# HYDROCLIMATOLOGIC ANALYSIS OF A LAKE FOR EARLY WARNING LAKE LEVEL FORECASTING: CASE OF LAKE CHIUTA IN SOUTHERN MALAWI

**MSc ( WATER RESOURCES MODELLING & GOVERNANCE) THESIS**

**By**

**TISUNGANE McARTHUR KAPALAMULA**
**BSc (Civil Engineering) - University of Malawi**

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**University of Malawi**
**Chancellor College**

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# DECLARATION

I, the undersigned, hereby declare that this thesis is my original work which has not been submitted to any other institution for similar purposes. Where other people's work has been used, acknowledgements have been made.

**TISUNGANE MCARTHUR KAPALAMULA**

**Full legal name**

**Signature**

**Date**

# CERTIFICATE OF APPROVAL

The undersigned certify that this thesis represents the student's own work and effort and has been submitted with our approval.

Signature……………………………….Date……………………………………
Cosmo Ngongondo, PhD. (Associate Professor)
**Main Supervisor**

Signature……………………………….Date……………………………………
Zuze Dulanya, PhD. (Senior Lecturer)
**Member, Supervisory Committee**

Signature……………………………….Date…………………………………
Maurice Monjerezi, PhD. (Associate Professor)
**Coordinator, Master of Science in Water Resources Modelling and Governance**

# DEDICATION

To my late daughter Ukulu Unathi Kapalamula who answered the Lord's call ten days after her birth on 4th October 2016

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# ABSTRACT

Lake Chiuta in Southern Malawi is a key water resource for the riparian community. The lake is a habitat to a diversity of fish species that sustain the peoples' socio-economic livelihoods. Climate change and variability in the lake's basin have been affecting the basin's hydroclimatology, resulting in inflow variability and varying lake levels. The absence of an early warning tool for forecasting the lake levels has often resulted in delayed decision making for relevant interventions like scaling up or down of agricultural and fishing activities. This study was therefore aimed at analyzing the hydroclimatology of the lake in order to develop an early warning mechanism for lake level forecasting. The study analysed various components of Lake Chiuta's water balance, to understand the role of climate forcing in lake level variation during 1960-2017. The study used hydroclimatic and historical satellite altimetry data. In the absence of discharge data from inflowing rivers, the monthly Water and Snow Model (WASMOD) was calibrated and validated in estimating catchment runoff using a runoff coefficient of 21.85%.The results show that the lake's catchment had a mean annual rainfall of 879.9mm during 1960-2009 with an insignificant trend. On the other hand, temperatures and over-the-lake evapotranspiration had rising and significant trends during the period, with a mean over-the-lake evaporation of 130.87cm/year. Mean maximum and minimum temperatures were 23.69 °C and 13.62 °C respectively. Lake outflows were estimated to a mean of 74.19 mm/month with an insignificant trend. Inflows will fluctuate between 938mm and 1329mm resulting in a single full lake extent from 2009 to 2030 at a 95% statistical confidence interval.

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# LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| GIS | GIS Geographical Information System |
| GPS | Global Positioning System |
| JICA | Japanese International Corporation |
| MASL | Meters Above Sea Level |
| MIWD | Ministry of Irrigation and Water Development |
| SDGs | Sustainable Development Goals |
| SONAR | Sound Navigation and Ranging |
| UN | United Nations |
| USGS | United States Geological Society |
| USBR | United States Bureau of Reclamation |
| WMO | World Meteorological Organisation |
| WASMOD | WASMOD Water and Snow Modelling Balance |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Lakes and reservoirs are important for many purposes such as domestic and industrial water supplies, flood control, hydroelectricity power generation, irrigation, recreation, navigation, fishing, atmospheric cooling, leaching of saline water intrusion, dilution of polluted water and provisional services to coastal ecosystems (Duan, 2014). The water stored in lakes and reservoirs plays a vital role in the economic development and many services that contribute to the well-being of communities up to kilometers downstream (even across administrative borders) and in localities in close proximity to lakes and reservoirs (Medina et al., 2008; Singh et al., 2010). Their key property is that they store excess water from periods of high rainfall which is then made available during dry spells (Duan, 2014). As the demand for water resources is increasing, storage of sufficient water to meet water demand during dry seasons and below-average rainfall years is becoming increasingly important (Van Der Zaag, 2014).

