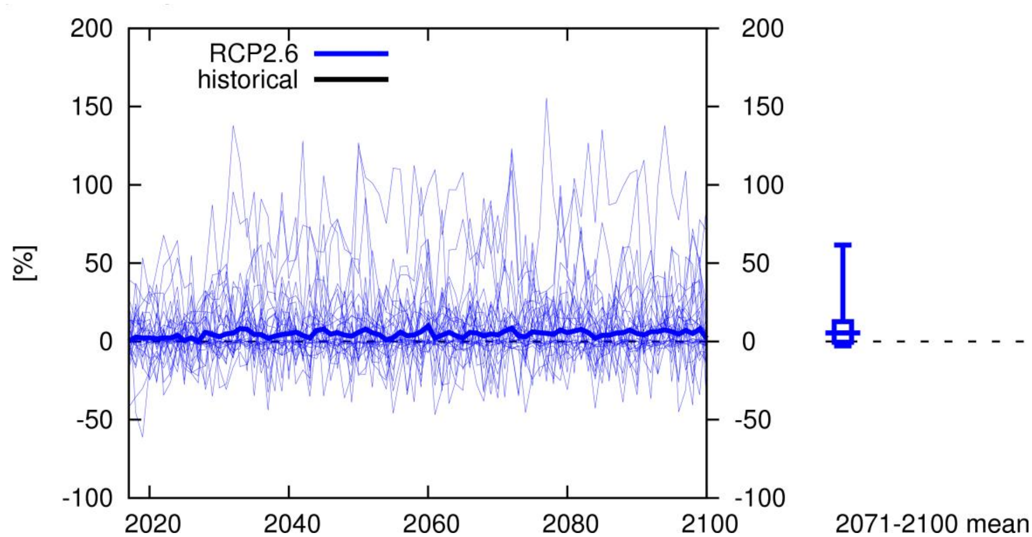

Figure 18: Relative evaporation change for RCP2.6 for the Lake Nakuru for 2071 to 2100

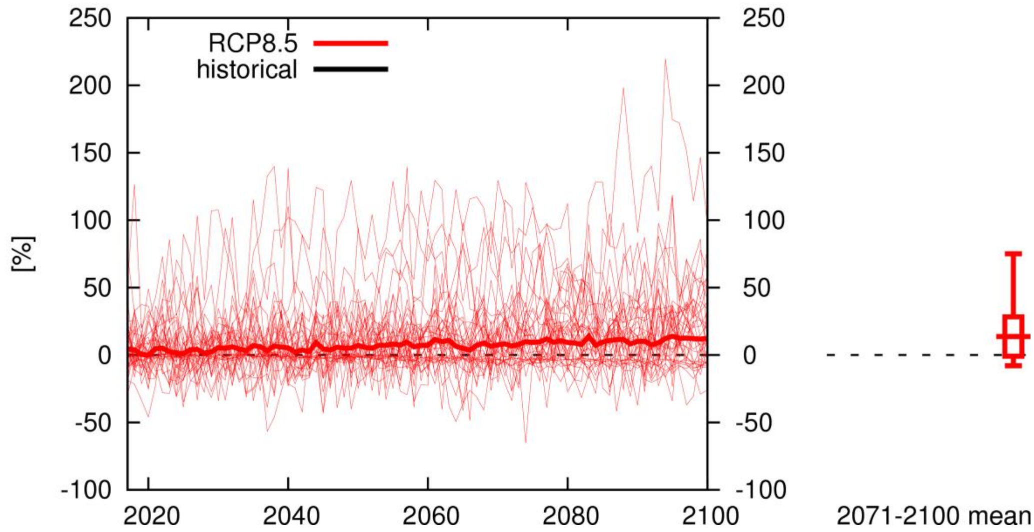

Figure 19: Relative evaporation change for RCP8.5 for Lake Nakuru

Relative evaporation is projected to increase by 10% and 20% for the 2071 to 2100 mean changes for RCP2.6 and RCP8.5 respectively.

