UNIVERSITY OF NAIROBI

INVESTIGATING THE IMPACTS OF CLIMATE CHANGE ON THE LEVELS OF LAKE MALAWI

BY

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DECLARATION

This Dissertation is my original work and has not been submitted elsewhere for examination, award of a Post Graduate Diploma in Operational Hydrology. Where other peoples work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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DEDICATION

This Dissertation is dedicated to my wife Onety Kaunda who has provided the moral support during the time of my in Nairobi Kenya. I would also like to dedicate it to the management of the Department of Water Resources for making it possible for me to pursue this important course on behalf of the Government of Malawi with the support of the GEF Early Warning UNDP Project.

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ABSTRACT

Lake Malawi is a shared transboundary water resources among Tanzania, Mozambique and Malawi. The lake is located in the southern east Africa between latitude 9° S and 15° S and longitude 34.68° E and after Lake Victoria and Tanganyika it's the third largest Lake in Africa. Levels of the lake have significantly dropped over recent years raising fears on water resources development and management as the lake provides about 95% of hydropower generation through the Shire River system, navigation services, water supply and irrigation opportunities.

The study examined the impacts of climate change on the levels of Lake Malawi and specifically analysed trends on climatological parameters, the inflow and outflow from the lake, lake levels, and simulated the water yield into Lake Malawi up to 2100. The data used in this study comprised of hydro-meteorological data sets from line institutions, Global Climatic Models (GCM) data the RCP4.5 scenarios and spatial data for the model. To achieve the main objective, the study carried out trend analysis of climatological parameters in decadal sets, correlation analysis of rainfall and lake levels, correlation of lake levels and outflow; SWAT modelling to simulate the water yield into the lake; and determined future climate impact on the levels of Lake Malawi.

The results of the study showed that the lake is very sensitive to climate variations where the cyclic fluctuations in levels are largely subjective to annual rainfall patterns. Temperature over Lake Malawi is increasing whereas evaporation shows a decreasing trend. Rainfall has been varying over time but the long term trend showed a decreasing trend similar to the runoff inflow into the Lake. Lake levels showed a significant drop as well as the outflow. The future projection showed water yield is anticipated to even drop as simulated by the model. Determining the Impacts of climate change on the future levels based on the baseline data from 2006 to 2035, the near future from 2036 – 2065 and the far future 2066 to 2095 the study showed that the water yield will reduce by 8.84%, hence levels are also expected to drop in future. Based on these future projections the study recommends further studies on strategies for climate change resilient and adaptation on the economic impact the levels have on human livelihood. Further studies on the decreasing evaporation over the lake while temperatures are rising would further provide better assessment of the impacts of climate change on the lake levels.

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AWSC	Available Water Storage Capacity
CGIR-CSI	Consortium of Spatial Information
DCCMS	Department of Climate Change and Meteorological Services
DEM	Digital Elevation Model
DFT	Discrete Fourier Transform
DWR	Department of Water Resources
ESCOM	Electricity Supply Commission of Malawi
Eta	Evapotranspiration Actual
ETp	Evapotranspiration Potential
GFFS	Galiway Flood Forecasting System
GIS	Geographical Information System
GRACE	Gravimetry Recovery and Climate Experiment
HRU	Hydrological Response Units
H_1	Positive Hypothesis
H_O	Null Hypothesis
ITCZ	Inter-Tropical Convergence Zone
MK	Mann Kendall
MoIWD	Ministry of Irrigation and Water Development
PET	Potential Evapotranspiration
RCMRD	Regional Centre for Mapping Resources for Development
R Studio	A system for statistical computation and graphics
SNHT	Standard Normal Homogeneity Test
ST	Soil Storage
STW	Soil Storage Withdrawal
SWAT	Soil and Water Assessment Tool
TRMM	Tropical Rainfall Measuring Mission
WBM	Water Balance Model
WMO	World Meteorological Organisation

CHAPTER 1

1.0 Introduction

1.1 Background of the Study

Water resources availability at any region is influenced by complex natural interactions between climatological conditions and the natural hydrological cycle processes. Global warming which is triggering climate change is expected to further exacerbate this compound natural interaction, in that way affecting water resources availability through changes of water balance elements such as temperature, rainfall, and evapotranspiration and runoff (Ngongondo et al., 2015). The declining levels of Lake Malawi have significant water resources issues in Malawi, as the Lake is a reservoir through the shire river system providing about 95% of hydropower generation, water supply, navigation services, and irrigation opportunity (Kumambala and Ervine 2010).

Lyons et al., (2010), showed that climate change characterised by extreme events is a susceptible cause of the dropping of Lake Malawi levels in recent years. Climate in the tropics has been governed by effective moisture changeability as a function influencing the movement of the Intertropical Convergence Zone (ITCZ), known to be the major driver of tropical monsoon systems. In addition to ITCZ migration, tropical lake basins are very sensitive in the evaporation-precipitation processes subsequently impacting on the levels of the lakes (Lyons et al., 2010). Tropical lake-levels such as Lake Malawi do vary naturally over time scales seasonal to historical, to millennial and more often over orbital time spans.

Deus et al., (2013) noted that Lakes are unique water resources bodies, very sensitive to changes in climate and environment. The study on water balance modelling of Lake Manyara further revealed that in the Rift valley East Africa, the landscape of the rift slopes and volcanic highlands play a key role in influencing local weathers that subsequently impact lake basins including Lake Malawi. Lakes are very sensitive changes in the water balance components and therefore there is no exception that Lake Malawi similarly is sensitive to changes in the water balance components. Over the last 100 years, lake levels have experience significant drop below the lake’s outflows causing a complete end to the natural hydrological cycle within the basin. Deus et al., (2013). Not only Lake Malawi levels have fallen in recent years, Awange et al., (2007) observed that in the last 5 years, levels of Lake Victoria has seen a historical drop in levels that has triggered concerns to water resources decision makers and its recent decline has raised concern on the possibility of the lake drying up since the 1960s, as the lake level has experienced significant fluctuation. Therefore a holistic approach in studying the water balance of lakes is very useful in water resources management. Deus et al., (2013). In studying the water balance of lakes, analysis should also include land cover/land use change, soil erosion, climate as they impact on the natural hydrological. Deus et al., (2013).

Global warming which is triggering climate change is expected to further exacerbate this compound natural interaction, in that way affecting water resources availability through changes of water balance elements such as temperature, rainfall, and evapotranspiration and runoff (Ngongondo *et al.,* 2014). However climate change has not uniformly generalised the changes in the water balance components globally as they also respond differently and in a study by Wang *et al.*, 2011 cited that the responses are marked by regional scenarios, therefore this calls for a need to assess responses in different climatic geographical zones.

This study, examined the impact of climate change on the levels of Lake Malawi. Key climatological parameters such as precipitation, temperature, evaporation, runoff and outflow are crucial in determining the water balance of the Lake Basin. Therefore the approach was to synthesis available hydrologic data and interpret their seasonal variability in time scales.

1.2 Objective

The main objective of this study was to investigate the impacts of climate change on the levels of Lake Malawi.

The specific objectives used to achieve the main objective were:

i. Determine trends in climatological parameters;
ii. Determine trends in inflow to and outflow from the lake;
iii. Determine trends in lake levels; and
iv. Determine the impacts of climate change on lake levels

1.3 Justification

Malawi is characterised as relatively rich in water resources with an abundance of fresh water in lakes, rivers, and groundwater aquifers. However, there are some imbalances that exist in the spatial and seasonal distribution of these natural water resources which is further exacerbated by climate change, deforestation, and poor land use practices. Aurecon, (2011). Rainfall, as the main driver of the terrestrial phase of the hydrological cycle, which is varying globally not sparing Lake Malawi basin in various ways. A study by Mbano *et al.,* 2009, noted that the impact of climate change on water balance scenario is rather intricate if catchment land use changes on water resources are considered.

Lake Malawi / Shire River system play a crucial role in the country socio economic sector. The Lake Malawi/Shire River System provides the hydropower energy generation having a total installation generation capacity of 280 MW. This system also provides irrigation potential to Malawi’s largest sugarcane plantation downstream of the Shire River and also supplies the second city of Blantyre with domestic and industrial water. In addition to contributing to economic gains through tourism the Lake serves for navigation services and also contributes through the fisheries industry (Kumambala & Ervine, 2010). Therefore studying the impacts of climate change on levels of Lake Malawi yields as a basis for assessment and decision making in water resources development and management within the Lake Malawi / Shire river system.

1.4 Area of Study

Lake Malawi is located in the southern east Africa between latitude 9° S and 15° S and longitude 34.68° E and is the third largest Lake in Africa after Lake Victoria and Tanganyika. It has a drainage catchment area of 126,500 km^2 together with the lake. Lake Malawi surface area is 28,800 km^2, with a stretch of 579 km long, 25 – 80 km wide. The lake has an estimated maximum depth of 700 – 785 m and estimated mean depth of 292m. The land catchment of Lake Malawi consists parts of Malawi with 66,810 km^2 (68.35%), Mozambique with 5.460 km^2 (5.58%) and Tanzania with has 25,470 km^2 (26%). Figure 1 shows the catchment of Lake Malawi. (Kumambala & Ervine, 2010).

Lake Malawi is part of the Great East Rift Valley and the rift valley is almost engulfed by the lake, and it is naturally controlled by a slopes basins about 5 km, and the arms of the rift valley go to about 1000 m above the surface of the lake, which has certainly influenced the shape and morphology of the Lake. (Lyons *et al,* 2010).

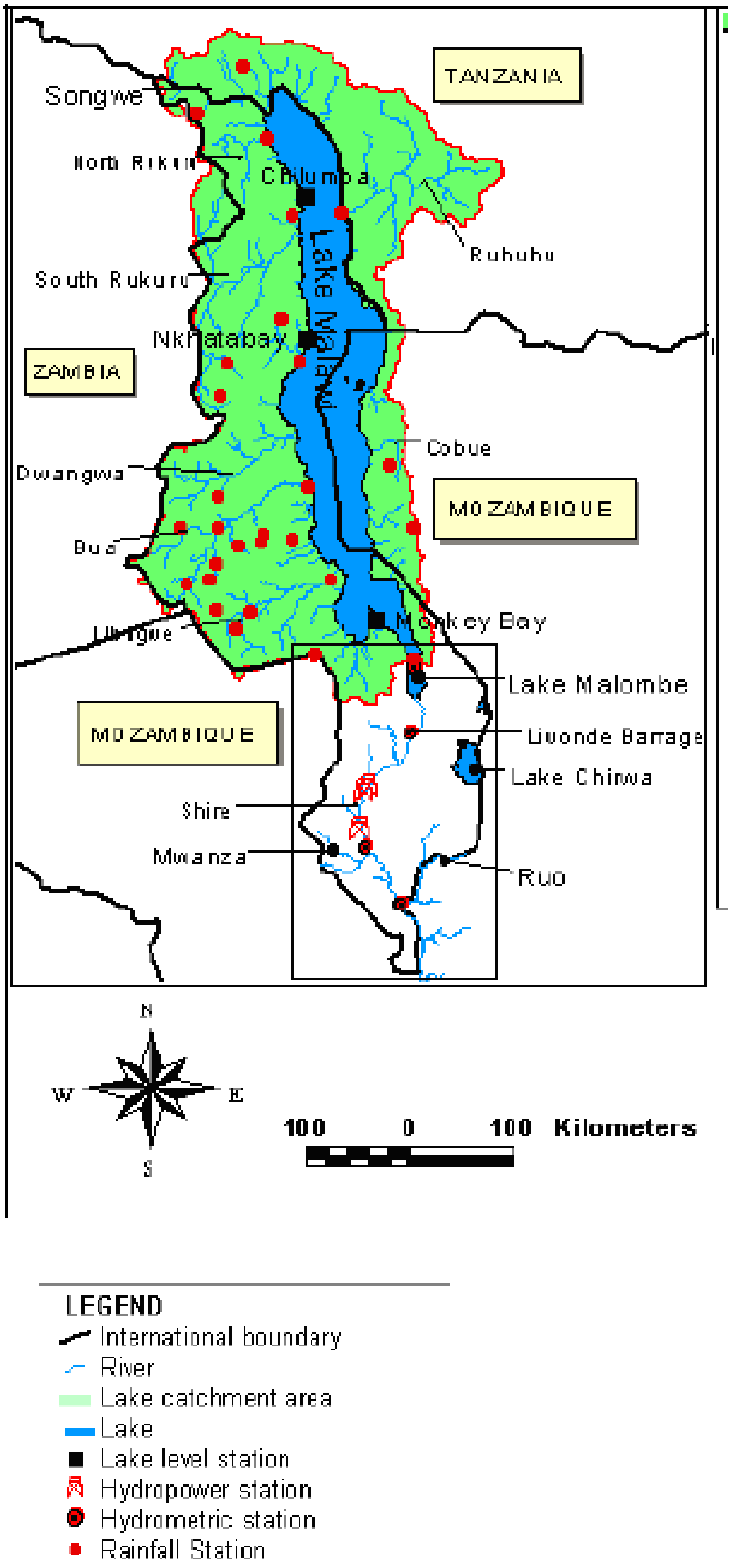

Figure 0-1 Lake Malawi Drainage System (Source Kumambala & Ervine, 2010)

1.5 Research Problem

Lake Malawi levels have significantly fallen causing serious water resources issues in Malawi. The Lake provides about 95% of hydropower generation through the Shire River system, navigation services, water supply and irrigation opportunity. There are fears that the historical low levels which were experienced between 1915 and 1935 when the lake and the shire river were cut into two with no flow from the lake. This resulted into a hydrological closure thereby affecting the water availability downstream. Imaginatively if this experience resurface again without proper water resources management then irrigation, water supply, hydropower generation, navigation services etc would be at risk hence the socio economic growth of the country derailed. The lowest lake level of 469m above sea levels was recorded in 1915. (Kumambala & Ervine, (2010). In the recent past, the level fell to an elevation of 472.94 metres in late 1997. In 2015, the lake levels are some of the lowest in many decades. In fact, the maximum level reached in 2015 was the lowest in 17 years at 473.32 m.a.s.l (MoIWD, 2015)

Climate change characterised by extreme events is a susceptible cause of the dropping of Lake Malawi levels in recent years. Climate in the tropics has been governed by effective moisture changeability as a function influencing the movement of the Intertropical Convergence Zone (ITCZ), known to be the major driver of tropical monsoon systems. In addition to ITCZ migration, tropical lake basins are very sensitive in the evaporation-precipitation processes subsequently impacting on the levels of the lakes (Lyons et al., 2010). Tropical lake-levels such as Lake Malawi do vary naturally over time scales seasonal to historical, to millennial and more often over orbital time spans.

Climate change and the development of human society can not only influence the quantity of water resources in basins but also has a serious impact on the exploitation, utilization, planning and management of water resources of human society and further affect the sustainable development of ecological environment and social economy (Ligang Xu *et al.*, 2014).

CHAPTER 2

2.0 Literature Review

This chapter examines other studies on the water balance of Lake Basins and how they affect the general water resources management and development. The insight into the literature review also focuses on studies on water basins in the east rift valley lakes as they lie within the same geographic tectonic stretch. Further and particularly this chapter gives an insight into Lake Malawi levels fluctuations.

Water resources bodies such as lakes in the hydrological cycle, provide essential services for human beings and the ecosystem in overall. Lakes provide a wide variety of ecosystem services even though they are particularly at risk to stress. According to Dessie *et al.*, 2015, Lakes overtime experience natural hydrological deficiencies such as declining of levels, water quality degradation through acidification, siltation, contamination and eutrophication. In response to such stress on the lakes, management strategies have been put in place to understand the lakes hydrological processes, their catchment and overall sustainable management of lakes. (Dessie *et al.*, 2015). This study addresses the detailed knowledge on the declining of levels of Lake Malawi as a result of variations of climatological parameters within the basin.

Awange *et al.*, 2008 observed that many studies have been carried out on lakes using time series and trend analysis using 30 years rainfall data, inflow, and Lake Victoria levels to analyse linearity and trends of climate parameters in reference to levels of the lake. Awange *et al.*, 2008 used linear trend. In order to predict, monitor and manage lake level changes its vital to analyse and relate climatic indicators of drought and rainfall with and lake levels (Awange *et al.*, 2008). Similar the analysis of climatological parameters of Lake Malawi basin require also to analyse trends in rainfall and levels as well.

2.1 Impacts of Climate Change on Water Resources

Climate Change also known as global warming is the rise in mean surface temperatures, commonly due to the burning of fossils. Bajracharya e*t al.*, (2016). Scientific studies show that climate change is mainly triggered by human use of fossils fuels that emits greenhouse gases into the air such as carbon dioxide. Heat within the atmosphere is trapped by these greenhouse gasses this then leads to effects on ecosystems such as rising sea levels, floods and droughts.

Climate is normally defined as the average weather over a long period and influenced by geographic terrain, and altitude, as well as adjourning water bodies and their wind currents. Bajracharya e*t al.,* (2016). It is a freely available natural resource, however human interference to the atmospheres has threatened this natural resource which in the future it has potentials to impact other spheres of the planet. This was discussed by Bajracharya e*t al.,* (2016) on the Impact of Climate Change on Water resources and livelihood in the HKH region. The earth is warming due to human caused factors emission such as of greenhouse gases. The climate is changing due to the earth warming thereby affecting the natural hydrological systems. It is no exception that lakes including Lake Malawi are also sensitive to changes in climate as well.

As a contributor to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cubasch, et al., (2013) cited that some indicators of climate change, ranging from responses such as atmospheric water vapour, precipitation, surface temperature, etc. Surface temperature is feasible the most regularly studied element in atmospheric researches. Flato *et al.,* 2013, highlighted that the observed variation in mean surface air temperature since 1950 from climate models simulate global temperatures that closely relate with the observed data over timescales. Flato *et al.,* (2013) indicated that quite often the multi-model mean correspond with the reanalysis to within 2°C, however there are numerous locations where there are larger deviation. If the climate global predictions are used this would therefore mean that temperatures across Lake Malawi will subsequently increase activating climatological variations thereby affecting the water balance of the lake.

Many studies including the Bajaracharya et al., (2016) show that water resources are under mounting pressure from the demands of growing population, economical activities and also from ever more evident impact of climate change. The changes to the hydrological cycle due to climate change will continue to deteriorate the quantity, quality and accessibility of water resources, hence putting more stress on the human population. These conditions will be further exacerbated by increasing natural disasters and their impacts on water for human populations. (Bajracharya e*t al.,* 2016).

2.2 Water Balance

In a Water balance analysis for the Tonle Sap Lake–floodplain system, Kummu *et al.*, (2014) noted that the water balance study presents and discusses the hydrology Lake system better and gives a basis comprehensive evaluation of the inflow discharge and outflow contributions by the various hydrological components of the system. Further, it demonstrates the significance and the influence interaction among the water levels, inflow, and outflow within the intricate hydraulic environment. Kummu *et al.*, (2014). The water-balance model basically consists of a series of equations, which, are executed in sequential order, estimate the amount of available water, soil water storage or contributing to runoff, at a monthly time step. In a Scientific Investigation Report Stochastic model for simulating Souris River Basin precipitation, evapotranspiration, and natural stream flow, Kelsey, *et al* (2016) found out that model inputs are in depth equivalents and consist of monthly precipitation, average temperature, and potential evapotranspiration (PET) along with static variables such as Available Water Storage Capacity (AWSC) and soil permeability (*Ks*). Similarly Popek *et al.* (2013), studied the Water budget of the Zdworskie Lake in 2008–2012 on monthly intervals by the water balance formulae equation.

A Case Study of Lake Alemaya on the Water Balance Study and Irrigation Strategies for Sustainable Management of a Tropical Ethiopian Lake Setegn *et al.*, (2011) observed that the disturbance of the natural hydrological system of lakes require systematic analysis and planning in order to track trends and fluctuation of the levels within appropriate or acceptance limits.