Hydroclimatology and climate change form the basis of forcing mechanisms that water bodies have to be contend with (Duan, 2014). Langbein (1967) defined hydroclimatology as the study of the climatic forcing upon land hydrology. Rainfall, evapotranspiration and imbalance between these two have been identified as the main focus of hydroclimatology. Ngongondo (2005) identified climate change as a source of rainfall variability in Mulunguzi catchment and due to this rainfall variability, flows in the Mulunguzi River became affected. During wet season, lake levels may rise as opposed to dry season when lake levels are likely to drop. Wet season results in increase of over-the-lake rainfall, followed by increased tributary flow and rise in lake level. Dry season consists of increased rates of evaporation, less rainfall and low run off resulting in depleted lake levels. This makes hydroclimatology parameters to have direct effect on lake levels. Analysis of hydroclimatological parameters may therefore be useful in early warning lake level forecasting. The total hydrological cycle is the basis of hydroclimatology thus it had been imperative that the overall hydrological water balance and the sensitivity of watershed run off to changes in climate be investigated. It is against this background that an analysis of Lake Chiuta's hydroclimatology is presented for use in early warning lake level forecasts.

## 1.2 Problem Statement

Lake Chiuta is the main water source for the area in Lake Chiuta's Basin (JICA, 2014). Of late, the lake has been experiencing frequent low inflows resulting in reduced storage. Previous studies have shown that Lake Chiuta is very sensitive to climate variability and has previously desiccated (Dulanya et al., 2012). In contrast Lake Malombe located on the similar latitude as Lake Chiuta and with same climate forcing mechanisms, has been noted to withstand climatic shocks much better than Lake Chiuta largely due to lake basin's morphology (Dulanya et al., 2012). Lake Malombe has a half-graben and a relatively shallow morphology due to its location on the rift axis whereas Lake Chiuta has a pan-shaped basin morphology (Dulanya et al., 2012).

Much as the differences were noted, long term monitoring of both Lakes Chiuta and Malombe is lacking. Lake level monitoring stations that are also not present further hampers decision making process. Smaller and shallower lakes in Malawi with the exception of Lake Chilwa have had little attention despite being very useful to socio-economic livelihoods of local inhabitants (Thomas et al., 2009). The mechanisms and frequency of the behavior of Lake Chiuta levels are however poorly understood as opposed to Lakes Malawi and Chilwa (Dulanya et al., 2012). Lake Chiuta has been known to dry up periodically (1973 being the worst recession) with factors and its response to climate forcing not well articulated (Dulanya et al., 2012). Therefore, there was a need to understand the long-term behavior of Lake Chiuta by making use of proxy data and approaches with practical temporal resolution. This study therefore endeavored to understand the lake’s hydroclimatology so that an early warning lake level forecasting mechanism could be developed.

## 1.3 Study Objective

The main objective of the study was to analyse the hydroclimatology of Lake Chiuta to enable the development of an early warning tool for lake level forecasting.

### 1.3.1 Specific objectives

Specifically, the study was aimed at:

a) Analysing hydroclimatic variables for Lake Chiuta.

b) Evaluating Lake Chiuta's response to climate forcing.

c) Developing a model for Lake Chiuta’s response in relation to its hydroclimatology which will be used as an early warning tool for the lake.

### 1.4 Study Justification

Water is a valuable resource that needs to be managed in a sustainable manner (Savenije, 2000). World governments through the United Nations adopted Sustainable Development Goals (SDGs), in which goal number six talks exclusively about water that it should be managed in a sustainable manner (UN, 2015). Therefore assessment of Lake Chiuta's hydroclimatology to be used in early warning lake level forecasts is of paramount importance as it forms part of cornerstones in comprehensive management of the water resource in the area. High water level forecast will be used to predict flooding conditions whereas low level forecast will be used to predict drought conditions which will allow users to make appropriate decisions in the water resources' management. Lakes thus require a comprehensive and effective water management and planning strategy.