4.8 Discussions

As depicted in section 4.3, Figure 4, it can be deduced that precipitation has been increasing since the year 2010 and this may have greatly influenced the rising water levels in the lake as demonstrated by the images acquired from (Onywere *et al.*, 2013). Figure 7 also shows that the depth of the lake has gradually been increasing since the onset of the rains in the year 2010. This could be highly attributed to increased surface run off and increased recharge of the lake from the Njoro, Makalia, Larmudiac and Enderit Rivers and also from direct precipitation into the lake.

Figures 5 and 6 show that temperature and evaporation have been increasing from the year 2007 to 2009, the same period when there was little/no precipitation, and drastically reduced from the year 2009 to 2010, the beginning of the precipitation season. According to Trenberth (2011), increased temperatures usually lead to increased evaporation and therefore drought. A warming of about 7% per 1°C increases the water holding capacity of the atmosphere. This is observed in the study with the temperatures and evaporation increasing in the year 2007 to 2009, which increased the water holding capacity of the atmosphere, and thus the beginning of rains in the year 2009.

According to IPCC (2007), changes in climate are evidently more and easily measured by temperature, though changes in atmospheric moisture, atmospheric circulation and precipitation are also observed as the whole climate system is usually affected. The moisture holding capacity of the atmosphere is caused to increase by temperature increases at a rate of about 7% per °C (Trenberth *et al.,* 2003). Collectively, changes on the hydrological cycle are effected, particularly, precipitation characteristics (type, intensity, amount, duration, frequency) and extremes (Trenberth *et al.,* 2003). Convergence of increased water vapour leads to more intense precipitation in weather systems, but reductions in duration and/or frequency, given that total amounts do not change much. It can therefore be deduced that a slight increase in temperatures drives a more rigorous hydrological cycle because the rate of evaporation is also increased which has direct effects on cloud formation, as intense precipitation are influenced when the water holding capacity of the atmosphere is increased, as observed in the year 2010.
Changes in the seasonal hydrological budget greatly affect endorheic lakes which at times may be extreme, resulting in drastic algal biomass crashes and big changes in community composition as have been observed in Lake Nakuru.

As more water was added into the lake, it diluted the mineral concentrations hence lowered the electrical conductivity of the lake. Fresh water has low conductivity. According to the observation made in Figure 11, the conductivity levels started decreasing from the year 2010, following the beginning of the rains. The relationship between conductivity of lake water and lake depth observed in the study reflects the concentration and dilution cycles of the lakes due to evaporation during dry seasons followed by recharge from river in-flows and water run-off during the wet seasons. These hydrological cycles have a profound effect on the water biota in the lakes (Githaiga, 1997).

Correlations coefficients in Table 1 showed the changes in lake conductivity and corresponding changes in population estimates of the phytoplankton. The insignificant coefficient between conductivity and phytoplankton ($r=0.437$, $p=0.386$) reflects the dilution cycles of the lake due to recharge from river in-flows and water run-offs during the wet season. The few aquatic species that are adapted to live in the highly alkaline water of the Lake Nakuru attain very high levels of biomass that serve as food for primary feeders. The blue green algal species, *Arthrospira fusiformis* is one such species and it is the for lesser flamingos' main food. As such, as the conductivity levels of the lake decreased, the phytoplankton levels in the lake also decreased since the conditions were not conducive for them to bloom.

Table 2 shows that conductivity had a positive strong correlation, with the lesser flamingo ($r=0.767$, $p=0.075$). This implies that low conductivity affects the growth of phytoplankton by creating an unsuitable environment for the phytoplankton to bloom. As the lesser flamingo depends on the phytoplankton for their feed, this subsequently demonstrated that the phytoplankton density could be a significant predictor of the lesser flamingo occurrence in Lake Nakuru. The observed high strong correlation ($r=0.731$, $p=0.099$) between the phytoplankton and lesser flamingo in Table 3 confirms that in saline lakes, the lesser flamingo distribution is influenced by feed availability.

4.8.1 Future climate predictions relative to the 1971-2000 baseline period

Figures 14 to 19 project an increase in temperatures, precipitation and evaporation for the period 2017 to 2100 under RCP2.6 and RCP8.5 relative to the baseline period 1971 to 2000 obtained from the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model ensemble.