Water balance of a water basin depends on climatological parameters to be analysed and the objective of specific studies. In the Water Balance Modelling study by Deus, et al., (2013) on

Lake Manyara using in situ remote sensing data the water balance modelling was performed successfully using remote sensing data even in complex climatic settings. This was achieved by using the distributed conceptual hydrological model compelled by remote sensing data to analyse the spatial and temporal variability of water balance parameters. Verification of trends of lake levels were done using satellite gravimetry GRACE data. In Deus et al., (2013) study the results revealed that the lake experiences high spatial and temporal variations, typical of a semi-arid climate with low precipitation and extreme evaporation.

Setegn *et al.,* (2011) further narrated that anthropogenic activities in any of the water balance parameters also affect the steadiness of the water balance and the variations of the levels. One major element of the radiation and heat balance of the lake and its surroundings are also represented by evaporation from the lake surface. Therefore Setegn *et al.,* (2011) concluded that lake level fluctuations of closed lakes are expressive pointers of climate changes.

According to *Kumambala & Ervine* (2010), the water balance which governs the water level behaviour of Lake Malawi is a compound of discharge into the lake, outflow, evaporation from and precipitation on the lake. *Kumambala & Ervine* (2010), also indicated that groundwater flow in previous studies has not been computed due to the unavailability of piezometric data within the lake basin. Figure 2.1 simulates the key water balance components on Lake Malawi.

Among many studies on Lake Malawi water balance, this study uniquely addresses the water balance concept of Lake Malawi with the latest data up to 2015 to show the current impact that climate change has on the lake levels unlike other previous studies that used collected data of more than 10 years and rather simulated the current status.

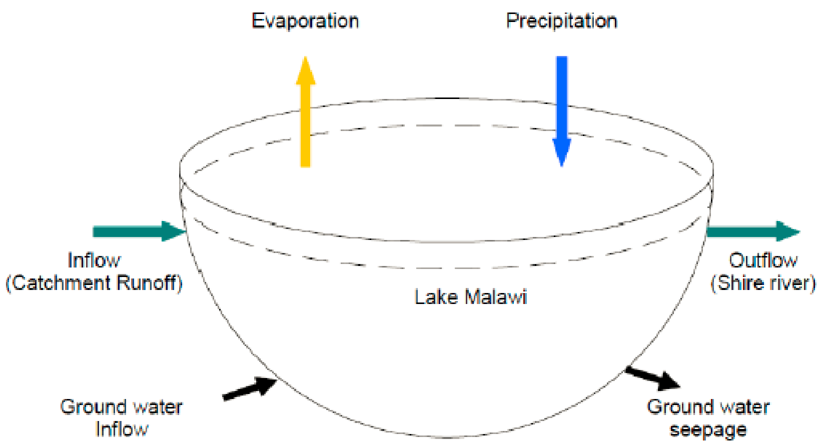

Figure 2-1 Water Balance components (Kumambala and Ervine, 2010)

2.3 Precipitation

In any one year the most reliable estimate of lake rainfall would be based on all the available records from gauges around the lake basin. (Piper *et al.*, 2009). In a study by *Nachiappan and Kumar* (2002) on the lake Nainital - Kumaun Himalaya, India using environmental isotopes., the input to the lake through direct rainfall over the lake was determined by Thiessen polygon method from the rainfall data at stations on the lake. The US Soil Conservation Service curve number method and the lake level trend analysis method was used to estimate the runoff into the lake.

In a study by Popek *et al*., (2013) in the Wielka Struga River catchment and in the Zdworskie Lake hydrological conditions were variable, largely dependent on the amount of rainfall. A great change with precipitation weakens the impacts of other conditions. The temperature changes the conditions of water balance by influencing the evapotranspiration and the soil water content. Other variables are controlled by the precipitation and appear to be less sensitive to the change in temperature. The impact of temperature decline is more significant than that of temperature rise noted by Ligang Xu *et, al.*, (2014) in the analysis of water balance and subsequent response to Climate Change in Poyang Lake Basin.

According to Melesse *et al.*, (2006), the estimate of spatial water balance of the Devils Lake basin was done using remotely-sensed data from Landsat TM and ETM+ sensors. The components of the surface water balance were calculated at the pixel level to determine the levels. The study demonstrated how to apply Geographical Information System (GIS) and remote sensing techniques in computing the water balance of the lake.

However Istijono *et al.,* (2016) Analysis of TRMM and ground-measured rainfall shows that the difference between inflow and outflow comes from direct rainfall over the lake. Yet, TRMM alone does not explain the remaining flow after rainfall events. Therefore studying the contribution of subsurface flow in the difference on inflow-outflow is very critical.

In the study of Water Balance of Lake Victoria, Yin and Nicholson (2009), calculated the average rainfall in the catchment by the weighted by a derived factor from a satellite analysis of precipitation over the lake and over the catchment.

2.4 Runoff

Water balance estimates are highly sensitive to runoff as commented by Yirgalem *et al.,* (2008) and for any sensitivity analysis of the water balance against precipitation, an established relationship of runoff with precipitation in any distributed model could be important. Inflow from the major rivers is one of the input in the water budget computation. The total inflow of the lake is the sum of the contributions of sub basins into the lake. In a study by Nossent *et al.,* (2009), as a contribution to the development of a water balance model for Lake Victoria, the Nzoia-catchment was analysed using the SWAT model which is a physically based, semi-distributed hydrological simulation model.

2.5 Evaporation

In regional water budget estimations, evaporation is one of the critical component in the water balance formulae, however in many studies evaporation is estimated due to lack of direct observations. (HWRP WMO, 2014). It is not easy to estimation evaporation from as there are a quite a number of criteria that can influence the evaporation rates. Factors such as climate status and physical geographical location of the water body and the surroundings. Further, the atmospheric moisture has the potential to transport stored heat energy in and out of the surface water body. However, the energy availability and the ease with which water vapour diffuses into the atmosphere fundamentally determines the evaporation rates. (Finch and Calver, 2008).

Evapotranspiration is often estimated with the assumption of mass and energy balances or a combination of the two, (Yirgalem *et al.*, 2008). Estimating evaporation using the Energy Balance Method of lakes is one of the best techniques for deducing evaporation according to Setegn *at, al.,* (2011). However, among many other methods the *Penman* (1948) has proven to be the most accurate method for estimation of evapotranspiration.

Modern studies show data can be downloaded from satellite images that process evaporation. *Muvudja et al.,* (2014) demonstrated that Catchment Potential Evapotranspiration (PET) data as well as lake surface evaporation data are acquired from Consortium of Spatial Information (CGIR-CSI) database of the CGIAR Global Research Partnership for a Food Sucure Future. These data had been generated using the data available from the World Clim Global Climate data as input parameters.

In the study of Lake General Carrera, Zambrano *et al.,* (2016) observed that the fact that the measurement stations along the lake do measure surface evaporation rather than the actual open water evaporation in the lake, regardless of the method of estimation, the annual water volume is not meaningful when compared with the outflowing water from the lake. Further to this it was found out that the average evaporation over the lake does not change the pattern of the outgoing water, while the average precipitation does change that of the incoming water fluxes. In many cases there are no rain gauges installed on the lake. However areal precipitation of lakes is calculated by interpolating between the off shore stations using an inverse distance weighted technique in ArcGIS. (Zhou *et al.,* 2013).

2.6 Lake Levels

Lake levels are a relative measure, not the actual depth of the lake but the difference between the actual levels to a point of reference known as a datum,. According to Muvundja *et al.,* (2014) on the study of the lake Kivu catchment noted that variations of levels of natural lakes, indicates changes in the hydrological budget either caused by variations in climatic parameters or shifts in runoff characteristics in the basin.

Awange *et al.,* (2008) showed that long-term analysis should incorporate climate parameters, in view of that lake levels are very sensitive to climate variations, similar in the study on Lake Victoria. In the study by Muvundja *et al.,* (2014) on Lake Kivu where the lake serves as the sole reservoir for the downstream hydropower dam observed that hydrological modelling provide useful information on the management of these dams. This is also true for Lake Malawi and the Shire River systems.

2.7 Hydrological Model

A hydrological model attempts to represent the reality of a water catchment area. Therefore being representation of hydrological system models are generally less complex than the real hydrological system and cannot always represent all the minute details of the system as discussed by Rwigi (2004) in a Comparative Case Study of Rainfall – Runoff models over the Nyando River Basin. A model is expected to simulate / estimate with accuracy the response of a system and through calibration information from the model can be used for planning, design and management of water resources. Hydrological models do aid in advancing the knowledge of how weather events influence catchment hydrology as discussed by Kalantari *et al.,* (2012) in assessing Usefulness of four hydrological models in simulating high-resolution discharge dynamics of a catchment adjacent to a road. According to Kalantari et al., (2012) suggested that in choosing models, some criteria have to be considered such as availability of input data; model availability; a model performance on an hourly basis; need for calibration and the results of previously tested models in practical applications. *Kalantari et al.,* 2012).

Mathematical catchment models may further be classified into two main groups, namely Determistic and Stochastic models. Determistic models attempts to simulate the physical hydrological processes in the catchment basically in the transformation of rainfall into effective runoff. These models imply a cause and effect relationship between chosen parameter values where results are obtained from the solution of certain prescribed equations. (Rwigi, 2004)

Estimating runoff in ungauged catchments is a frequent problem in hydrology. In hydrological modelling, prior knowledge about the physical system is often simulated by defining prior arrays feasible parameter values. In a study by Almeid *et al.,* (2013) parameter for data-scarce and estimation problems for gauged catchments are improved by measuring hydrological states and fluxes. However for ungauged catchments, data can just fed into the likelihood function. Almeid *et al.,* (2013). As such conceptual models are normally calibrated by specifying feasible parameter arrays and then taming parameter sets on observed system responses.

The SWAT model is a conceptual model that encompasses land use changes, soil and hydrological parameters. A study on Sustainable soil and water resources: modelling soil erosion and its impact on the environment by Sander *et al,* (2012) commented on soil and water being essentially important for providing enough food to meet world needs. Therefore the ongoing loss of soil volume and fertility from land use caused by soil erosion impact the global food production sustenance. Sander *et al,* (2012) also discussed that erosion to be the cause of eutrophication of inland surface water bodies, and underground water pollution.

It should be noted that that carrying out water balance study may be difficult if the largest part of its catchment is un-gauged and the inflow is unknown. However using a remote sensing approach yields the ungauged shortfall. (Deus *e, al.,* 2013)

The water-balance model for estimating natural stream flow, uses monthly precipitation, temperature, and Potential Evapotranspiration (PET) to estimate runoff from selected headwater basins and intervening sub basins of the River Basin. The water-balance model are calibrated and verified using historical climate inputs and stream flow data, according to Kelsey *et al.,* (2016). Monthly precipitation and temperature data for each of the data sets are aggregated to obtain seasonal total precipitation and average temperature. (Kelsey, *et al* 2016)

Typically a water balance model represent the catchment physical hydrological processes mathematically and describes the inflow and out flow within the hydrological. Water balance models are useful in water resources management as they aid in forecasting on the future increase or decrease of the yield in the catchment. *Kumambala & Ervine*, (2010). The impacts of climate change on hydrology usually are estimated by setting up scenarios for changes in climatic parameter inputs to a hydrological model. Conventionally rainfall/discharge data sets are integrated with the digital elevation maps data to construct a hydrological model that in turn simulates the water balance of water basins. *Bastawesy et al.* (2015). In the study by *Bastewesy et al* (2015) GIS was used to manipulate multiple datasets in development of distributed hydrological model for the Ugandan lakes of the Upper White Nile basin.

Like with other models, the SWAT model requires three dynamic inputs (monthly precipitation, average temperature, and PET) and two static inputs (soil water storage and permeability) to simulate natural stream flow at selected stream flow-gauging stations. Calibration of the model relies heavily on stream flow estimates at various gauging stations throughout the River Basin; therefore, selection of gauging stations with long and continuous stream flow records is critical. (Neitsch *et al.,* 2009).

2.8 SWAT Model

The Soil and Water Assessment Tool (SWAT) a river basin, scale model created in the early 1990s was essentially developed to predict the Impact of land management practices on water, sediment and agriculture chemical yields in large intricate watersheds with multiple soils, land use and management conditions over long spells of time. Neitsch *et al,* (2009). A paper by Neitsch *et al.,* (2009) stated that SWAT is a physically based model, require specific weather information such as rainfall/temperature, soil properties, terrain and land use practices of the catchment. This SWAT technique is unique rather than incorporating the regression equations to describe physical relationships between input and output variables parameters of the catchment.

According to Winchell *et al.,* (2013) SWAT directly models input data collected from and as a result of the physical water circulation, sediment transport, nutrient movements and crop growth. The SWAT model operates in the ArcSWAT an ArcGIS extension graphical user interface environment. In ungauged catchments, SWAT comes in as a solution as data modelling can be done and where the relative impact of substitute input data such as changes in land management practices, climate vegetation, etc on the water quality or other hydrological variables can as well be quantified.

In a study on analyzing long time series of hydrological data with respect to climate variability, Winchell, *et al.,* 2013 observed that SWAT is widely used in many countries including the U.S. and Europe to carry out assessment of the impact of global climate on water resources. Winchell, *et al.,* 2013 further stated that the SWAT model is also applied to support various catchments and water quality modelling assessments by evaluating the current with the projection be at national or regional scales. Winchell, *et al.,* 2013 observed that SWAT is a continuous time model, specifically designed to simulate runoff and can also be used for a detailed single event flood routing.

Modelling using SWAT, normally a watershed is demarcated into a number of sub-basin and these sub-units have different areas of land use even soil properties or soils dissimilar properties which impact the hydrology of the catchment.

Neitsch et al, (2009) discussed that modelling in SWAT, simulation of hydrology is divided into two parts. There is the land part of the hydrological cycle which overall takes controls of the amount of water, sediment load, nutrient cyclic and pesticide loads from each sub-basin to the main channel. The other part is the water routing phase of the hydrological process which takes care of the movement of water sediments along the channel network to the outlet of the catchment. In order to simulate the output from the watershed, the SWAT requires climatic parameters such as wind speed; relative humidity daily precipitation; minimum /maximum air temperature; and solar radiation.

SWAT model can generate daily weather data from average monthly values, however sub-basin values are generated autonomously and there is no spatial correlation of created values between or with other sub-basins values (Neitsch *et al,* 2009).

2.9 Impact of Climate Change on Lake Basins

In the last twenty years, research scientist have been actively conducting research on effects of climate change on water resources and have achieved significant results. Studies on runoff change show that climate change in different regions has different impacts on the quantity of water resources (Ligang Xu *et, al.* 2014). In high latitude areas and humid tropical areas runoff will increase by between 10% – 30 % by the middle of 21^{st} century while mid latitude areas and arid tropical areas the runoff will decrease 10% – 30 % due to reduced precipitation and increasing evapo-transpiration rate as described by Ligang Xu *et, al.* (2014).

The analysis of the impacts of climate change on the quantity of water in the Nile River Basin Tazebe *et al*., (2010) showed that the quantity of water increased with the precipitation enhancement in the early 20st Century. Moreover, until the mid 20st Century, the quantity of water decreased due to the precipitation reduction. Also Zhang *et al.* (2009) discussed that temperature rising and precipitation reduction is one of the important reasons for the reduction in river runoff in the middle reach of Yellow River in recent years.

Ye *et al*., (2013) noted that studies on different basins in different parts of the world have shown that, rainfall variation is the main factor affecting the quantity of water resources. The impact of temperature rising on water resources is mainly causing variations on rainfall, evaporation and other hydrological factors.

In other case studies Zilefac (2014), observed that using precipitation as a predictor to discharge in the basin, a very high correlation is found with a strong linear relationship between the two fields. However, a monotonic trends analysis on Lake Chad for discharge and precipitation between 1948 and 1988 showed most stations have experienced significant negative trends and that precipitation decreased by 19% with the 1965-1988 period accounting for 76% of the decrease while discharge decreased by 36% with the 1978-1988 period accounting for 86.7% of the decrease. This implies climate variability is responsible for Lake Chad water balance; the amplitude of water resources degradation is exacerbated by other causes which could be of anthropogenic origin, accounting for 17% of the discrepancy.

CHAPTER 3

3.0 Methodology

The data used in the study and methods used to achieved the objectives are presented in this section.

The methods that were used to achieve the objectives of the study included data screening and filling of missing data; trend analysis of rainfall, lake level, discharge, temperature and evaporation data of Lake Malawi basin; correlation analysis of rainfall and levels, correlation of levels and outflow; SWAT modelling to simulate the water yield into Lake Malawi; and used climate RCP4.5 scenarios projection data for future Impact evaluation of levels of Lake Malawi.

3.1 Climatological Data sets

For any research to be successful, it is dependent on the handling of and the quality of data. As such Inference is based on four key aspects i.e Hypothesis, Sampling, Designing and Interpretation. Therefore integral part of these four elements of Inference lies the 'data aspect'. (*Kothari,* 2004). Data collection, processing and analysis is important. This study collected multiple data sets from different sources in order to achieve the specific objectives.

The data used in this study were spatial data, hydrological and meteorological data. A brief discussion of availability, quality, statistics and management of these data sets is presented in this section.

3.1.1 Spatial Data

Spatial data include the Digital Elevation Model (DEM), land cover and soil types. The DEM was obtained from Regional Centre for Mapping Resources for Development (RCMRD) with ground resolution of 90m (http://geoportal.rcmrd.org/layers , 10th May 2016). Land use and soil type was obtained from Malawi Spatial Data Portal (MASDAP) (www.masdap.mw , 13th May 2016). These spatial data were for purpose of hydrological modelling using the SWAT model in ArcGIS 10.0 software.

3.1.2 Lake Levels

This is the measured elevation of the lake surface with reference to the mean sea level. Lake Malawi has three (3) lake level monitoring station i.e at Chilumba (17C1), at Nkhata-Bay (16G1) and at Monkey Bay (3A2). The lake level is the mean of these three stations. Measurements are manually read and taken twice a day in the morning and later in the afternoon. These stations have automated data collection facilities but were however not operational for period of this study. The water level data for Lake Malawi was collected from Ministry of Irrigation and Water Development, Department of Water Resources. The data length is from 1950s to 2015, however the study analysed 30 year period from 1985 to 2015 to justify as basis for minimum length for climatology study.

The Lake Malawi levels as described above is the mean of the three monitoring stations. Table 3.1 below tabulates the stations locations. The RGS is the Regular Gauging Station number which uniquely identifies each station as assigned by the Department of Water Resources in Malawi.

Table 3-1 Lake Level Monitoring Stations

Serial	**Name of Station**	**RGS No.**	**Latitude (°S)**	**Longitude (°E)**	**Elevation**
1.	Lake Malawi at Chilumba	17C1	-10.436367	34.244938	489.19
2.	Lake Malawi at Nkhata-Bay	16G1	-11.608556	34.294941	508.15
3.	Lake Malawi at Monkey-Bay	3A2	-14.082148	34.914824	486.24

3.1.3 Runoff

Discharge data is a product of stream flow level gauging procedure, conventionally converted from water level data using a specific rating curve unique for each hydrological station. The rating curve is generated by hydrologist from gauging procedures. This rating curve is a relationship between stage and discharge. However these gauging procedures are time consuming and costly to implement hence a rating curve developed to overcome this. Lake Malawi basin from Malawi's side has several hydrological stations and for the purpose of this study, one representative catchment was selected i.e South Rukuru which is in the northern part of Malawi. Since the northern part contributes the most lion share of the inflow and

South Rukuru is the biggest catchment in the region hence this was selected as a fair representative of the Inflow to the Lake. Further the South Rukuru contributes about 33% of inflow into the lake. Therefore analysis using the basin would give a general synopsis as part of Lake Malawi basin. The Department of Water Resources in Malawi operates a network of 157 water level monitoring station countrywide including the Lake Malawi basin. All the stations had data sets for different time periods but data ranges from 1950s to 2010.