Lake Chiuta's importance as a source of water resource cannot be overemphasized and assessment of the lake's hydroclimatology will be crucial for early warning predictions for water levels of the lake. Lake Chiuta is home to lots of flora and fauna like fish species that are used as a source of food and for commercial activities for the communities around the lake (Njaya et al., 1997). The lake also serves as a main water source for various uses in the basin on top of maintaining the ecological integrity of that area (Njaya et al., 1997). However there has not been an accurate way of predicting flows and level recessions or booms in the lake. The absence of a mechanism to predict flows and levels in a water body is detrimental to the management of a water resource (Burton, 1999). Lake Chiuta's shoreline has already been determined to extremely vary by Dulanya et al. (2012).

In Malawi, most hydroclimatology research studies have been conducted in Lake Malawi and Chilwa (Kidd, 1983; Neuland, 1984; Drayton, 1984; Kumambala and Ervine, 2010; Mbale, 2014). Very little research has so far been conducted on Lake Chiuta and it has not been exclusive. Chipeta (1972) investigated Lake Chiuta hydroclimatology whilst researching on Lake Chilwa's cyclic changes whilst Kalk et al. (1979) referred on Chiuta's hydroclimatology in investigating Lake Chilwa's changes in a tropical ecosystem. Dawson (1970) analysed Chiuta's geology.

Planners and water users of Lake Chiuta can then use information about the lake's hydroclimatology to forecast lake levels. This early warning venture will then result in stakeholder swift action on mitigation measures, allocation of proposed infrastructure in addition to proper water resources management. The conservation function of a lake focuses on the control and provision of water for water supplies, recreation, navigation and irrigation, while flood control aims to reduce flooding through the retention of water during flood events (Muala et al., 2014). The installation and operation of public facilities, like water pipelines, involve significant amounts of spending, and therefore need to be carefully planned and for smooth planning, accurate forecasting of flows and levels of the water resource itself is of paramount importance (Duan, 2014). Therefore, this research study presents an interactive, user-friendly decision-support tool for lake level forecasting. This will then contribute to bridging the gap between research and practice in improving the way water resources management decisions are made at present.

### *1.4.1 Study Key Assumption*

Hydroclimatology in Lake Chiuta has a direct bearing on the resultant lake level and that the lake basin is a homogeneous lot.

## 1.5 Thesis Outline

Chapter 1 is the introduction consisting of background to the research problem, objectives of the study, research justification. Chapter 2 has covered literature review of the study, and Chapter 3 has presented the study area and methodology section where methods employed in undertaking the study have been laid out in addition to the description of the study area. Chapter 4 has presented research results and discussion of results while Chapter 5 has provided conclusions drawn from this research and recommendations.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Lakes are natural resources that react differently to different climate forcing mechanisms. Many lakes worldwide are being affected by climate change and variability which is impacting on their temperatures, lake levels and runoff (Mason et al., 1994). Hydroclimatology affect lake levels and takes into account hydrometeorology as well as surface and near the surface processes of evapotranspiration, run off, groundwater flow flux and possibly interception (Langbein, 1967). The gross hydrological cycle is therefore a basis of hydroclimatology on which the overall water balance of a lake is analysed.

Climate change has a great potential to reduce water resource availability. Analysing changes in climate regime variables like temperature, rainfall can therefore assist in providing some understanding of resultant changes in lake inflows and resultant lake levels (Setegn et al., 2011). Fluctuations in lake levels and surface area, especially in areas without significant anthropogenic disturbance to the water budget, have been known to be indicators of the climate on decadal and million-year time-scales (Lofgren et al., 2000). Understanding such fluctuations can provide a means of forecasting a future state of the lake. At periods between 2 to 100 years for instance, lakes respond to climate forcing mechanisms as a result of cycles such as El Nino and Southern Oscillation (ENSO), Sunspots, Oceanic Sea-Surface Temperature

Anomalies (SSTA) (Ropelewski and Halpert, 1987; Cobb et al., 2003). An understanding of how these forcing mechanisms affect the climate regime can therefore be of great value in setting up early warning forecasting mechanisms for lake levels.