As you will note, the rate of increase in temperature, precipitation and relative evaporation in RCP8.5 are expected to be higher than that in RCP2.6. This is attributed to the fact that RCP8.5 is characterized by a business-as-usual scenario with increasing greenhouse gas emissions over time, leading to high greenhouse gas concentration levels as opposed to the RCP2.6 which describes an all-out effort to limit global warming to below 2°C with emissions decreasing sharply after 2020 and zero from 2080 onward.

Based on the precipitation projections (Figures 16 and 17), it is expected that the mean depth of the lake will increase over time as the discharge is largely influenced by precipitation, which is also positively correlated with the temperature. Increased precipitation will therefore result in increased discharge over the projection period.

As explained above, a slight increase in temperature drives a more vigorous hydrological cycle, and therefore, as the projections indicate increasing temperature levels, it is anticipated that the hydrological cycle will be highly vigorous during the projection period, which assumes that ultimately, the hydrological cycle will be altered, producing more intense precipitation, characterized by thunderstorms (Trenberth, 2011).

The increase in discharge over the projection period will cause the conductivity levels in the lake to decrease, which reflects the increasing concentration and dilution cycles of the lakes due to evaporation during dry seasons followed by recharge from river in-flows and water run-off during the wet seasons respectively. The decrease in conductivity levels will consequently change the condition of the lake creating an unfavourable environment for phytoplankton bloom, thereby decreasing feed availability for the lesser flamingos and as a result reducing the number of the lesser flamingos in the lake due to their migration to other lakes which harbour their preferred food supply and with suitable living conditions.

Based on the fact that the lake area has a negative precipitation/evaporation deficit, increasing temperatures would drive a higher rate of evaporation and therefore higher conductivity due to evaporative concentration, over the projected period.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

As observed from the study, climate change and climate variability can cause significant impacts on saline lakes by causing changes in their physicochemical characteristics. This has been evidenced by the variations in precipitation and temperature which impacts on the phytoplankton availability, determined by the chemical and physical characteristics of the lake.

There have been fluctuations on the lesser flamingos' population as a result of climate variability. These were due to the changes in rainfall that affected the physicochemical composition, lake depth, and the surface area of the lake whose ultimate impact is observed in the abundance of the phytoplankton (food for the lesser flamingos).

This study suggests that, the shift and succession in phytoplankton species are interrelated with the variations in the physicochemical factors of the lake, specifically conductivity which are greatly influenced by climatic variability.

The study also suggests that population dynamics of the lesser flamingos may be influenced by availability of their main food, *Arthrospira fusiformis* which is in turn influenced by physico-chemical properties of water and also by climate variability.

Based on future projections, it is expected that the lake will continue increasing in surface area and depth by the year 2100 due to increased precipitation thereby affecting the populations of the lesser flamingos and phytoplankton, as the physicochemical factors of the lake will change as well during the projected period.

5.2 Recommendations

As data from one of the key stations for the study (the Plant Breeding Research Centre – Njoro (9035021)) was not available, it is recommended that the Kenya Meteorological Department and the Plant Breeding Research Centre collaborate so as to ensure availability of data for research purposes. This data would have been useful for comparison purposes between the two stations and especially since both capture different catchment areas.

Continuous monitoring and analysing meteorological parameters in the lake basin should be done in order to record and assess the variability in climate.

In order to manage and utilize the waters of Lake Nakuru sustainably, and enhance precipitation regularity, there needs to be an enforcement of government policy on illegal water abstractions and massive afforestation of indigenous trees.

There needs to be more information generated in regard to the status of water resources, and especially the current rates of utilization and the rate of replenishment and other changes that may affect the availability and quality of water, in order to maintain and improve water quality and surface flows in Lake Nakuru

Assessments of climate vulnerability need to be carried out in order to come up with mitigations and adaptations measures unique to Lake Nakuru basin informing actions to be taken in order to minimize the negative impacts of climate vulnerability/change, and exploit the beneficial ones.

Since current activities taking place at the basin wide catchment have level negative implications on the long-term survival of the lake and its inhabitants, it is imperative to increase investments in conservation efforts/strategies in the Lake Nakuru catchment area.

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