South Rukuru River at Mlowe whose RGS number is 7G18 is on the downstream of the South Rukuru catchment into Lake Malawi. This station was used as the inflow into Lake Malawi. The station has a long time series dating from 1954 to date. Lake Malawi receives most of the inflow discharge from the northern part of Malawi, part of the central region and also from Tanzania.

In order to determine the amount of discharge into Lake Malawi, selected hydrological stations were selected as runoff into lake Malawi. Table 3.2 is a list of hydrological stations used for the Runoff inflow into Lake Malawi.

Table 3-2 Inflow Hydrological station into Lake Malawi

Serial	**Name of Station**	**RGS No.**
1.	Songwe at Mwandenga	9B7
2.	Lufira at Ngerenge	9A2
3.	North Rukuru at Mwakenja	8A5
4.	North Rumphi at Mphoka	7H3
5.	South Rukuru at Mlowe	7G18
6.	Lweya at Mzenga	16E15
7.	Bua at Tembwe	5C1
8.	Chirua River at Mtambe	15A1
9.	Lifyozi River at Nyoni	15B14
10.	Lingadzi River at Kaniche	15A8
11.	Dwambadzi at Nthanda	16E6
12.	Linthipe at Malapa	4B9
13.	Nadzipokwe River at Mua Mission	3E1

3.1.4 Meteorological Data

For the purpose of this study meteorological data consisted of Rainfall, Evaporation and Temperature data sets. Rainfall data sets are conventionally obtained by measurements using rain gauges. For this study daily interval data was used as an input to simulate discharge data in the SWAT model. However for time series analysis monthly precipitation was used for trend analysis over Lake Malawi. Evaporation data is normally collected from an Evaporation pan and Malawi uses the America Class A standard Evaporation Pan. The acquired data sets was computed using the Monthly PET Penman-Monteith (mm). The meteorological data sets were obtained from the Department of Climate Change and Meteorological Services (DCCMS). Table 3.3 is a list of meteorological stations that were used for this study. The station code M*i*, is used here only for the purpose of convenience.

Table 3-3 Rainfall and Evaporation Stations

Serial	**Name of Station**	**RGS No.**	**Latitude (°S)**	**Longitude (°E)**	**Elevation (m.a.s.l)**
1.	Karonga	M1	-9.952536	34.244938	486.6
2.	Vinthukutu	M2	-10.436367	34.244938	489.19
3.	NkhataBay	M3	-11.608556	34.294941	508.15
4.	MonkeyBay	M4	-14.082148	34.914824	486.24

3.1.5 Global Climatic Models Data

In order to simulate the future yield into Lake Malawi, the study acquired Global Climatic Models Data projections. The daily projected data was acquired from the Cordinated Regional Climate Downscaling Experiment (CORDEX) (www.cordex.org, 12th June 2016). The CORDEX was chosen as it has Africa climate projections simulated by the Representative Concentration Pathways RCA4. The CORDEX Data is a subset of Global Circulation Models from the CMIP5 project and has 9 models with the Representative Concentration Pathways (RCP) 4.5 and the 9.0 scenarios. Among the 9 models the MIROC model was chosen as the data almost close to the observed data. The 9.0 scenario was the extreme which was not used in this study but the study used the RCP4.5 scenario which stabilizes radioactive forcing at 4.5 watts per meter squared in the year 2100 without ever exceeding that value. (Thomson et al., 2012) The data resolution for the whole Africa domain is 0.44°.

The projected data from the MIROC model was from 2006 to 2100. The RCP4.4 scenario as mentioned above was selected among other scenarios simply because during the time of the study the CORDEX had three scenarios the 2.6, 4.5 and the 8.5. However the study did not look into the future extreme scenario i.e using the 8.5. The 2.6 scenario is the lowest emission where the 4.5 scenario tends to trade a middle part between the lowest emission 2.5 and the high emission 8.5 scenario. The 2.5 scenario is the STRONG mitigation of emissions which is very unlikely for Malawi and the 8.5 is the NO mitigation. Hence the 4.5 scenario bring in the balance as it is a more realistic and achievable. As such the 4.5 scenario balances this emission projection, hence its selection was justified for this study. (www.cordex.org, 12th June 2016).

3.1.6 Limitation of Data

Data availability and adequacy were the main limitations. As stated above the Department of Water Resources operates a river network of 157 stations, however due to financial constraints within the department most hydrological data are hard to find in adequate quantities. This is then characterised by prolonged missing data. In order to carry out a comprehensive water balance of Lake Malawi it was required to compute all the inflow into the lake.

3.2 Data Quality Control

The collection of hydrological data is crucial to evaluating the quantity and quality of the world’s water resources, as well as to improving knowledge understanding of the global hydrological processes. Hydrological data contribute to sustainable water resources management as well as to weather and climate-related scientific and application issues as stipulated in the HWRP WMO (2014).

Data quality is therefore a crucial component in any research and it is therefore important to subject data to various quality control checks before carrying out any research in order to establish their quality. Data quality control (QC) is a product oriented process to identify and flag suspect data after they have been generated. QC includes both automated and manual processes to test whether the data meet the necessary requirements for quality outlined by the end users as described by Abeysirigunawardena *et al.,* (2015).

Scientific test on hydrological data is crucial to ensure credible output as the data is acquired from different data sources, different instruments and varying data collection techniques. In a short communication on the critical values of the standard normal homogeneity test by Khaliqa & Ourda, (2007) stated that climatological data frequently contain homogeneities because of logistic issues, such as changing of station sites, equipment variations, and sometimes in the data collection methodology. Hence, it is crucial to critically look into homogeneity discrepancies in undertaking water balance studies. This can then be achieved by estimating for missing data using appropriate estimation techniques.

3.2.1 Estimation of Missing Data

Filling in of missing gaps in hydrological studies is very important to yield valuable and meaningful outputs. One very important aspect of hydrologic modelling is the estimation of the total precipitation and its distribution within a watershed. Missing data maybe estimated by many methods, which include the arithmetic mean, auto-correlation, regression analysis, isopleth's analysis, normal ratio, inverse distance and seasonal mean among other methods. (Elshorbagy et al., 2009). In this study filling in of missing rainfall data was done using the normal ration method.

$$\mathrm{Px} = \frac{1}{n}\sum_{i=1}^{i=n} \frac{Nx}{Ni} Pi$$

Equation (3-1)

Where: Where Px is the missing rainfall data for any storm at the interpolation station 'x', Pi is the rainfall for the same period for the same storm at the "ith" station of a group of index stations, Nx the normal annual rainfall value for the 'x' station Ni the normal annual rainfall value for 'ith' station.

Missing records were estimated by where significant correlation of $r_{x,y} \geq 0.5$. The sample linear correlation coefficient ($r_{x,y}$) was computed based on the following equation:

$$rxy = \frac{Cov(x, y)}{\delta x \delta y}$$

Equation (3-2)

The Arithmetic mean method was used to average the rainfall, temperature, water levels and evaporation records. In this study they were 3 meteorological stations were selected on the shore of Lake Malawi and the mean of these stations were identified as ideal to represent the average trend of this climatological factors over Lake Malawi. Equation gives the calculation of areal rainfall.

$$\bar{x} = \frac{1}{n}\sum_{1=n}^{n} xi$$

Equation (3-3)

Where n refers to the number of stations in the catchment, x_i refers to the daily recorded data by the i^{th} station and refers to the average value.

3.2.2 Homogeneity Tests

According to Machiwal and Jha, (2006) referred homogeneity as the data in the series that belong to a population, and hence have a time invariant mean and non-homogeneity evolves due to other reasons such as station changes, changes in methods. Sources of inconsistency in records would emanate from changes in observational procedures, e.g change of gauge plates. It is therefore important to test for homogeneity before carrying out any study using the data as the input. The quality of the data determines the reliability and accuracy of the hydrological model being used. Ahmad and Deni,(2013) pointed out that homogeneous climate series is classified as series which are only influenced by the changes in climate.

In this study Homogeneity test were carried in order to detect if the data sets over time belong to the same population. In general, when the hydrological data series is homogeneous, it means that data records were recorded with similar instruments, techniques, and environments.

This study used the SNHT for homogeneity test and this statistical test is illustrated below:

A statistic *T(d)* compares the mean of the first d years of the record with the last of *(n – d)* years which is written as:

$$T(d) = d\bar{z}\frac{2}{1} + (n-d)\bar{z}\frac{2}{2}, d = 1,2.........n$$

Equation (3-4)

$$\overline{z1}\frac{1}{d}\sum_{i=1}^{d}(y1-\bar{y})/s$$

and

$$\overline{z2} = \frac{1}{n-d}\sum(y1-\bar{y})/s$$

Equation (3-5)

are the mean values of *i z* during the first *d* years and the last (*n – d*) years respectively. A high *T* value in year *d* implies that a break is located in the year *d*. The test statistic T_0 is defined as:

$$T_0 = \max_{1 \le d \le 0} T(d)$$

Equation (3-6)

The probability of rejecting the null hypothesis when T_0 exceeds a certain critical value is depended on the sample size. Then the series would be classified as inhomogeneous at a certain level; e.g. 95% level of significance.

3.3 Basic Statistical analysis

Many statistical analysis assume that the sample of data set used for any study has a frequency distribution close to normal. Several statistical analyses of hydrologic time series data in water resources analysis are focused on the following key assumptions: the data is homogenous, stationary, has no shifting trends, non-periodic with no persistence. (Machiwal and Jha, 2006).

Basic statistical analysis was carried on water levels, annual rainfall, and runoff in order to establish the frequency distribution and variability of data in the Lake Malawi basin. Some statistics that were computed included computing the mean, maximum, minimum and the standard deviation on the data sets.

The standard deviation was computed using the following equation:

$$s = \sqrt{\frac{\sum (x - \overline{x})2}{n - 1}}$$

Equation (3-7)

Where: s = Standard Deviation, x = each value in the data set, $\bar{x}$ = Mean of all values in the data set, n = Number of values in the data sets.

3.4 Standardisation of Data sets

In order to analyse hydrological data sets of different climatological parameters, there is need to standardize the data sets in order to bring all the variables into proportion to one another, i.e to be in the same comparable units. This was done through the normal standardization using the following equation:

$$X_i = \frac{X_i - \overline{X}}{\sigma}$$

Equation (3-8)

Where: X_i = Each Data point I, $\bar{X}$ = is the Mean of the Sample population data, S_x = is the sample deviation of all sample data points. The standardization was done on water level, rainfall, temperature and discharge data sets. This was plotted in order to compare and contrast the trends in the time series of climatological parameters.

3.5 Testing for Normal Distribution

Water levels data was tested for frequency normal distribution test using the Kolmogorov-Smirnov test: which is a is a nonparametric test of the equality of continuous, one-dimensional probability distributions that can be used to compare a sample with a reference probability distribution (one-sample K–S test), or to compare two samples (two-sample K–S test). (Chakravarti, *et al.*, 1967).

$$F_n(x) = \frac{1}{n}\sum_{i=1}^{n} I\left[-\infty, x\right](X_i)$$

Equation (3-9)

Where: $I_{[-\infty,x]}(X_i)$ is the indicator function, equal to 1 if $X_i \leq x$ and equal to 0 otherwise Kolmorog statistics given as:

$$D_n = \sup_x |F_n(x) - F(x)|$$

Equation (3-10)

Where Sup $_x$ is the supremum of the set of distances. If the sample comes from distribution F(x) then D_n converges to 0 almost surely in the limit when n goes to infinity.

3.6 Trend Analysis

Time series is a plot of time sequence against hydrological data. The main aim of carrying time series data analysis is to spot and define quantitatively each of the causing processes underlying on a given order of records (Machiwal and Jha, 2006). Time series analysis in hydrology is used to support water resources experts in building mathematical models to generate hydrologic records for hydrological forecasting, trends and shift detection and commonly to fill in missing data and extrapolation (Machiwal and Jha, 2006). In this study a time series plot for rainfall, evaporation, temperature and water levels was analysed for trends.

Different statistical test methods are used to detect trends in hydrological and hydro meteorological time series; these are classified as parametric and nonparametric tests. *Ahmad et al.*, (2014). The most common nonparametric tests for working with time series trends are the Mann-Kendall. *Kendall* (1975) (MK) and Spearman's rho tests. In this study the MK was used to detect significant trend analysis for all the hydrological and meteorological data sets. The Mann-Kendall test is the most common one used by researchers in studying hydrologic time series trends. The generation of the Mann-Kendall and standardized test statistics is shown in the following mathematical equation:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sig}\left(X_j - X_i\right),$$

$$\operatorname{sgn}\left(X_j - X_i\right) = \begin{cases} +1 & \text{if } \left(X_j - X_i\right) > 0 \\ 0 & \text{if } \left(X_j - X_i\right) = 0 \\ -1 & \text{if } \left(X_j - X_i\right) < 0, \end{cases}$$

$$V(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\left(t_p - 1\right)\left(2t_p + 5\right)\right],$$

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{VAR}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{VAR}(S)}} & \text{if } S < 0. \end{cases}$$

Equation (3-11)

In these equations, X_i and X_j are the time series observations in chronological order, n is the length of time series, t_p is the number of ties for pth value, and q is the number of tied values. Positive Z values indicate an upward trend in the hydrologic time series; negative Z values indicate a negative trend. If $| Z | > Z_{1-\alpha/2}$, (H_0) is rejected and a statistically significant trend exists in the hydrologic time series. The critical value of $Z_{1-\alpha/2}$ for a p value of 0.05 from the standard normal table is 1.96.

3.7 SWAT model

SWAT was selected for this study to simulate the water yield in into Lake Malawi. The model is a free software available on the internet and as such there were no additional cost. The SWAT is a popular model among many watershed hydrologists interested in studying the impact of agricultural activities and land use management on the overall watershed health including stream flow and water quality. (Neitsch *et al.*, 2009). The model is an open source software that can be duplicated for any watershed but requires Digital Elevation Model (DEM), Soil type data for Lake Malawi catchment and land use data which already have been acquired for this study. Using the model, simulation of the water yield into Lake Malawi was achieved.

The South Rukuru catchment was delineated and Hydrological Response Units (HRU) were generated. Using the DEM the slopes of the catchment were determined and river channels were generated. The model was fed in with daily rainfall data for the catchment, soil and land use data and the model generated discharge data.

Therefore in order to simulate the water yield of Lake Malawi, daily rainfall acquired from Global climatic data was fed into the model to project the water yield from 2006 to 2100. SWAT as conceptual model computes the water balance based on the following equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

Equation (3-12)

Where: SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day *i* (mm H_2O), Q_{surf} is the amont of surface runoff on day i (mm H_2O), E_a is the amount of evapotranspiration on day *i* (mm H_2O), W_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm H_2O), and Q_{gw} is the amount of return flow on day *i* (mm H_2O) (Neitsch *et al.*, 2009).

Monthly time series time series data sets of more than 30 years were acquired to analyse and determine the trend of climatological factors impacting the lake level fluctuations. The basic and commonly used water balance equation of lakes is simply the inflow (i.e precipitation, runoff, Groundwater Inflow) less the outflow results in the change of storage. In the context of Lake Malawi the equation can be expressed as follows:

$$\pm\Delta S = P - O_{Shire} + R + G_{inflow} - ET$$

Equation (3-13)

Where: $\pm\Delta S$ = Change in Storage, P = Precipitation, O_{Shire} = Outflow into the Shire River, G = Groundwater Inflow, R = Runoff, ET = Evapotranspiration.

In Calculating evaporation and rainfall, *Zambrano et al* (2016) suggested that to complete a lake water balance computation you require the water inputs and outputs volume from rainfall and evaporation. Therefore the Thiessen polygons method (Hartkamp et al. (2001), which accounts for that is expressed below:

$$P_m = \frac{\sum^{n} I = 1P1.Ai}{\sum I = 1Ai}$$

Equation (3-14)

Where Pi is the precipitation of station I, Ai is the area of the influence of station I, *N* is the number of stations and P_m is the average rainfall in the basin. Errors due to this estimation (usually due to over or under estimation of areas of influence) are considered within the margin of error of computing the water balance. The balance is estimated in units of volume, so each of the variables involved in estimating the balance should be converted to units of volume. This is computed monthly over the climatology data. Of course, the closer to the in situ station, the greater the accuracy of the determined amounts of precipitation and evaporation water inputs and outputs, respectively.

3.7.1 Future Projection on Impacts of Climate Change on Lake Levels

The SWAT model was also used to simulate future inflows and outflows that were computed with baseline values to determine impacts of climate change on lake levels. The impact of future Lake Malawi levels was evaluated based on the following equation:

$$IMPACT = \frac{FL - BL}{BL} \, x \, 100$$

Equation (3-15)

Where: FL = Future Level, BL = Baseline level

The projection was divided into 3 sets the Baseline Level starting from 2006 to 2035, the Near Future from 2036 – 2065 and the Far Future from 2066 to 2095.

CHAPTER 4

4.0 Results and Discussions

This chapter discusses the results from the various methods used in this study. The study was based on the assumptions that the data acquired reflect the true outcomes from the hydro-meteorological sites sourced from respective line institutions as well as the GCM data.

The following sub section discusses the findings:

4.1 General Pattern of Rainfall over Lake Malawi

Rainfall over Lake Malawi varies over time and the frequency distribution as shown in 4.1 shows that monthly rainfall between 0 – 50mm has a high frequency implying that there are more months with low or no rainfall. Therefore rainfall as the main source and contributory of increase in levels of Lake Malawi, with this frequency distribution levels of Lake Malawi will rise for a short period and recced in the preceding months.

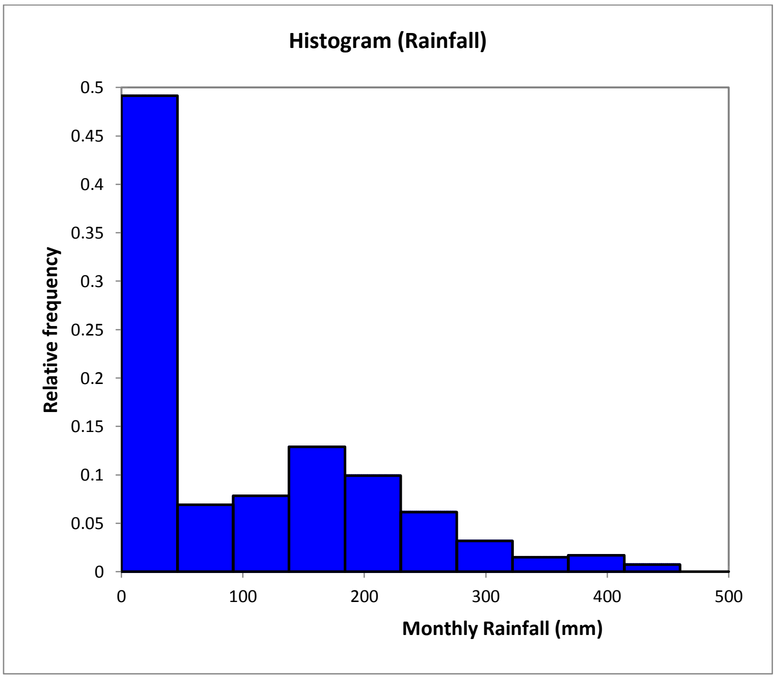

Figure 4-1 Histogram for Monthly Rainfall over Lake Malawi

The results from Table 4.1 demonstrates that the frequency distribution of rainfall over lake Malawi lying between the 0 – 46 is the most occurrence period over lake Malawi. This implies as discussed above expected low or no rainfall periods are dominant over the lake. The results from the table show that the peak rainfall experienced on Lake Malawi has a very low frequency simultaneously interpreting that the peak levels observed on Lake Malawi has a low probability of occurrence.