Forecasting may be defined as the process of looking into naturally occurring scenarios in a system with the long-term goal of being able to predict the future behavior of a state on the basis of system knowledge and past behavior (Lowe and Webb, 1991). This involves the process of predicting the future of a state of a variable based on analysis in trends of past and present data (Makaridaki and Hibon, 1979). Analysis of hydrological extremes' return periods is used in conjunction with forecasting to provide an estimation of future state a hydrological variable (Kizza et al., 2011). Forecasting is an essential requirement for developing conjunctive use of water resources in any catchment as it deals with hazards and risks in decision making (Diamantopoulou et al., 2006). This is where data on flows and levels in a water body becomes crucial in planning and designing of water resources infrastructure, water body operation and flood control (Diamantopoulou et al., 2006). However, data availability for forecasting is normally a challenge especially in many developing countries due to a myriad of problems such as lack of monitoring stations at the desired temporal and spatial scales, lack of research attention, capacity and political will (Sene and Farquharson, 1998).

Street –Perrot and Harrison (1985) identified three types of lakes. The first type are atmosphere controlled lakes where the main source of input is precipitation and lose water through evapotranspiration. The second type are amplifier lakes where the main input water is derived from inflowing runoff and loses water through evaporation. The third type are reservoir lakes which derive input from runoff and discharge it though an outflowing river. Lake Chiuta largely falls into the amplifier category although it has elements that combine all three types in that it receives significant amounts of water as over the lake precipitation and also has catchment runoff.

## 2.2 Hydroclimatic Parameters

Rainfall, evapotranspiration, temperature, runoff are hydroclimatic parameters of paramount importance for use in lake level forecasting (Muvundja et al., 2013). Rainfall is the main driver of the hydrological cycle and once climate forcing on rainfall occurs, changes in the whole hydroclimatology occur resulting in lake level variability (Duan, 2014).

### *2.2.1 Catchment and Over-the-Lake Rainfall*

Catchment rainfall determination is of paramount importance as it may be used as an input to rainfall – runoff models in case of lack of lake inflow readings. Rainfall data used may either be rainfall directly falling over lake or rainfall overland which constitute catchment rainfall (Yin and Nicholson, 2002). Over-the-lake rainfall is counted directly as a major input to a lake water balance and catchment rainfall can be used indirectly to estimate runoff where stream gauging is incomplete (Neff and Killian, 2013). Although rainfall data is a key component of the water balance and the hydrological cycle, its scarcity is a key challenge. (Ferguson and Znamensky, 1981; Kizza et al., 2011). Application of satellite data products as an alternative to the scarce conventional rain gauge has been explored by various studies (e.g. Cathrene, 2002; Mulinde, 2005; Hughes and Slaughter, 2007; Li et al., 2007; Li et al., 2013).

#### 2.2.1.1 *Methods of Rainfall Estimation*

Remote sensing techniques have also been used to provide precipitation in cases where there is a deficiency of precipitation gauges. This may provide precipitation data over a lake by measuring the atmospheric conditions of precipitable water (Duan, 2014). Tropical Rainfall Measuring Mission Precipitation (TRMM) B343 product has been used in hydroclimatology and lake level research (Awange et al., 2008; Swenson and Wahr, 2009; Muvundja et al., 2013). Precipitation data is obtained at high spatial resolution in conjunction with the integration of TRMM 3B43 precipitation product at 0.25-degree resolution and Normalized Difference Vegetation Index (NDVI) from SPOT vegetation satellite (Duan, 2014). This then creates an improved product of monthly pixel based precipitation data. However precipitation data from satellite products requires local calibration with observed gauge data (Duan, 2014).

Roskar (2000) estimated catchment rainfall by storing data in time series and gridded form where by Fourier series analysis was applied to find periodic behavior. This tool that involves decomposing a particular time series data into sum of waveform wavelengths, helped check periodic behavior whereas Lyons et al., (2011) estimated rainfall by rearranging the steady state water balance model with basin-averaged precipitation rate as a function of over-the-lake evapotranspiration, evapotranspiration over-the-land, lake catchment area and lake outflow. Precipitation may also be derived by dividing a particular basin into small basins and adding constituents from the basins to make the gross sum using GLERL and NOAA (De March et al., 2012).

In case of lack of precipitation or minimal gauging stations, weather radar techniques can be used. However, their use is not common due to costly hardware and software requirements. Their demands and problems to effectively deal with various types of errors that may affect radar data make the process tough (De March et al., 2012). Still, the use of radar precipitation in large scale hydrological forecasting gives detailed information concerning precipitation distribution over a basin as compared to the conventional precipitation gauges (De March et al., 2012). In some cases the use of Doppler radar permits the direct measurement of precipitation over an area without the need to extrapolate observation mode at single sites (Neff and Killian, 2013). GIS-based systems may also be used to estimate precipitation (Comair, 2010).

Over-the-lake rainfall as a direct input in water balance models may be readily estimated by installation of rain gauges over a particular lake but, just as in the case of Lake Chiuta, such measurements may be minimal. This necessitates the use of rainfall measured in the nearby land and shoreline to come up with lake rainfall (Kebede et al., 2006; Rientjecs et al., 2011; Duan, 2014).

#### *2.2.1.2 Precipitation Concentration Index*

Precipitation Concentration Index (PCI) is a strong pointer of temporal rainfall distribution at various annual scales (De Luis., 2011). PCI calculates an index as a function of rainfall squared per summation of rainfall squares represented as a percentage. The Precipitation Concentration Index (PCI) is determined in accordance with Coscarelli and Caloiero. (2013) and Shi et al. (2013) as follows:

$$PCI = \left\{\left(\frac{\sum P_i^2}{(\sum P_i)^2}\right)\right\} 100 \ldots\ldots 1$$

Where *PCI* is the Precipitation Concentration Index and $P_i$ is the monthly rainfall. This index is a Fourier index with a long tradition on natural system analyses like rainfall systems. Oliver (1980) proposed PCI as a useful tool in analysing rainfall concentration and rainfall erosivity. Various PCI scale limits have been stated by

Oliver (1980) to signify the magnitude and condition of the rainfall distribution based on the particular PCI. PCI of less than 10% indicates a uniform distribution of rainfall, that between 11% and 15% represents a moderate rainfall concentration. PCI of 16 – 20% represents an irregular rainfall distribution pattern and PCI values of over 20% indicate a very strong irregularity in rainfall distribution pattern.

#### *2.2.1.3 Standardised Precipitation Evapotranspiration Index (SPEI) and Standardised Precipitation Index (SPI)*

The WMO recommends analysis of the SPEI and SPI in assessment of drought conditions. SPEI is a multi-scalar index on climatic data that may be useful in determining the onset, duration and magnitude of a drought condition (Serrano et al., 2010). On the other hand, SPI is used to signify drought on a range of time scales as well but unlike SPEI that uses both rainfall and evapotranspiration as inputs, SPI uses rainfall only as input. These hydroclimatic indices are highly useful in understanding how lake levels have evolved in addition to determining high or low lake levels at a certain temporal variation (Serrano et al., 2011; Serrano et al., 2012). SPI generally deals with the probability of occurrence of an observed rainfall amount in comparison with the rainfall climatology at a certain location over a long-term reference period (Stagge et al., 2014). Negative SPI and SPEI values are an indication of rainfall deficit where as positive SPI, SPEI values are an indication of rainfall surplus (Begueria et al., 2010).

### ***2.2.2 Over-the-lake Evapotranspiration***

Evapotranspiration over the lake is a key component of the water balance owing to the seasonal nature of the climate. Klaassen et al. (1998) stated that methods of determining lake evapotranspiration may be two-fold, namely: direct and indirect methods. Direct methods involve physical measurements as in pan evaporation estimation of lake evaporation while indirect methods basically involve the use of equations for example the Penman-Monteith and Thornthwaite Equations among others.

Determination of over-the-lake evapotranspiration is of paramount importance in water budget studies. Granger and Hedstron (2010) modelled hourly rates of evaporation from small lakes using a relationship between the wind speed over a lake surface with  evaporation rate being the basis for the model, the relationship was linear (Equation 2):

$$E = a.u \qquad \ldots 2$$

Where u is the 2 m wind speed over water [m/s]; E is expressed as the latent energy flux [W/m$^2$]. The coefficient, a, was determined as a function of the horizontal gradients (land-lake contrast) of temperature (T).