Table 4-1 Descriptive statistics for the Rainfall intervals Over Lake Malawi:

Lower bound	Upper bound	Frequency	Relative frequency	Density
0	46	263	0.492	0.011
46	92	37	0.069	0.002
92	138	42	0.079	0.002
138	184	69	0.129	0.003
184	230	53	0.099	0.002
230	276	33	0.062	0.001
276	322	17	0.032	0.001
322	368	8	0.015	0.000
368	414	9	0.017	0.000
414	460	4	0.007	0.000

Rainfall over Lake Malawi from 1968 to 2015 has been varying over time seasonally and over orbital time scales. Figure 4.2 shows rainfall pattern from 1969 to 2015 where only the effective rainfall months from November to June. The dry period have been omitted in order to determine the actual trends and it shows rainfall is decreasing statistically insignificant with MK seasonality test also showed a decrease a p-value of 0.044 implying that there is also seasonal decrease in rainfall patter over Lake Malawi.

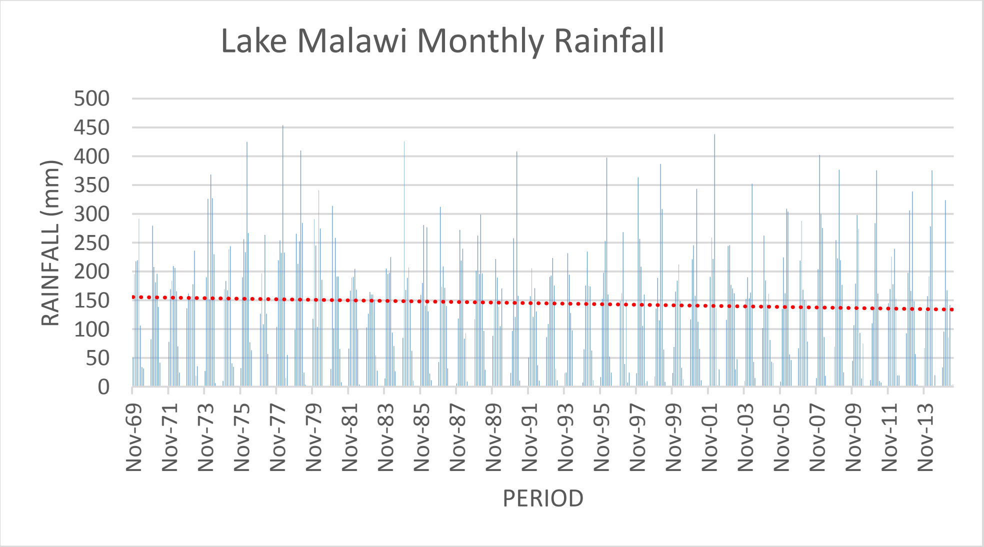

Figure 4-2 Mean Monthly Rainfall over Lake Malawi

4.2 Runoff into Lake Malawi

Runoff into Lake Malawi was simulated with the SWAT model. The South Rukuru catchment was delineated using the SWAT model and land use maps and soil maps were added on the catchment were later used to simulate discharge data into Lake Malawi. Figure 4.3 shows the delineated catchment of South Rukuru basin a representative of inflow into Lake Malawi. The model created HRU for the catchments and one single outlet.

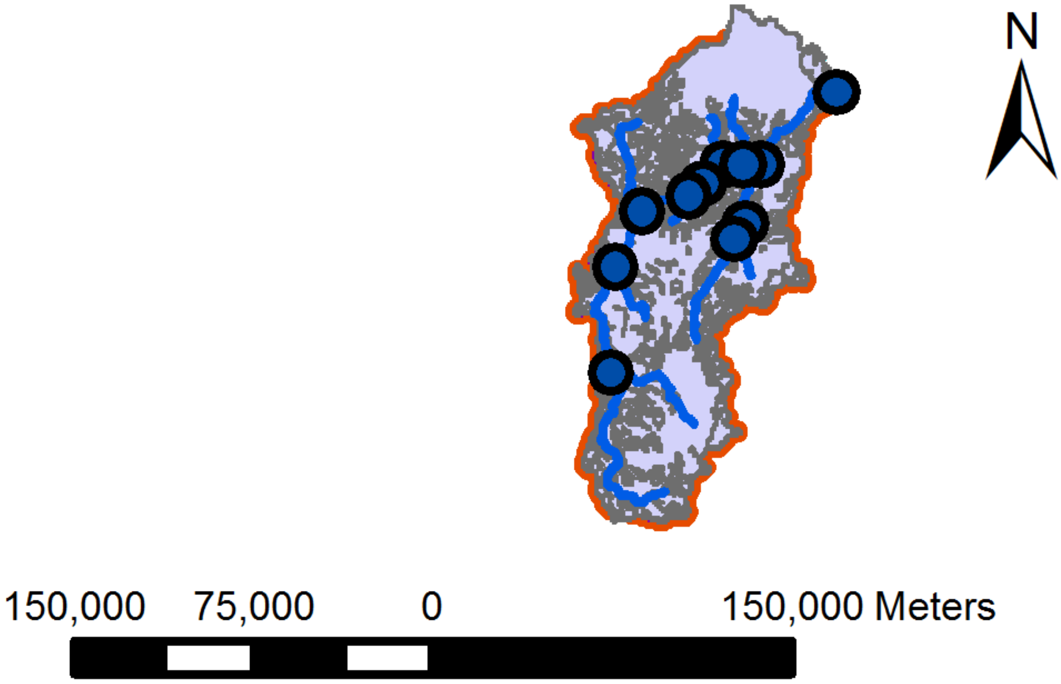

Figure 4-3 South Rukuru Catchment

The delineated catchment has a minimum elevation of 478 m.a.s.l and a maximum elevation of 2548 m.a.s.l. This also describes the gradient of the catchment and flow direction of water in the basin. The following statistics from the model the following statistics were generated:

Statistics:

Min. Elevation: 478
Max. Elevation: 2548
Mean. Elevation: 1347.61227855443
Std. Deviation: 263.630295580604

The delineated catchment resulted in 21 sub basins and the watershed catchment area of 1,232,237ha. Table 4.2 also shows that the catchment had 9 classified soil types and has 7 types of land use with Forest and Agriculture land use dominant in the catchment. These soil types and land use have impact on the hydrology of the basin.

Table 4-2 Land Use, Soil and Slope Distribution of South Rukuru

		Area [ha]	**Area[acres]**	
Watershed		1,232,237	3,044,919	
Number of Subbasins: 21				
		Area [ha]	**Area[acres] %Wat.Area**	
LANDUSE:				
Forest-Evergreen	→ FRSE	510,469	1261394.5540	41.43
Eastern Gamagrass	→ EGAM	38,457	95029.5064	3.12
Cocoa Tree	→ COCT	228,960	565771.8190	18.58
Agricultural Land-Close-grown	→ AGRC	448,344	1107881.4618	36.38
Water	→ WATR	3,290	8130.3158	0.27
Commercial	→ UCOM	2,669	6594.6481	0.22
Timothy	→ TIMO	47	117.1881	0
SOILS:				
	AGAWAM	7,096	17535.8014	0.58
	BLASDELL	38,930	96198.0326	3.16
	COLRAIN	33,337	82378.2212	2.71
	DUXBURY	832,986	2058348.8326	67.6
	ELDRIDGE	39,757	98241.5155	3.23
	ELMWOOD	104,623	258528.0336	8.49
	FREDON	21,626	53438.5052	1.76
	KARS	22,472	55530.1575	1.82
	WHATELY	131,410	324720.3936	10.66
SLOPE:				
	0-10	793,714	1961306.5183	64.41
	30-10	339,925	839971.6678	27.69
	30-9999	98,598	243641.3070	8

The study shows that the inflow into Lake Malawi from South Rukuru river has decreased over time. Figure 4.4 shows that the decrease was insignificantly with a p-value of 0.001 from the MK test and also true for the seasonality trend. The drop in the discharge would be as a result of the decrease in precipitation over south Rukuru which has also decreased insignificant. However the drop in the runoff of South Rukuru would be attributed to anthropogenic land use practices on South Rukuru catchment. However the study did not focus on the land use management of South Rukuru.

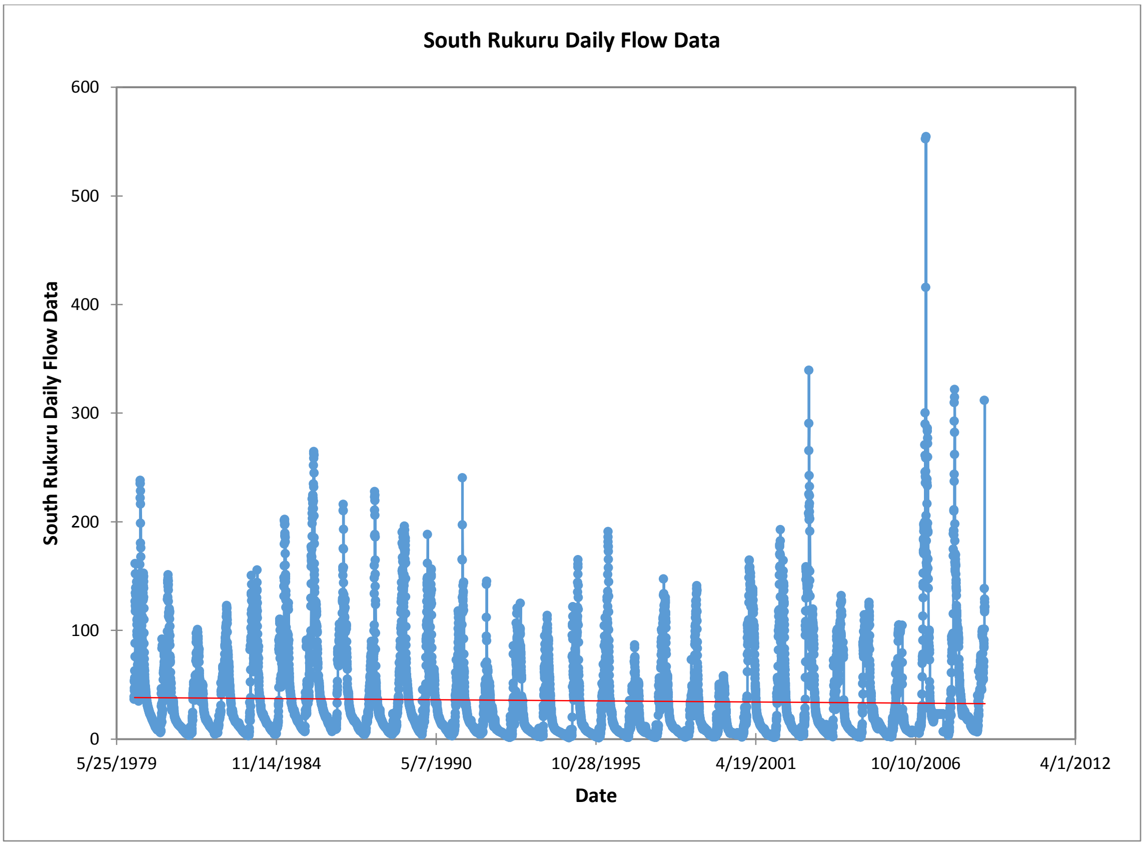

Figure 4-4 Daily Flow Graph for South Rukuru River

Similar to rainfall variations, the study also found out that the inflow into Lake Malawi also determine the levels. Figure 4.5 illustrate that monthly mean levels respond to the monthly mean inflow where there is an increase in inflow there is also an increase to the levels and the same happened when there is a decrease.

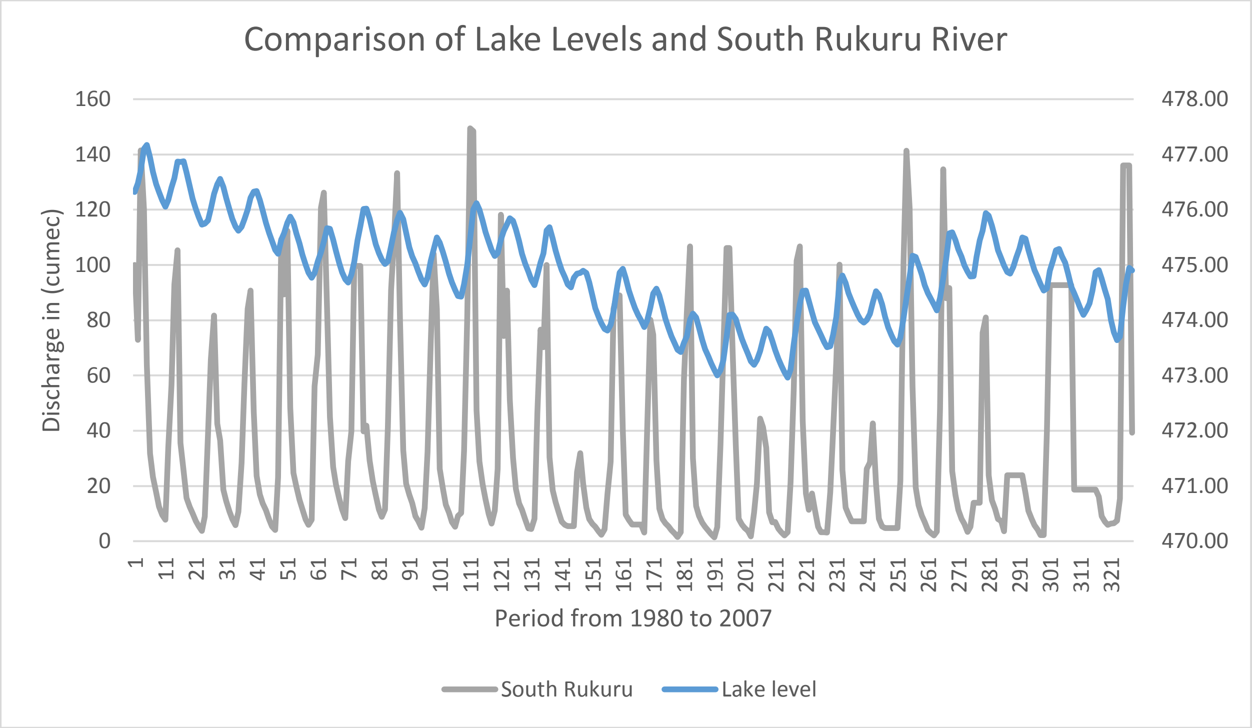

Figure 4-5 Comparison of lake levels and South Rukuru

4.3 General Evaporation Pattern over Lake Malawi.

Figure 4.6 show the evaporation trend over Lake Malawi. Statistical test showed that evaporation over Lake Malawi is decreasing significantly with the MK test detected a p-value of 0.003 meaning that there is a trend in the time series.

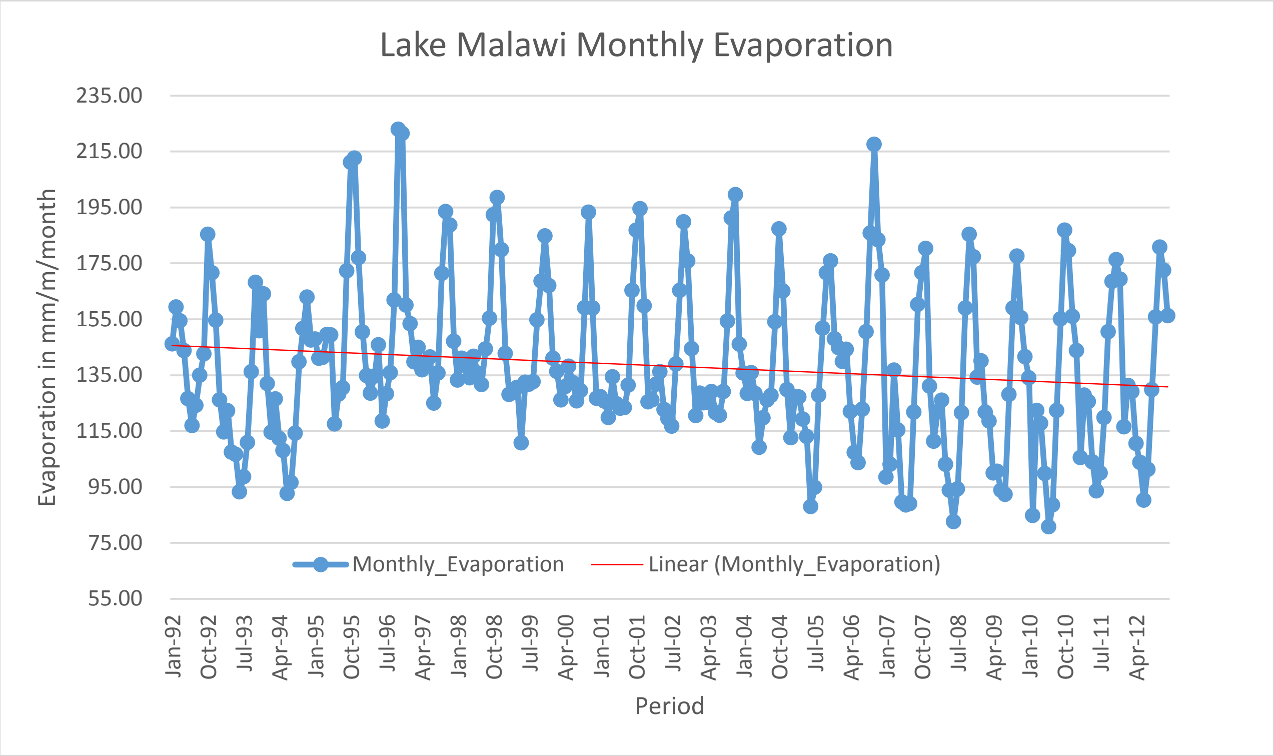

Figure 4-6 Trend Test on Lake Malawi Monthly Evaporation Data

In Table 4.3 the study showed that from 252 observations of evaporation records from 1992 to 2012, the maximum evaporation on Lake Malawi was 222.825 and minimum evaporation at 80.750. The minimum evaporation was recorded in the cold months of the year i.e May, June, and July periods.

Table 4-3 Evaporation statistics over Lake Malawi

Variable	Observations	Minimum	Maximum	Mean	Std. deviation
Monthly Evaporation	252	80.750	222.825	138.234	28.445

Kendall's tau	-0.124
S	-3934.000
Var(S)	1788613.333
p-value (Two-tailed)	0.003
Alpha	0.05

4.4 Temperature Trends over Lake Malawi

In the northern and central part of Lake Malawi the MK test showed an increase in temperature while the southern part showed a general stable conditions. However figure 4.7 shows the monthly mean Temperature over Lake Malawi increasing but statistically insignificant. Temperature variations over Lake Malawi has seen an insignificant increase over time, however unlike other climatological parameters, temperature varies less than other parameters.

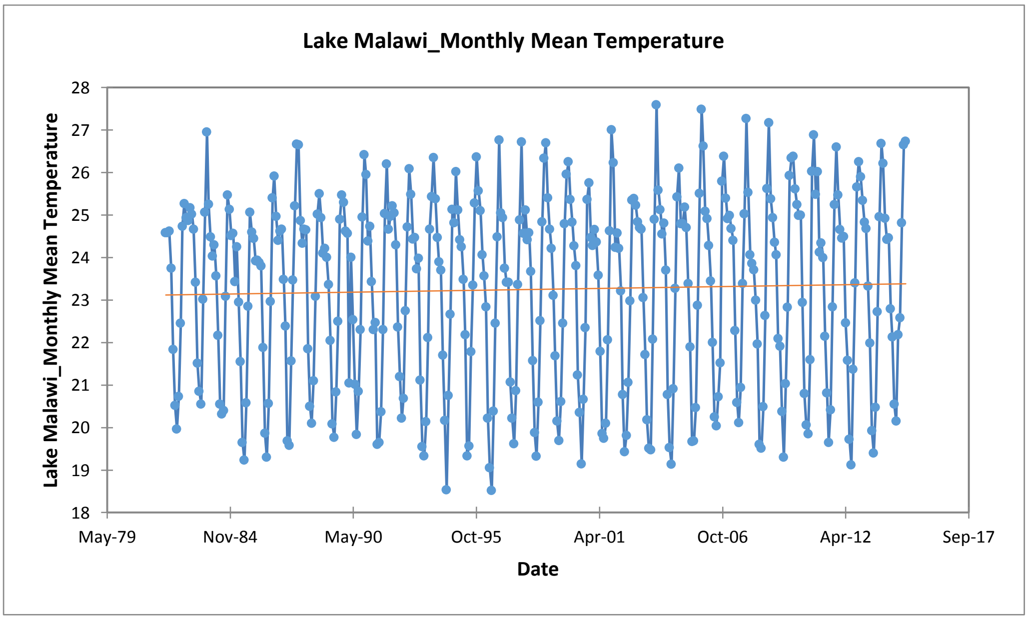

Figure 4-7 Lake Malawi Monthly Mean Temperature

The MK seasonality test showed a p-value of 0.461 as shown in Table 4.4 implying that there is no trend in the data, therefore temperature has not changed over 1979 to 2012. From the table the temperatures vary from a minimum of 18 to a maximum of 27 degrees annually.

Table 4-4 Trend Test statistics for Lake Malawi Mean Temperatures

Summary statistics:

Variable	Observations	Minimum	Maximum	Mean	Std. deviation
Lake Malawi_Monthly Mean Temperature	396	18.517	27.594	23.253	2.209

Mann-Kendall trend test / Two-ailed test (Mean Temperatures):

Kendall's tau	0.026
S	1988.000
Var(S)	6873571.333
p-value (Two-tailed)	0.449
alpha	0.05

4.5 General Pattern of Lake Malawi Levels.

In the study as shown on Figure 4.8 shows the general cyclic behaviour of Lake Malawi from 1970 to 2015. From 1970 to 2015 the lake has a unique pattern over years where there are sharp rises as well as decreases. In order to understand the causes of these cyclic variations the data set was split into decadal portions to examine the influence of other climatological parameters.

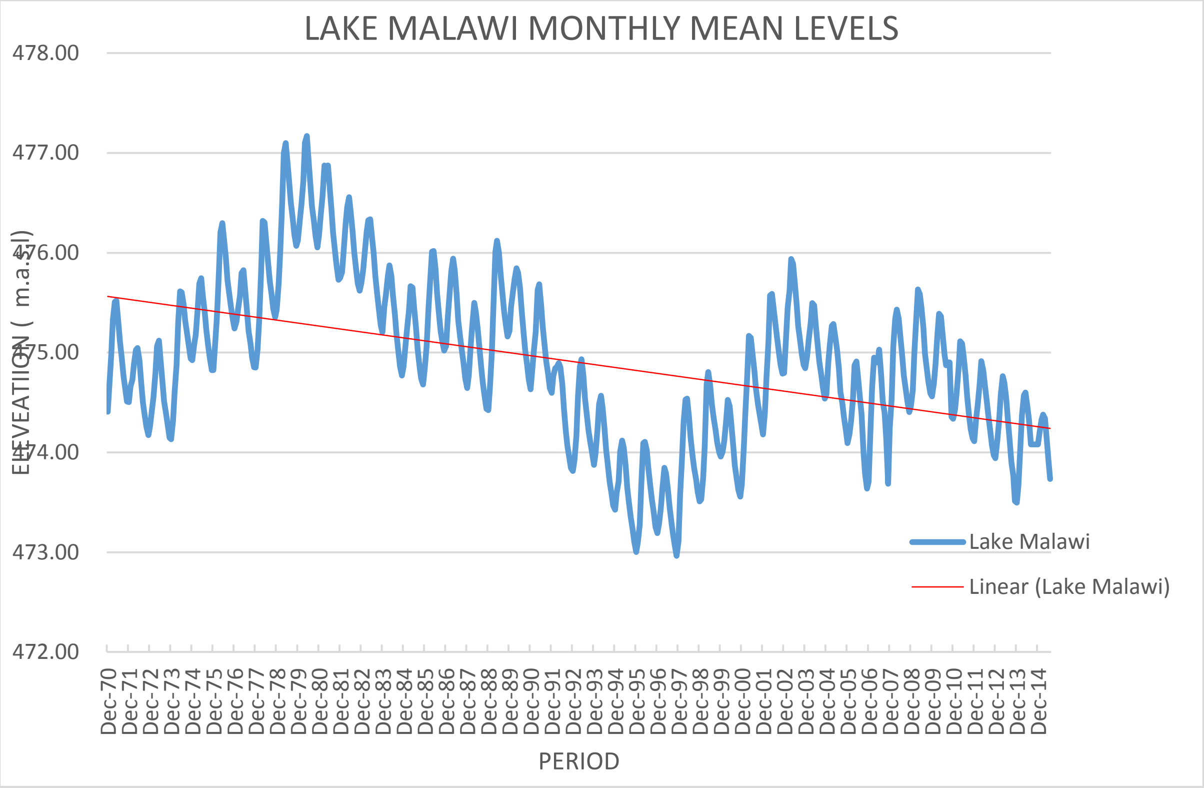

Figure 4-8 Lake Malawi Monthly Mean Levels from 1970 to 2015

The trend test on the levels was conducted and Figure 4.5 tabulates the test statistics where monthly mean levels deviate with 0.819 and the mean for the population is 474.901 m.a.s.l. The MK test resulted in a p-value of 0.001 indicating that there is a trend in the data and the kendall ‘s tau of -0.316 thus a negative trend.

Table 4-5 General Lake Malawi Levels Statistics

Summary statistics:

Variable	**Observations**	**Minimum**	**Maximum**	**Mean**	**Std. deviation**
Lake Malawi	536	472.964	477.169	474.901	0.819

Kendall's tau	-0.316
S	-45358.000
Var (S)	17157768.667
p-value (Two-tailed)	< 0.0001
alpha	0.05

A homogeneity and trend test was conducted for Lake Malawi Mean levels for the period 1970 to 2015. Test conducted on lake Malawi levels using the SNHT showed that the data is not homogeneous over the period from 1970 to 2015. Figure 4.9 shows the homogeneity test on the levels and as earlier on discussed homogeneity can be a result of different environmental changes to the station, measurement or data observation. Consultation were conducted where the data was sourced and it was found out that no major changes occurred at the observational sites, this being the case the data has been accepted on conditions that the study would like to further probe the causes of the declining of the levels as an impact to changes on climatological parameters.

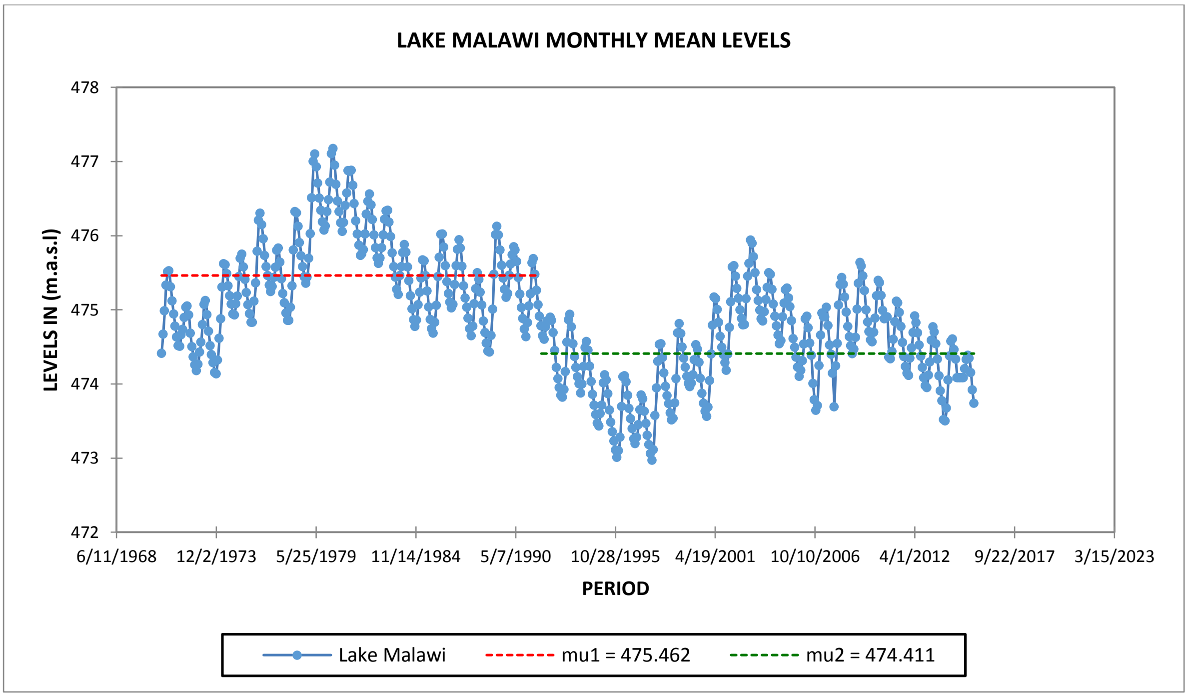

Figure 4-9 Homogeneity Test for Lake Malawi levels

The levels were tested for frequency distribution and Figure 4.10 shows the frequency distribution of levels. The results show that the monthly Lake Malawi levels have a normal distribution i.e bell shaped. From the figure this also entails that the peak and low levels have a very frequency occurrence over time.

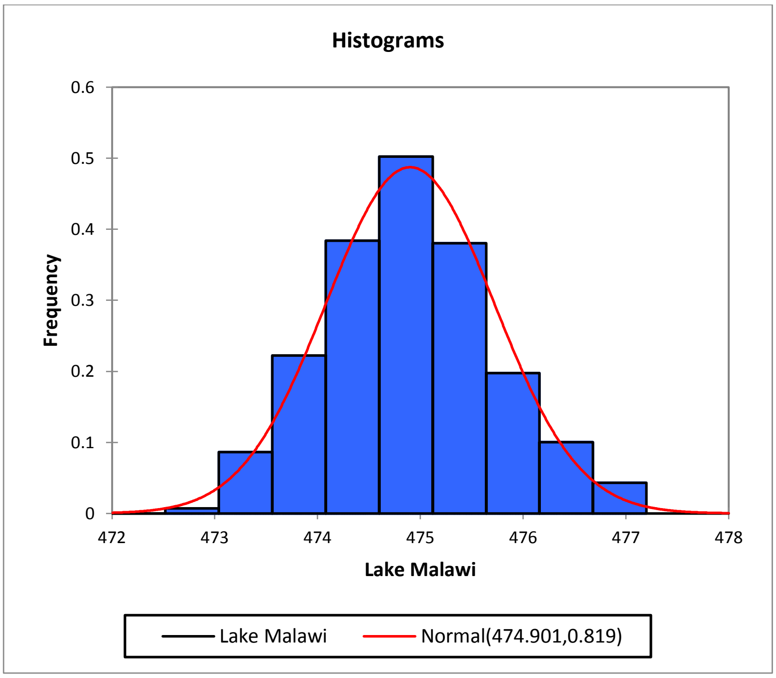

Figure 4-10 Histogram for Lake Malawi Levels

The normal distribution statistics of levels are shown in Figure 4.6 where the peak levels in the region of 476.68 to 477.2 occurred just 12 times from 1970 to 2015 and the lowest levels of the time series in the bound between 472.52m.a.s.l and 473.04m.a.s.l occurred only twice. In reference to the statistics the probability of the levels in the future to drop below 473.04 are very slim, similarly for the future levels to go beyond 476.68 m.a.s.l has a low frequency occurrence.

Table 4-6 Descriptive Frequency Statistics for Normal Distribution for Lake Malawi Levels

Lower bound	Upper bound	Frequency	Relative frequency	Density (Data)	Density (Distribution)
472	472.52	0	0.000	0.000	0.002
472.52	473.04	2	0.004	0.007	0.010
473.04	473.56	24	0.045	0.086	0.039
473.56	474.08	62	0.116	0.222	0.107
474.08	474.6	107	0.200	0.384	0.199
474.6	475.12	140	0.261	0.502	0.249
475.12	475.64	106	0.198	0.380	0.211
475.64	476.16	55	0.103	0.197	0.121
476.16	476.68	28	0.052	0.100	0.047
476.68	477.2	12	0.022	0.043	0.012

4.5.1 Lake Levels and Rainfall Correlation

The study analysed the relationship that exists between rainfall and lake levels as a first step into analysing further interactions that influence the fluctuations of lake levels. Table 4.7 show the correlation computations of lake levels and rainfall between the years 1970 to 2015.

Table 4-7 Correlation between Lake Levels and Rainfall from 1970 -2015

1970 to 1980

	Rainfall	*Lag0*	*Lag1*	*Lag2*	*Lag3*	*Lag4*
Rainfall	1					
Lag0	0.033601	1				
Lag1	0.308935	0.951728	1			
Lag2	0.466323	0.830792	0.95278	1		
Lag3	0.507764	0.68153	0.836322	0.95464	1	
Lag4	0.443879	0.546652	0.695262	0.843984	0.956793	1

1990- 2000

	Rainfall	*Lag0*	*Lag1*	*Lag2*	*Lag3*	*Lag4*
Rainfall	1					
Lag0	-0.03434	1				
Lag1	0.239717	0.94976	1			
Lag2	0.415905	0.817006	0.947095	1		
Lag3	0.483523	0.637464	0.8095	0.945422	1	
Lag4	0.409215	0.458783	0.625598	0.804732	0.94439	1

2000 to 2010

	Rainfall	*Lag0*	*Lag1*	*Lag2*	*Lag3*	*Lag4*
Rainfall	**1**					
Lag0	0.026181	1				
Lag1	0.365631	0.912863	1			
Lag2	0.574094	0.708616	0.912383	1		
Lag3	0.619024	0.442142	0.705494	0.911001	1	
Lag4	0.515092	0.176709	0.435492	0.701179	0.909838	1

2010 to 2015

	Rainfall	*Lag0*	*Lag1*	*Lag2*	*Lag3*	*Lag4*
Rainfall	1					
Lag0	-0.04751	1				
Lag1	0.287688	0.899074	1			
Lag2	0.504579	0.661883	0.890727	1		
Lag3	0.551146	0.367333	0.640002	0.88398	1	
Lag4	0.38806	0.095928	0.329749	0.618592	0.878499	1

The correlation between Lake Levels and rainfall show that the Lake respond to rainfall after 2 to 3 months with a mild correlation exists on lag3 which is 3 months. However there is no good correlation of rainfall and Lake Malawi levels. This implies that there are other climatological factors that have effect on the levels of Lake Malawi.

4.5.2 Standardised Pattern of Lake Levels and Rainfall between 1970 – 1980

During the period 1970 – 1980 The levels of Lake Malawi show a significant rise. However rainfall has also a rise but not significant. Figure 4.11 shows that levels only rise when rainfall is above long term average. The lake rainfall relationship also shows that when rainfall is below long term average levels began to drop.

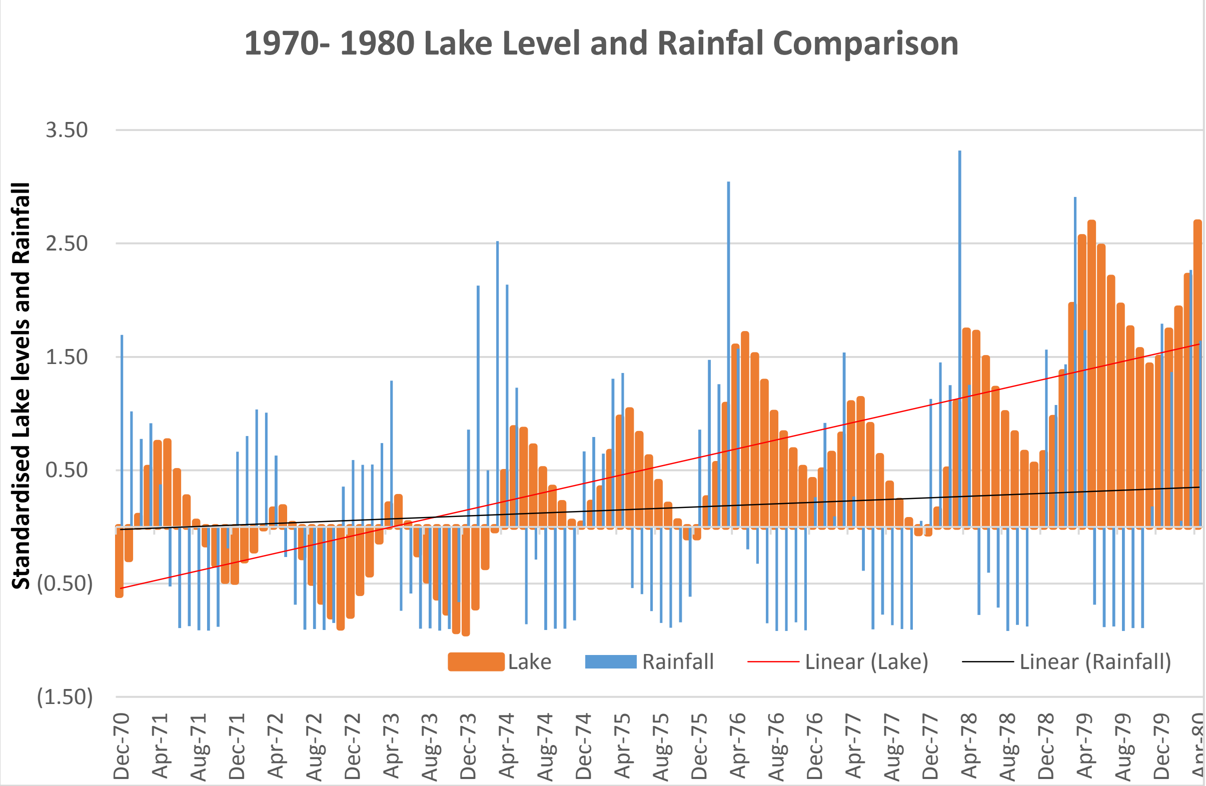

Figure 4-11 Standardised Lake level and Rainfall between 1970 – 1980

The inflow runoff to the lake was analysed based on the discharge into the lake and Figure 4.12 shows the inflow and lake level analysis from 1970 to 1980. The levels responded with a positive trend increase as a result to the increase in inflow. The significant rise in levels was observed from 1974.