Gibson et al. (1995) in assessing evaporation from a small lake, used three independent experimental methods and a simplified model called Priestley – Taylor model that provided a good approximation of evaporation and the heat transfer using the Bowen Ratio as stated by Yin and Nicholson (2001) while Mbale (2013) and Mohammed (2012) estimated wetland evaporation and lake evaporation respectively by employing remote sensing technology. Evaporation may also be assumed (Thomson and Mzila, 2015) but this requires accurate estimations of evaporation factors, a feat that might not be easy to be achieved.  Evaporation over the lake may also be estimated using satellite based methods (Velpuri et al., 2011).

Winter et al. (1995) evaluated 11 equations for determining lake evaporation for a small lake (Table 1), by comparing the modified DeBruin-Keijman, Priestly-Taylor and modified Penman models. These models needed air temperature, wind speed, relative humidity and net radiation. The net radiation was the only variable that was available in all areas which was a key limitation of the methods.

**Table 1: Lake Evaporation Equations Evaluated by Winter et al. (1995)**

| Method | Equation |
|---|---|
| Brutsaert-Stricker | $E=(2\alpha-1)\left(\frac{s}{s+\gamma}\right)(Q_n-Q_x)-\left(\frac{\gamma}{s+\gamma[0.26(1+0.86U_2).(e_o.e_a)]}\right]$ |
| DeBruin | $E=\left(\frac{\propto}{\propto-1}\right)1.141\left(\frac{\gamma}{s+\gamma}\right).\left[\left(3.6+2.5(U_3)\right)(e_o-e_a)\right]$ |
| DeBruin-Keijman | $E=\left[\frac{SVP}{0.95SVP+0.63\gamma}\right].(Q_n-Q_x)$ |
| Hamon | $E=\left[0.55(D-12)^2\left(\frac{SVD}{100}\right)\right]2.54$ |
| Jensen-Haise | $E=\{[((0.014T_a)-0.50)(Q_s)]0.000673\}2.54$ |
| Makkik | $E=\left[0.61\left(\frac{s}{s+\gamma}\right)\left(\frac{Q_s}{L}\right)\right]-0.012$ |
| Mass transfer | $E=NU_2(e_o-e_a)$ |
| Papadakis | $E=0.5625[e_o max-(e_o min-2)]$ |
| Penman | $E=\left(\frac{s}{s+\gamma}\right)(Q_n-Q_x)+\left(\frac{\gamma}{s+\gamma}\right)[(15.36(0.5+0.01U_2)).(e_o-e_a)]$ |
| Priestly-Taylor | $E=\alpha\left(\frac{s}{s+\gamma}\right)[\frac{(Q_n-Q_x)}{L}]$ |
| Stephen's-Stewart | $E=\{[0.0082T_a)0.19].\{\frac{Q_s}{1500})\}2.54$ |

Here $\alpha = 1.22$ is the Priestley-Taylor empirically derived constant, dimensionless: $\frac{s}{s+\gamma}$ $and\, \gamma/(s+\gamma)$ are parameters derived from slope of the saturated vapor pressure-temperature curve at mean air temperature; $\gamma$ is the psychrometric constant, $Q_n$ is net radiation (in calories per square centimeter per day); $Q_s$ is solar radiation (in calories per square centimeter per day); $Q_x$ is change in heat stored in the water body (in calories per square centimeter per day) ; $U_3$ and $U_2$ is wind speed at 2 or 3m respectively, above surface (in meters per second); $e_o$ is saturated vapor pressure (in millibars); $e_a$ is vapor pressure at temperature and relative humidity of the air (in millibars); SVP is saturated vapor pressure at mean air temperature (in millibars per degree kelvin); SVD is saturated vapor density at mean air temperature (in grams per cubic meter); $T_a$ is air temperature in degrees Fahrenheit for the Jensen-Haise and Stephens-Stewart equations; $L$ is the latent heat of vaporization (in calories per gram); $N$ is the mass transfer coefficient (dimensionless); $e_o max$ and $e_o min$ are the saturated vapor pressures at daily maximum and minimum, respectively, air temperatures (in millibars).

Roberts et al. (1997) specified five methods of estimating lake evaporation as Water Budget, Energy Budget, Mass Transfer, Combination of Mass Transfer and Energy Budget, Empirical Formula Methods.

#### *2.2.2.1 Water Budget Method*

In this method lake evaporation is estimated by taking into account summations of lake inflows minus summation of lake outflows minus lake’s change in storage (Equation3)

$$P + V_i + V_{ig} = V_{os} + V_{og} + E_L + D_s + T_L \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

Where $P$ is daily precipitation; $V_i$ is Daily Surface Inflow into the lake; $V_{ig}$ is Daily Groundwater Inflow; $V_{os}$ is Daily Surface Outflow from the lake; $V_{og}$ is Daily Seepage Outflow; $E_L$ is Daily Lake Evaporation; $D_s$ is Increase in Lake Storage in a day; $T_L$ is Daily Transpiration Loss.

All quantities in units of volume (m$^3$) or depth (mm) over a reference area. Equation 3 can then be rearranged as

$$E_L = P + (V_i - V_{os}) + \left(V_{ig} - V_{og}\right) - T_L - D_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

Roberts et al. (1997) indicated that this method is prone to errors as any measurement errors that may be in the water budget parameters, greatly affect the residual flux which is evaporation.

#### 2.2.2.2 Energy Budget Method

Eldho (2006) indicated that this method of evaporation is based on the application of the law of conservation of energy which states that energy is neither created nor destroyed but it can only be transformed from one form to the other. The energy available for evaporation is determined by considering the incoming energy, outgoing energy and energy stored in a particular body over a known time interval as in the following equation 5:

$$H_n = H_a + H_e + H_g + H_s + H_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

Where $H_n$ is net heat energy received by the water surface; $H_a$ is sensible heat transfer from water surface to air; $H_e$ = heat energy used up in evaporation; $H_g$ = heat flux into the ground; $H_s$= heat stored in a water body; $H_i$ = net heat conducted out of the system by water flow; All energy terms in calories per square mm per day.

Estimation of evaporation in a lake by energy balance method has been found to give satisfactory results with errors of the order 5% when applied to periods less than a week (Eldho, 2006). Since evaporation takes energy, then the method works on the principle that a sum of energy reaching the lake must be equal to the total energy leaving the lake. This method makes use of solar radiation energy where by reflected solar radiation, net longwave radiation, energy transferred from the lake bed and reflected are taken into account (Roberts et al., 1997).

#### *2.2.2.3 Mass Transfer Method*

According to Eldho (2006), this method is also known as aerodynamic method and is based on turbulent transfer of water vapour from an evaporative surface like a lake to the atmosphere. The mass-transfer method is one of the oldest methods for determining lake evaporation and is still an attractive method in estimating free water surface evaporation because of its simplicity and reasonable accuracy. Mass-transfer methods are based on the Dalton equation which for free water surface can be written as:

$$E = C(e_s - e_a) \quad \ldots 6$$

Where $E$ is free water-surface evaporation; $e_s$ is the saturation vapor pressure at the temperature of the water surface; $e_a$ is the actual vapor pressure in the air; $C$ is an empirically determined constant involving some function of wind speed.

#### *2.2.2.4 Combination of Mass Transfer and Energy Budget*

Eldho (2006) also specified a combination of mass transfer and energy budget methods. From the original Penman-Monteith equation and the equations of the aerodynamic and canopy resistance, the FAO Penman-Monteith equation has been derived as:

$$ET_{\circ} = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

Where $ET_{\circ}$ is reference evapotranspiration [mm day$^{-1}$]; $R_n$ is net radiation at the crop surface [MJ m$^{-2}$ day$^{-1}$]; $G$ is soil heat flux density [MJ m$^{-2}$ day$^{-1}$]; $T$ is air temperature at 2 m height [°C]; $u_2$ is wind speed at 2 m height [m s$^{-1}$]; $e_s$ is saturation vapour pressure [kPa]; $e_a$ is actual vapour pressure [kPa]; $e_s$ - $e_a$ saturation vapour pressure deficit [kPa]; $\gamma$ is psychrometric constant [kPa °C$^{-1}$].