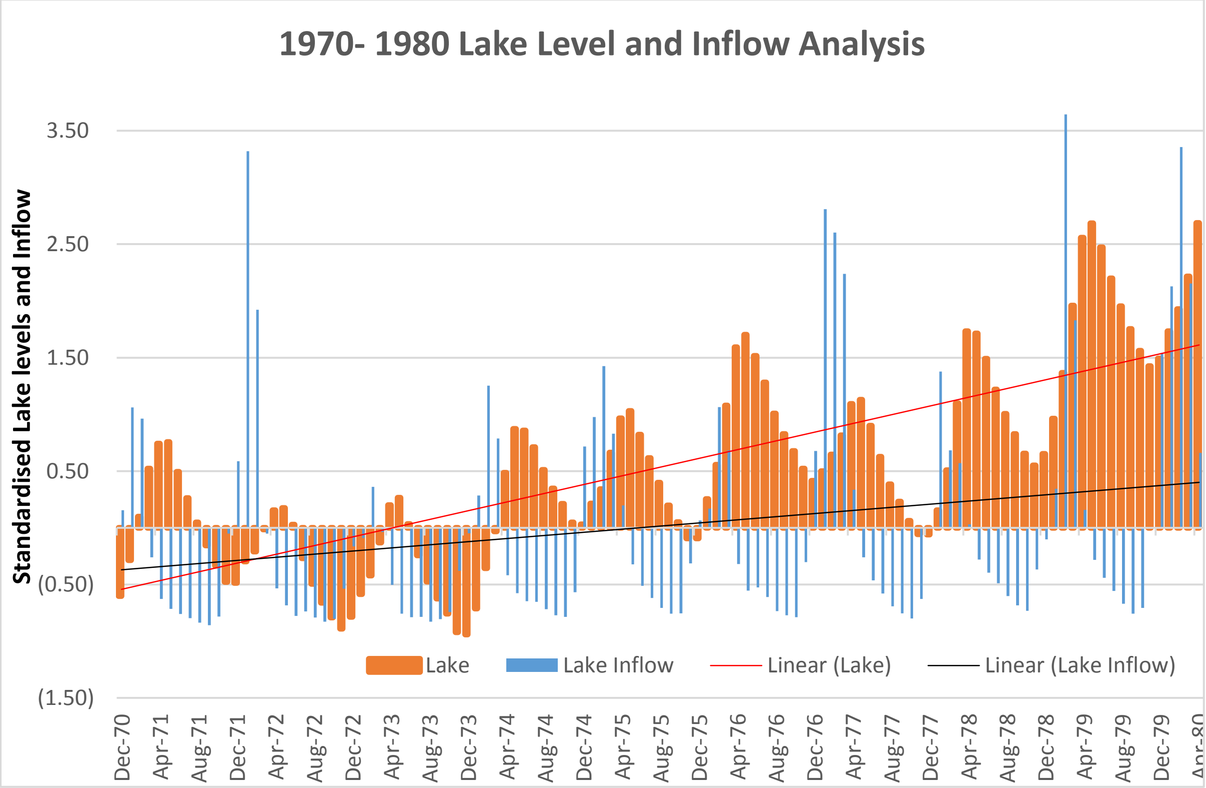

Figure 4-12 Standardised Lake level and Inflow between 1970 – 1980

4.5.3 Standardised Pattern of Lake Levels and Rainfall between 1980 – 1990

The period 1980 – 1990 Lake levels / Rainfall analysis as shown in figure 4.13 depicts a decrease trend even though rainfall has a very insignificant rise. However rainfall is just below the long term average. As noted when rainfall is at normal or below the long term average the Lake levels began to drop. This situation was worsened with the inflow into the lake with no trend and most of the years the inflow was just below normal as seen in Figure 4.14.

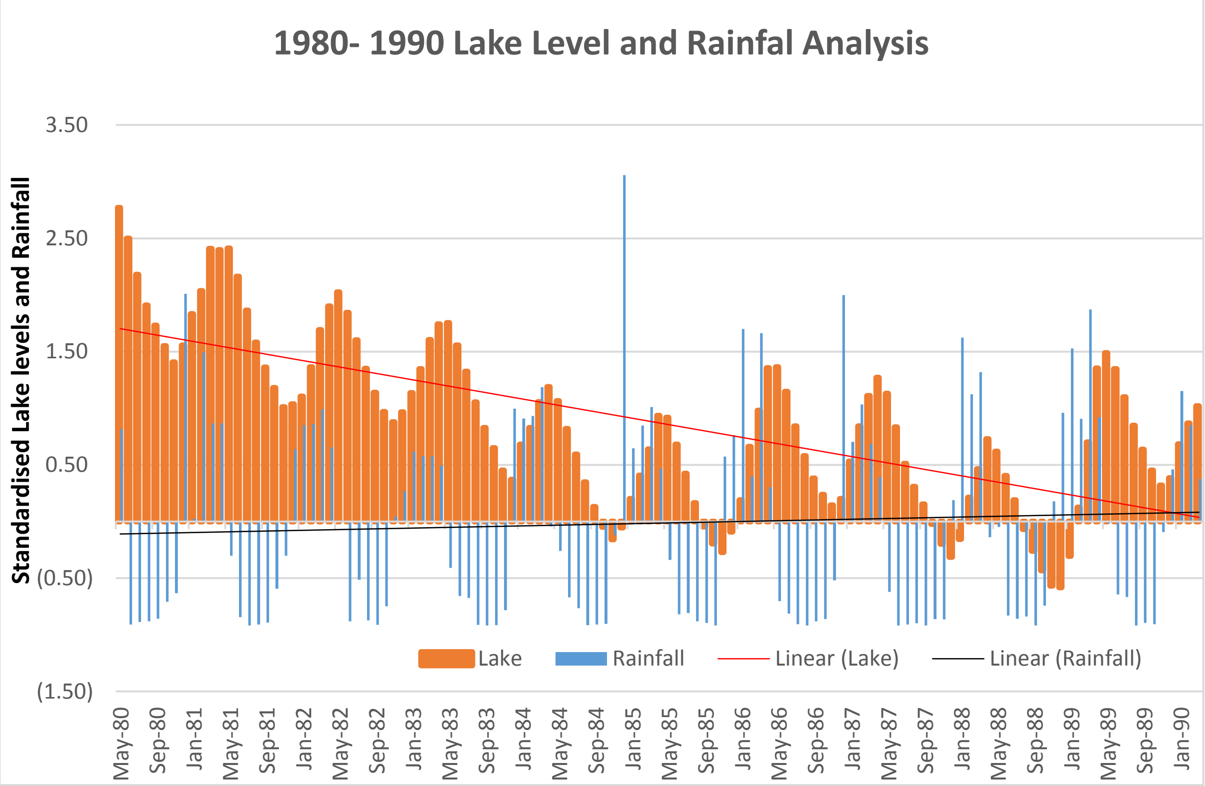

Figure 4-13 Standardised Lake level and Rainfall from 1980- 1990

The decadal 1980 to 1990 show a significant drop in levels as illustrated in figure 4.14. Analytical this was as result of the inflow yield was mostly below normal. Further the inflow show no trend during the same period. As observed levels are very sensitive to rainfall and inflow trends such that if rainfall and inflow are at long term average or below long term average the levels began to drop. In the case where the inflow in most of the years was below normal then a sharp decrease is experienced as was the case in the 1980 to 1990 period.

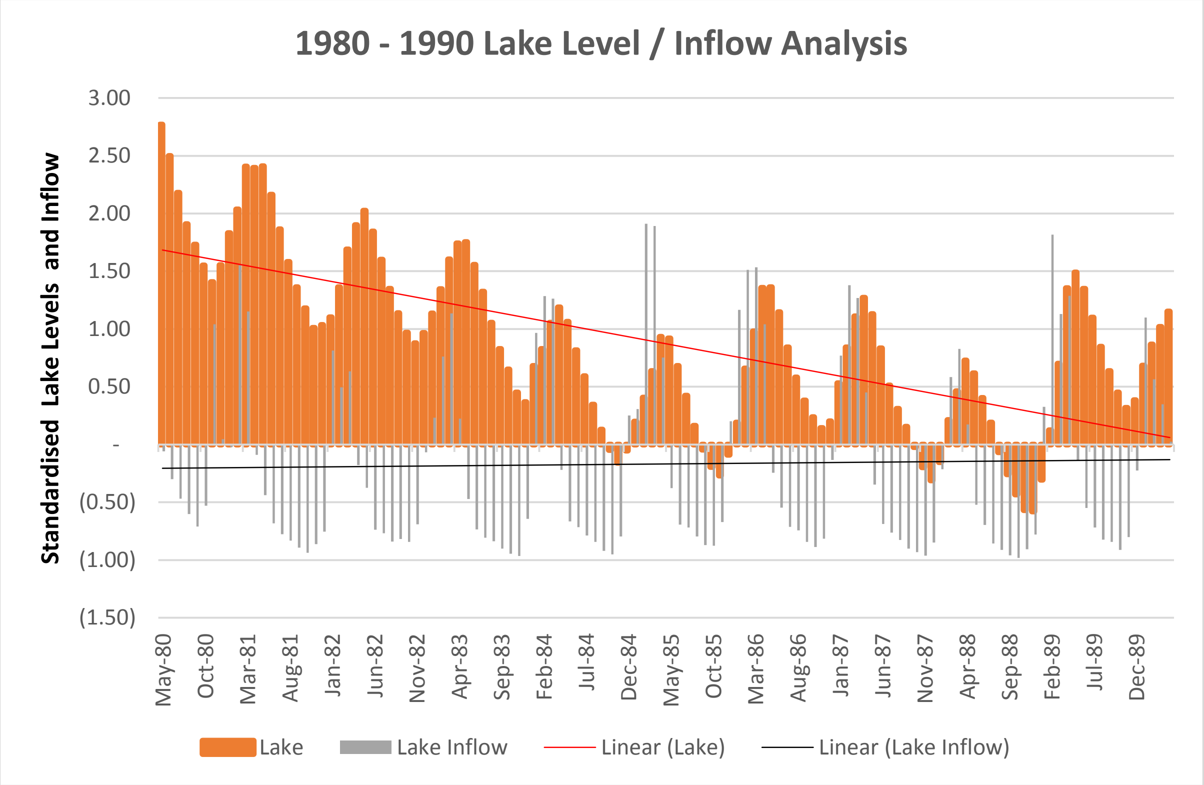

Figure 4-14 Standardised Lake Level and Inflow between 1970 -1980

4.5.4 Standardised Lake Levels and Rainfall Pattern from 1990 – 2000

Figure 4.15 show the decadal period 1990 to 2000 show a continued significant decrease trend of Lake Levels and an insignificant rise of rainfall and runoff. As discussed earlier the lake levels began to rise when rainfall and runoff is above long term average if this condition is not true the levels will continue to significantly drop.

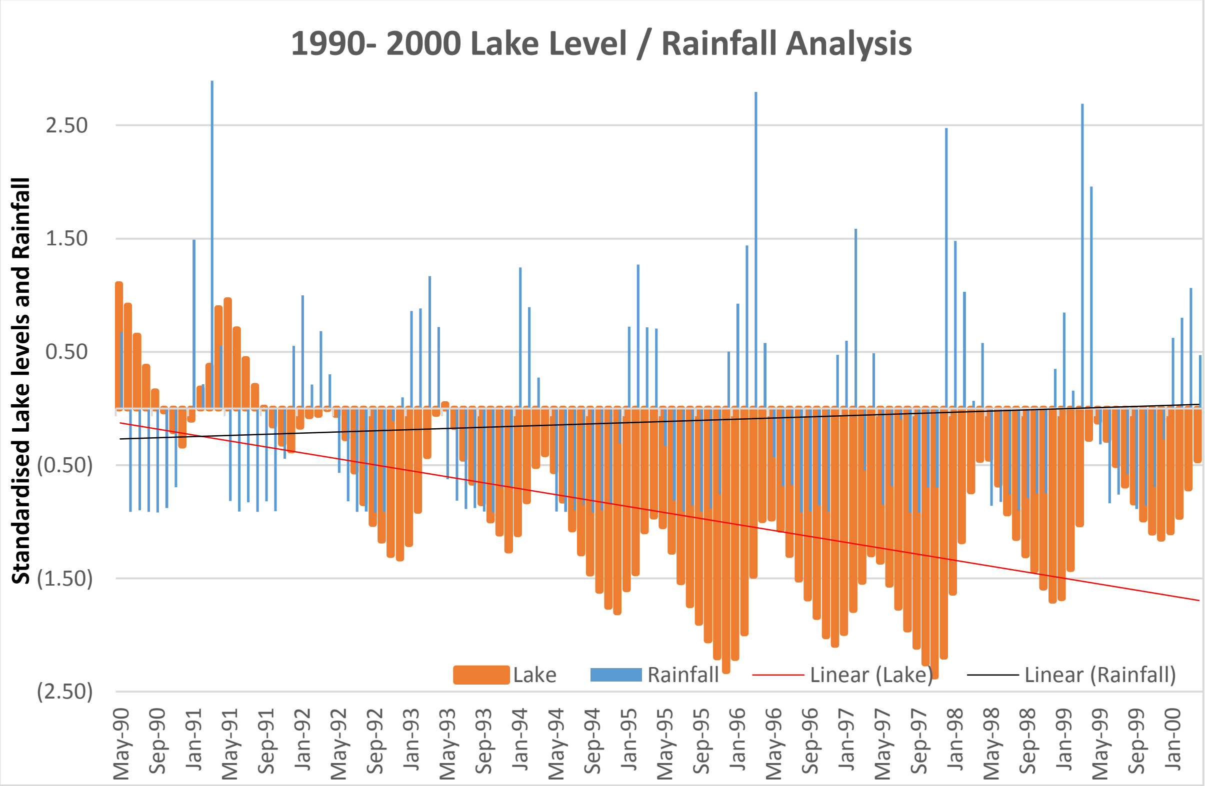

Figure 4-15 Standardised Lake Levels and Rainfall from 1990 -2000

The period 1990 – 2000, the levels continued to drop contrary the Inflow during the same period had a positive trend as shown in figure 4.16. The inflow was a result of positive trend in rainfall, however the positive trend for both inflow and rainfall occurred within the zone of below the long term average hence the levels continued to drop

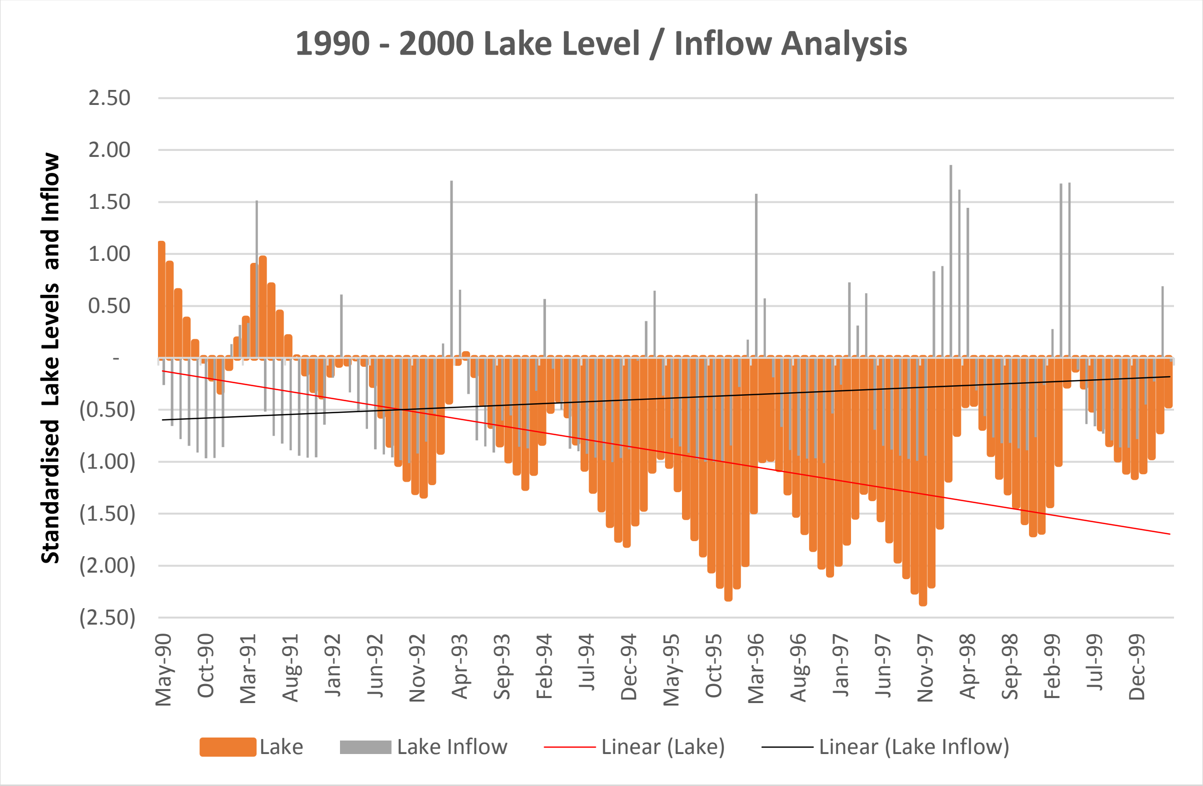

Figure 4-16 Standardised Lake levels and Inflow from 1990 – 2000

The Temperature trends over the period of 1990 to 2000 show an increase of temperature though not significant. However Evaporation has increased significantly over the period. The increase in evaporation was also impacting the decrease in levels. Figure 4.17 show the temperature / evaporation analysis and the study found out that the significant trend increase in evaporation exacerbated the declining of the levels hence a continued drop was experienced.

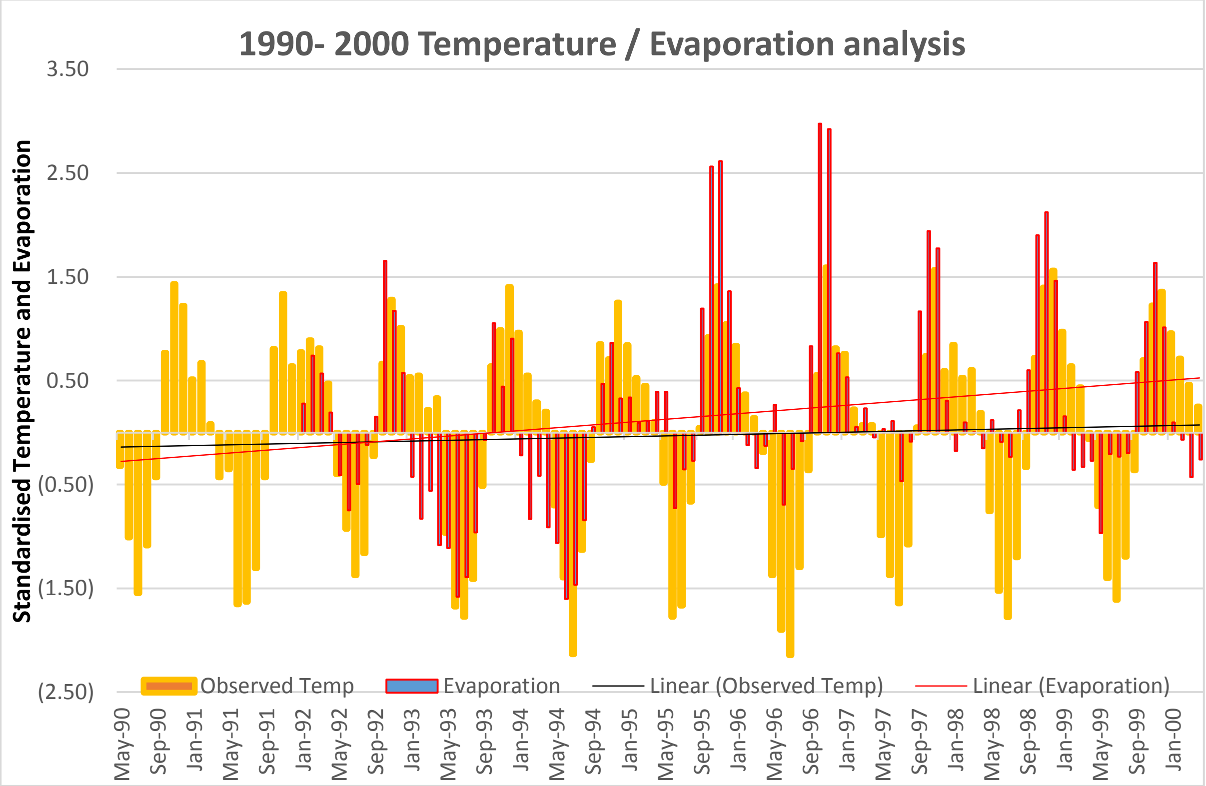

Figure 4-17 Standardised Temperature and Evaporation Trends from 2000 – 2010

4.5.5 Standardised Lake Levels and Rainfall Pattern from 2000 – 2010

In the 2000 to 2010 period Lake Malawi levels increased not significantly as a result of increase to rainfall pattern within the same period. The rainfall increase was also not significant. Figure 4.18 show the 2000 – 2010 lake level/rainfall comparison depicting the increase.

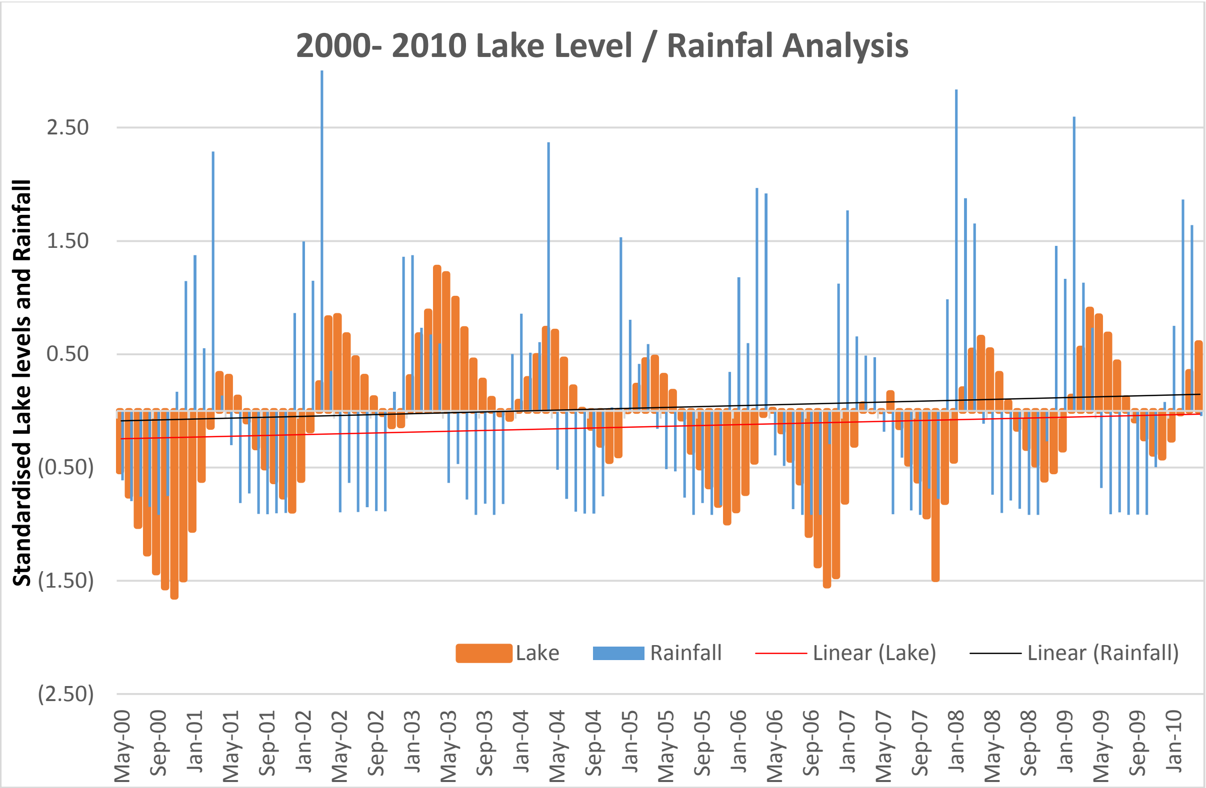

Figure 4-18 Standardised Lake Levels and Rainfall from 2000 – 2010

As observed in figure 4.19 the period 2000 – 2010 experienced an increase in trend of levels though not significant. This was as a result of the inflow into the lake that increase significantly and in most of the years the inflow was above the long term average.

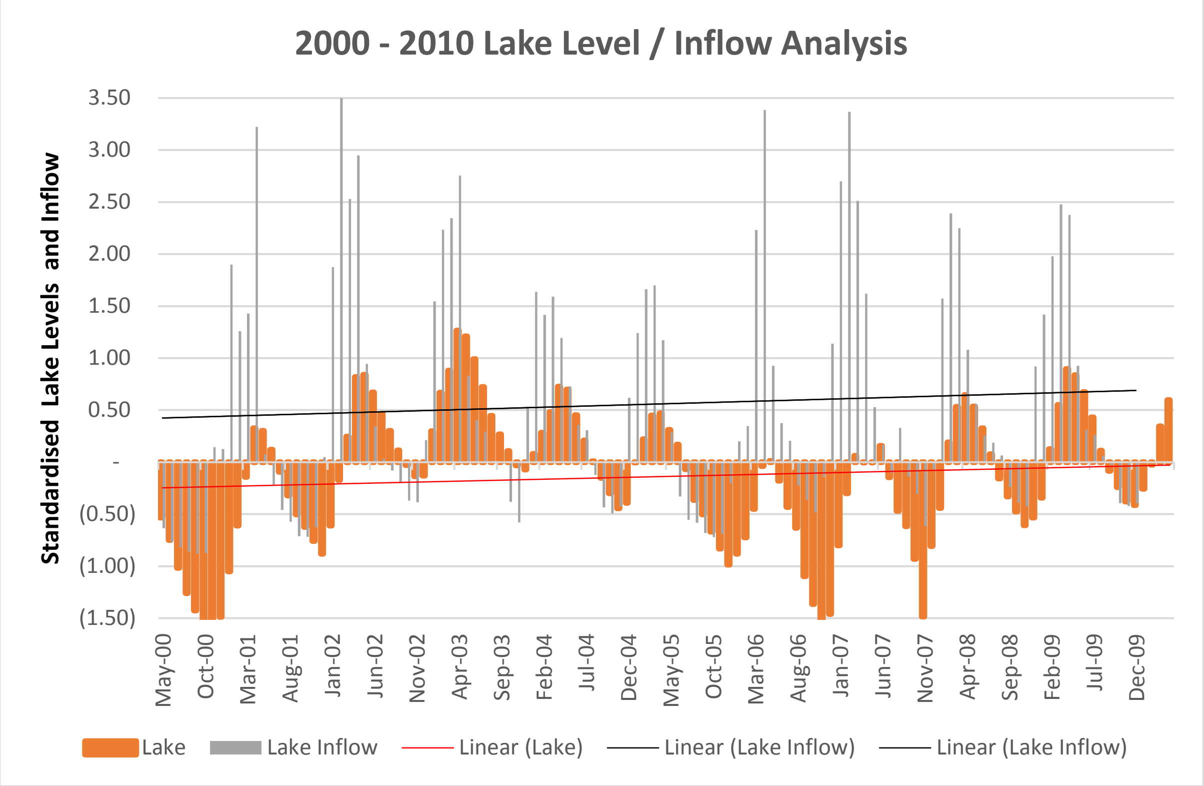

Figure 4-19 Standardised Lake level and Inflow from 2000 – 2010

The period 2000 to 2010 show a decrease in evaporation and an increase in temperature as observed in figure 4.20. Temperature provides the latent heat for vaporisation and general when temperature increase evaporation may increase. However evaporation is a compound reaction that is also influenced with other factors apart from temperature. These factors that influence notable include the moisture saturation, cloud cover, wind speed etc. However the study did not in-depth specifically analyse the evaporation factors over Lake Malawi.

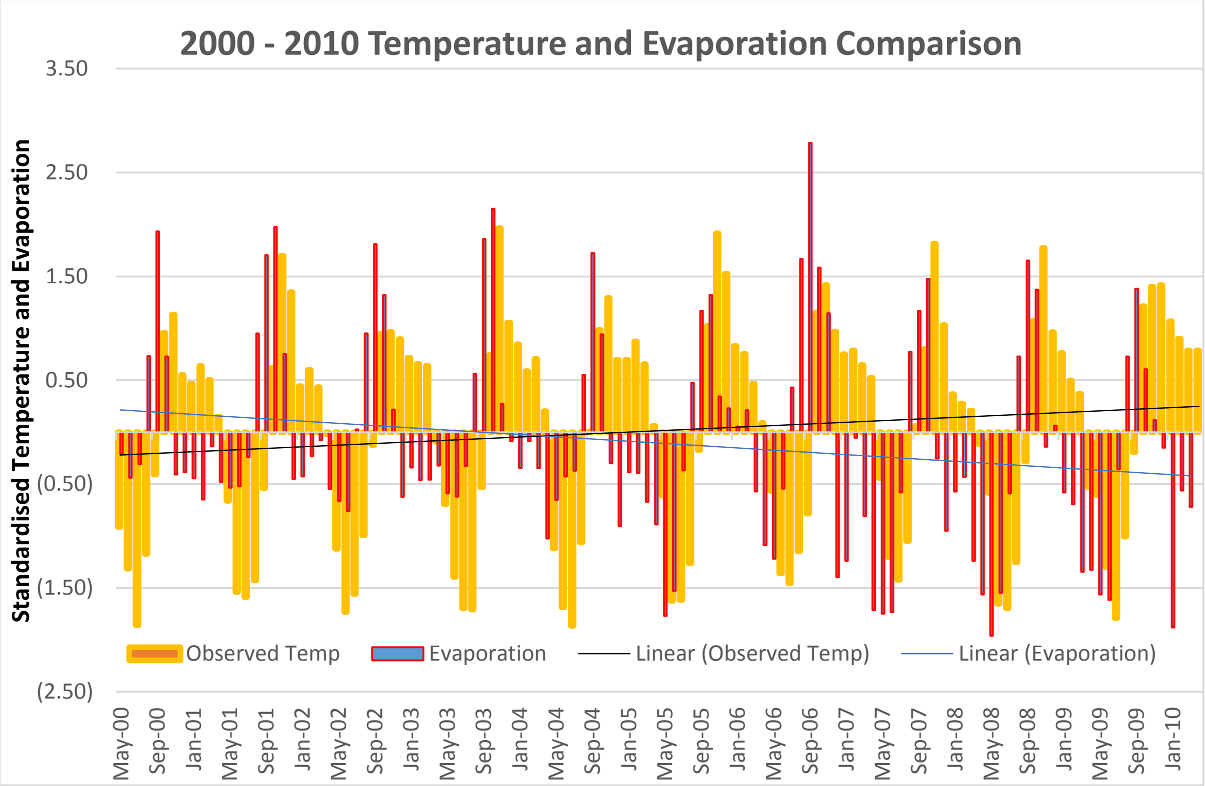

Figure 4-20 Standardised Mean Air Temperature and Evaporation from 2000 – 2010

4.5.6 Standardised Lake Levels and Rainfall Pattern from 2010 – 2015

The period 2010 to 2015 showed a significant drop in levels of the lake as shown in figure 4.21. As discussed in previous scenarios the levels continue to drop as long as the inflow and rainfall is at the long term average or below. However the period 2010 2015 showed an increase in rainfall pattern insignificantly. The trend increase would not generate enough influence for levels to rise hence the levels continued to drop.

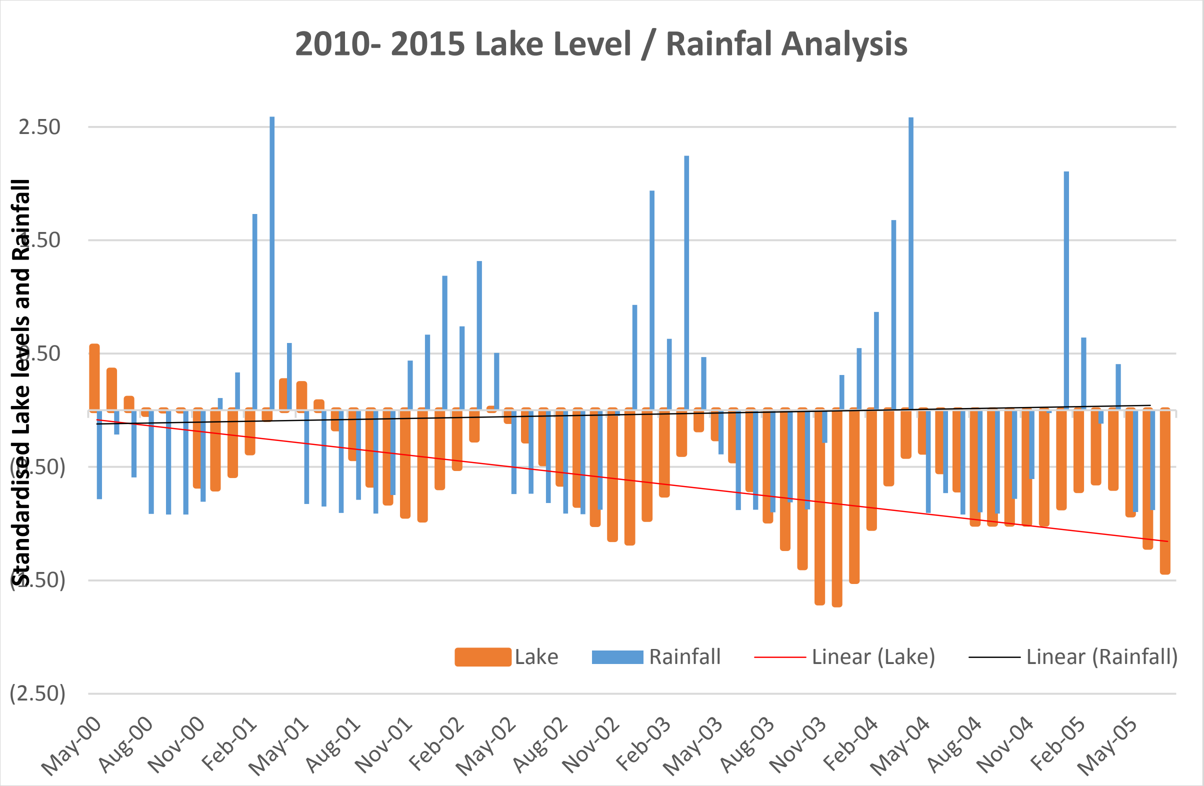

Figure 4-21 Standardised Lake Levels and Rainfall from 2010 – 2015

The period 2010 to 2012 show a continued increase in temperature and evaporation as illustrated in figure 4.22. This being the case this resulted in levels dropping due to the increase in evaporation. Evaporation has been varying over time and whereas temperature had no significant trend, this shows that evaporation is still being influenced by other climatological conditions that keep varying over time.

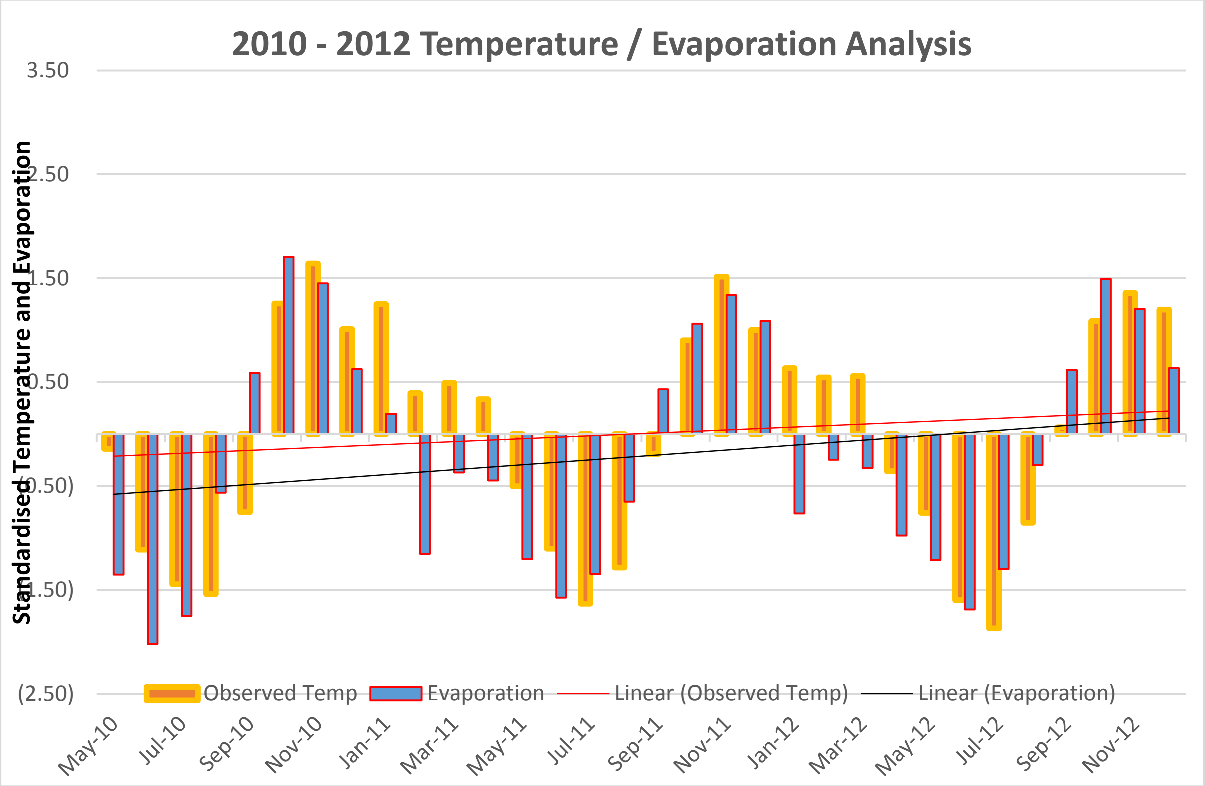

Figure 4-22 Standardised Mean Air Temperature and Evaporation from 2010 – 2012

4.6 Outflow

The study found out that the outflow of the Lake , i.e the Shire river the flow has been varying over time but under human interference where the levels of the lake are regulated thus determining the outflow. Figure 4.23 shows a time series plot of the Shire River from 1980 to 2015. The Shire river flows are dependent on the Lake levels and this is being regulated by the barrage managed by the Electricity Supply Commission of Malawi (ESCOM). The low Lake Levels from 1991 through to 2002 resulted in strict regulation of the barrage to avoid further reducing the already low lake levels that would have severe impact on the Lake level shire system.

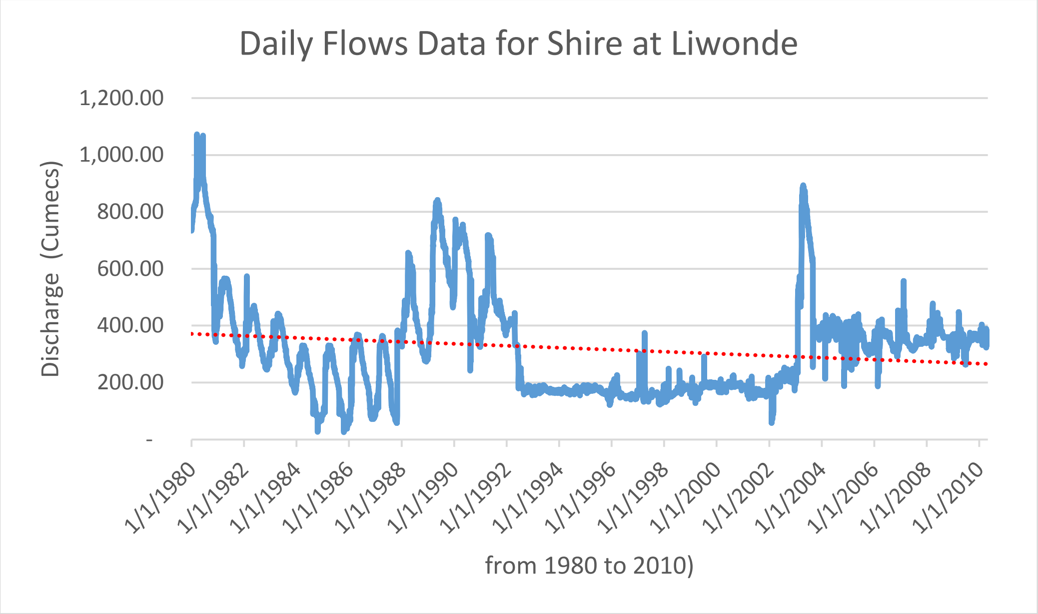

Figure 4-23 Lake Malawi Outflow – Shire River

From the daily discharge observed on the Shire River, it is clear that the pattern does not show a seasonal trend. This is because the outflow of the Lake is controlled by the Barrage. The barrage is used to regulate the flow for hydropower generation downstream of the Shire river system for multipurpose usage such as large scale irrigation, hydropower, water supply etc. The study also used the Pearson correlation and find out that the outflow of the Lake i.e the Shire river has a better correlation to the levels.

The MK statistical test showed that the outflow has a negative trend as shown in Table 4.8. The shire river has a mean of 318.045m^3/s and the flows deviates around 179.471m^3/s.

Table 4-8 Outflow - Shire River Statistics

Summary statistics:

Variable	Observations	Minimum	Maximum	Mean	Std. deviation
Shire Flow Data	11077	25.713	1072.998	318.045	179.471

Kendall's tau	-0.028
S	-1718974.000
Var(S)	151036505457.333
p-value (Two-tailed)	< 0.0001
alpha	0.05

Figure 4.24 is showing the correlation existing between Lake levels and the Shire river, yielding a strong correlation value of 0.9. This implies that the shire flows are dependent on the Lake levels and as such flows on the Shire river can be projected using the regression method.

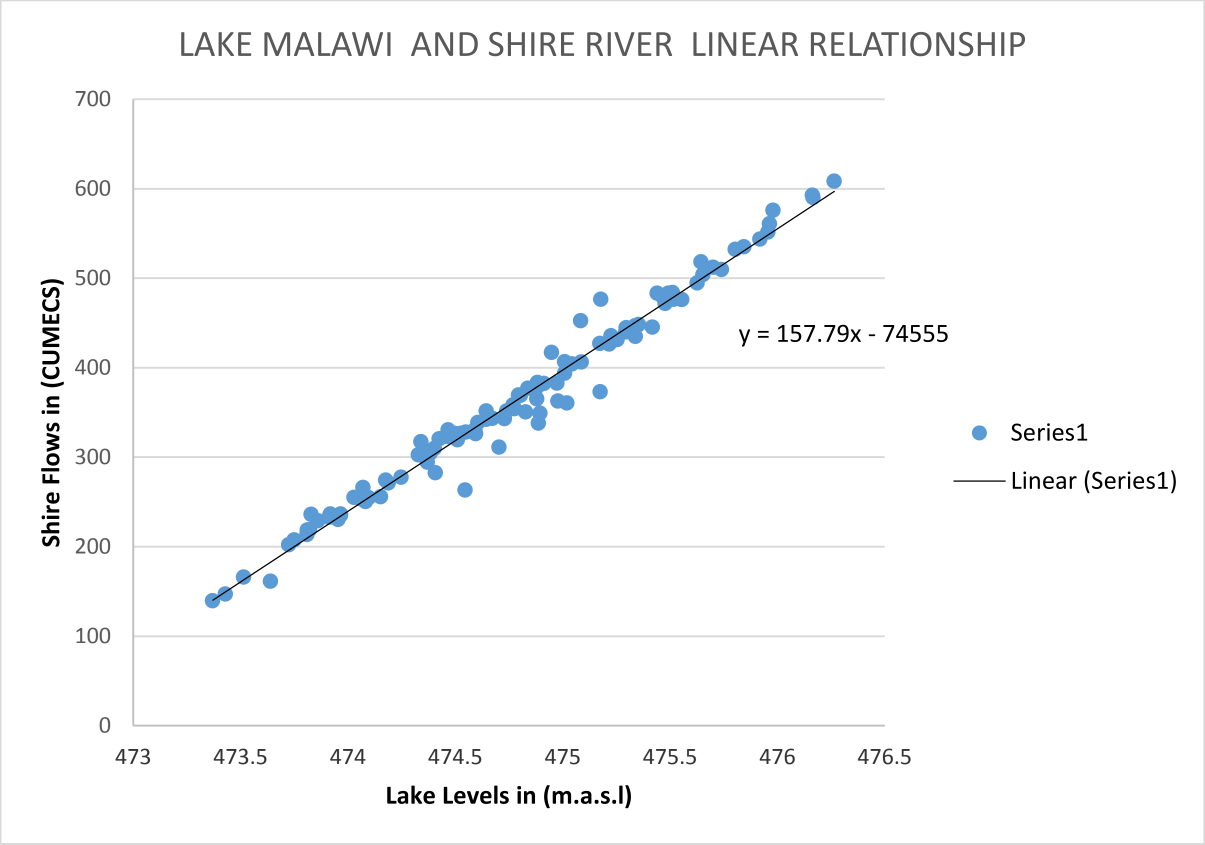

Figure 4-24 Correlation of Lake Malawi levels and Shire River Discharge

4.7 Modelling Water Yield of Lake Malawi

The study showed that climate change is the driving force behind the declining of Lake Malawi levels and that the Lake is very sensitive to climate variations over time. Using the Global Climate Projection and the baseline data developed with the SWAT model, the study thereby evaluated the impact of climate change on lake levels.

The SWAT model computed the water yield into Lake Malawi and one of the input into the model was the Projected Climate Data. Figure 4.25 shows the comparison of observed rainfall and projected model data. Based on this analysis the projected data was found to be close to the observed and therefore it is expected that the projected data up to 2100 can then determine the water yield into the lake that will subsequently forecast the levels of the Lake in the future.

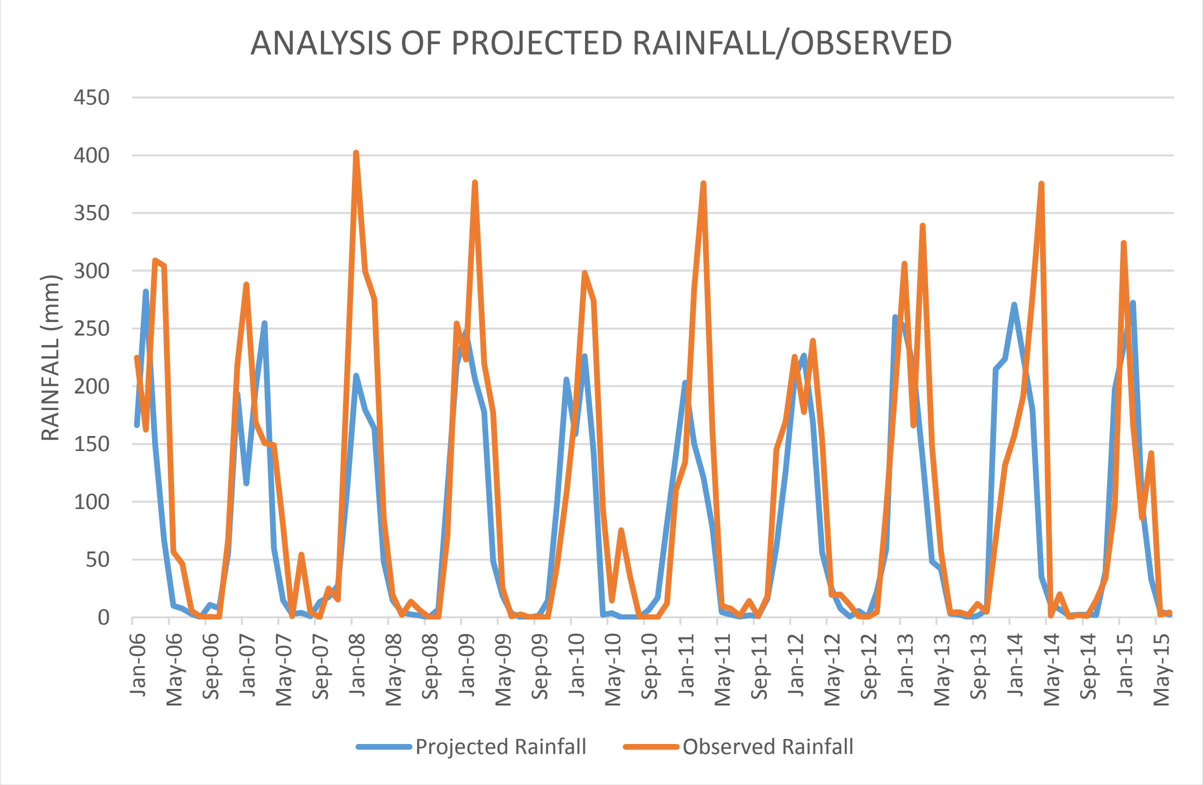

Figure 4-25 Comparison of observed and model rainfall

The water yield is a result of the computation of the water balance by the SWAT model. Figure 4.26 below shows the observed rainfall trend over Lake Malawi from 2006 to 2015 and the computed water yield from the SWAT model up to 2036. Rainfall as a main controller of lake levels is expected to vary over the next 30 years. If the projected data is to go by Lake Levels are expected to continue the recession from 2017 to 2020 and the following year rainfall above average is therefore anticipated. However it is very unlikely that the 2021 rainfall may overturn the lake level deficit that has been dropping for the past 5 years before 2021. The projected data shows that rainfall is generally expected to drop up to 2036, this being the case then it's very unlikely for lake levels to rise. This will further be exacerbated by the fact that land use practices will still be growing hence pushing more stress on the water resources and impacting on the decrease of Lake Malawi levels.

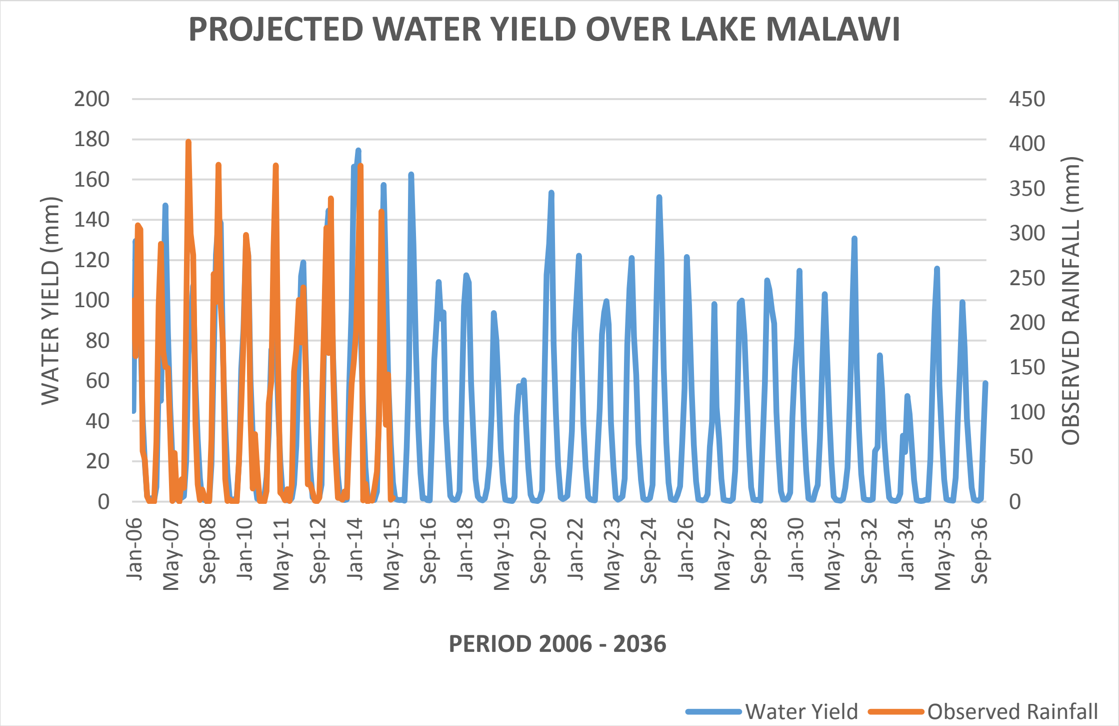

Figure 4-26 Projected water Yield over Lake Malawi from 2006 – 2036

In order to assess the Impact of Climate Change on the Lake levels of Lake Malawi. The 30 year average Water yield is tabulated on Table 4.9. The Baseline was taken to be from 2006 to 2035, the Near Future was from 2036 – 2065 and the Far Future is from 2066 to 2095. Analysis on the future impact of climate change it has on the levels of Lake Malawi, Table 4.9 tabulates the water yield projections showing that the yield will reduce by 8.84%. It is therefore expected that the levels of Lake Malawi will continue to drop in the near future, however as observed from table, the water yield is projected to increase in the months of November, December and January. Even though these months are projected to have a good water yield but this is expected to be eluded by the dry periods where the water yield projection will be reduced significantly by a larger deficit.

Table 4-9 Monthly Water Yield Projection

	Baseline Water Yield (2006 – 2035) in mm	**Near Future Water Yield (2036 – 2065) in mm**	**Far Future Water Yield (2066- 2095) in mm**
Jan	79.125	87.95433	94.39167
Feb	109.892	103.7473	104.0003
Mar	104.989	86.03367	81.94233
Apr	64.102	46.913	42.78433
May	31.963	22.46233	19.6
Jun	11.963	5.814333	4.159
Jul	1.718333	1.155333	1.005333
Aug	0.925667	0.759667	0.771
Sep	0.836	0.583667	0.639333
Oct	1.481	1.965333	3.136333
Nov	11.339	16.73467	20.407
Dec	45.672	48.83633	56.379

Figure 4.27 shows the 30 years average Water yield projection. As seen from the graph the water yield in the near future is expected to reduce, however in November December and January an increase is anticipated. Nevertheless as discussed above the impact of climate change on the water yield of Lake Malawi will reduce by 8.84%. With this it is therefore expected that levels of Lake Malawi will continue to drop in the near future although season variations are anticipated as well.

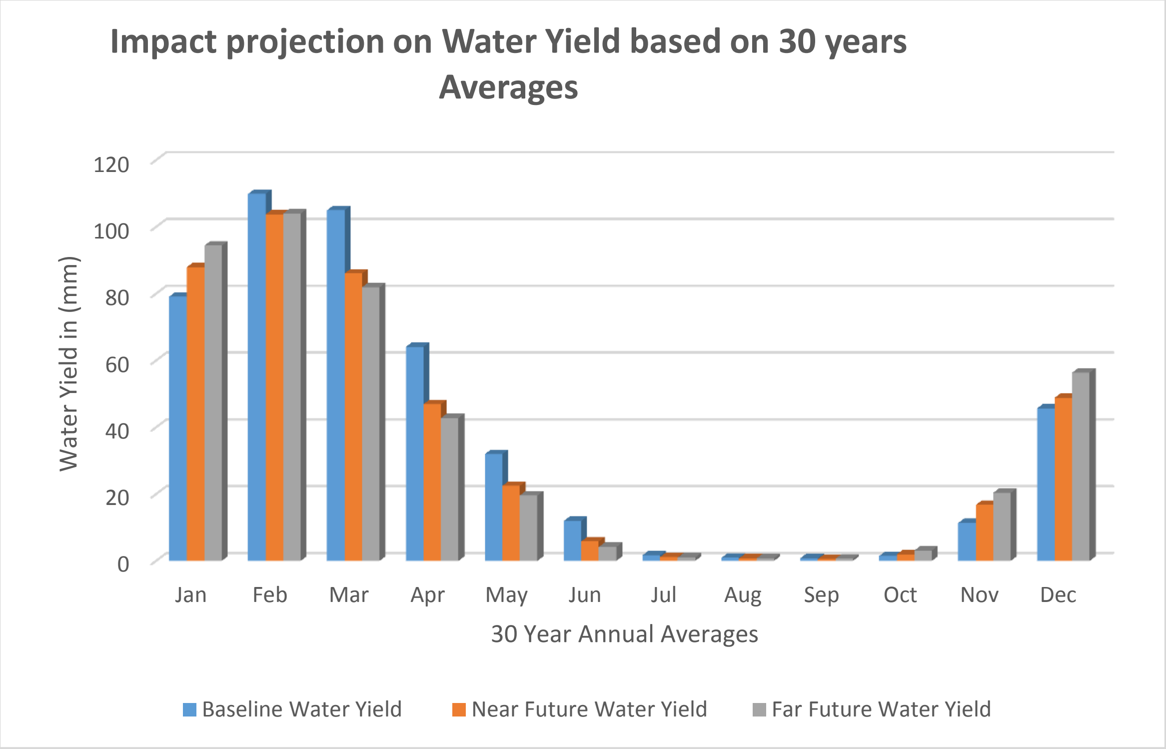

Figure 4-27 Impact Projection of Water yield based on 30 years average

5.0 CONCLUSION AND RECOMMENDATIONS

This chapter discusses the conclusion and recommendations of the study.

5.1 Conclusion

This research gave a first insight on the lake level variability, and it was a first step in understanding the whole basin hydrological balance and how it is influenced by climate variability. The study investigated impact of climate change on the levels of the Lake Malawi. Specifically the study determined the trend of climatological parameters and impact it has on the levels of Lake Malawi. The results of the study can therefore be concluded as follows:

Lake Malawi levels continue to drop over the years due to rainfall and runoff at normal or below long term average. Rainfall is affected by other climatological parameters such as global warming that in other parts causes reduced rainfall or changes in rainfall variation. Subsequently this has impact on the levels of the lake. Temperature continue to rise over the past years and this conforms the IPCC (2013) global climatic projections as surface temperature increases by 0.74°C over the last 100 years. Mean air temperature over Lake Malawi also continue to rise but insignificantly, however the rise of temperature in some of the years induced an increase to evaporation over the lake. However the study found that from 2000 to 2010 temperature was increasing and evaporation was decreasing. In the same period the levels were drastically dropping.

Decreasing of evaporation is a combination of factors which are subject to changes in atmospheric demand as a result of changing radiation, cloud cover, wind speed, and changes in vapour pressure. However the study did not acquire sufficient data to analyse evaporation factors due to time and resources.

Runoff into Lake Malawi is gradually decreasing though insignificant. However runoff is also influenced anthropogenic land use changes over the catchment. Malawi has a high population density country that relies mainly on agriculture and use of natural resources for energy use. This in turn has exacerbated and stressed the land use which over time have increased runoff over a short period of time and forcing long dry spells implying a reduced inflow into the lake over time.

The water yield for Lake Malawi will continue to vary over the near future and far future. Evaluating the Impact using baseline data, near future and far future projections show that the water yield will decrease of 8.84% and therefore the levels are also expected to drop. The study found out that in the short term thus from 2017 to 2020, the water yield will drop even further.

5.2 Recommendations

As discussed by the findings of this study that Lake Levels will always fall down when rainfall or runoff is at normal or below the long term average. Also considering global climatic projections of increased temperature thus causing extreme and rainfall variations. It would be therefore unlikely to be receiving every season rainfall above long term average. Therefore the study has recommended the following:

1. The study observed that any variations in the natural hydrological behaviour of the lake will certainly have impact on Malawi socio economic. The lake levels have impact on hydropower generation, irrigation and water supply. There is need to further carryout studies on Lake Malawi climate resilient and adaptation on the impact it has on the economy and human livelihood.

2. Runoff into the lake driven by rainfall showed that runoff at normal or below the long term average levels continue to decline. The runoff into the lake is also influenced by anthropogenic activities over the catchment There is need to comprehensive investigate land use changes that impact runoff into Lake Malawi.

3. This study and other studies have concurred that climate change is the driving force on the decline of Lake Malawi levels. The study has showed that rainfall is generally decreasing insignificant over long periods. The proposal will be to further study the necessary parameters causing the decrease in evaporation over Lake Malawi in view of increasing global temperatures.

4. Of many uses that the lake serves Malawi, hydropower seems to be the most economical important use. In respect to decline of levels due to climate change there is need to study other alternatives for hydropower generation within or outside the shire river catchment.

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