#### *2.2.2.5 Empirical Formulas using MET data – the USBR & USGS Formula*

The USBS and USGS specified an estimate of lake evaporation by using an empirical formula as follows (Eldho 2006):

$$E_{lake} = 4.57T + 43.3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

Where $E_{lake}$ is over the lake evapotranspiration in cm /year is assumed to be a function of temperature. $T$ is the mean temperature in Degrees Celsius per year.

### *2.2.3 Lake Runoff*

Hydrological modelling may be used in estimating runoff as was used by Kizza et al. (2009) and Yu et al. (2015). Estimates of lake inflows like runoff may involve basin–scale rainfall-runoff modelling and some studies on runoff predictions on basins with no or a few gauging stations (Duan, 2014). Models may also be used to estimate river discharge (Setegn et al., 2008). One such model that is used to estimate river discharge is the WASMOD (Xu, 2002).

Using weather data, runoff may also be estimated on a pixel by pixel mode with the use of an Evapotranspiration model (e.g. VegET) as was used by Velpuri et al. (2011). A Water Partition and Balance Model (WAPABA) that is based on the Budyko framework can also be used to estimate runoff in an ungauged catchment scenario like that of lake Chiuta (Muvundja et al., 2013). The other part of lake runoff of interest are groundwater flows. When inflow measured data are scarce, estimates of lake evaporation and lake connection with groundwater can be problematic and the water balance in lakes then becomes incomplete (Duan 2014). However, groundwater flows can be estimated if all other components of the water balance are measured with high accuracy and precision (Duan, 2014). Approaches for groundwater flow estimation have been suggested by Yihdego (2010) and Thomson and Mzila (2015).

Individual water balance components have been identified by using satellite data (Duan, 2014). Bastiaanssen and Chandrapala (2003) and Shilpakar et al. (2011) estimated river flow using interpolations from rain gauge stations and satellite derived evapotranspiration and root zone storage changes. Gao et al. (2010) estimated runoff using satellite based precipitation, evapotranspiration. In a case of lack of satellite measurements, runoff may be estimated from water balance components like precipitation, evaporation, soil moisture and total water storage that may be measured (Duan, 2014).

### 2.3 Possible Lake Level Trajectory into the near Future

Lake level trajectory into the near future can be forecasted using trends and models (Mason et al., 1994). The approaches involve analysis of the present situation of a lake to forecast a future scenario. A detailed lake level monitoring analysis and forecasting is therefore required for accurate suggestions of a lake level future trajectory (Duan, 2014).

### *2.3.1 Lake Level Analysis and Forecasting*

Accurate data on the water balance constituents is crucial for lake level analysis in addition to water supply and demand management. In case of impractical in situ measurements, satellite data and application of specific interpretation of algorithms may come in (Duan, 2014). Wherever possible, hydrological models have been used to simulate natural responses of lakes be it inflows, water losses, outflow, precipitation and evaporation (Brater, 1972). Lake water budget models have been used widely in lake level analysis related researches (Gibson et al., 2006; Kebede et al., 2006; Li et al., 2007) and have helped in assessing the causative mechanisms behind lake – level variations in a variety of tropical lake basins (Lyons et al., 2010). Lake levels can be modelled by the water budget approach as specified by Velpuri et al. (2011) and as done by Brater (1972) in coming up with a deterministic lake water balance model. Lyons (2010) employed an energy balanced hydrological model that predicted critical lake recessions from analysis of seismic – reflection and deep lake drill-core data where-by bottom morphology of the lake was assessed by use of seismic–reflection profiles collected across the basin. The data used to build the model may be from observations of level fluctuations, historical gauge data and, altimetry observations from satellites (Alpe, 2015). The model may therefore follow a lake level modelling approach as used by Velpuri et al. (2011).

Satellite altimetry data has been used in remote sensing to derive water levels in lakes for over fifteen years (Muala et al., 2014). It is a fact that water bodies influence regional climate as they have different radiative and thermal properties as compared to soils and vegetative surfaces therefore remote sensing techniques may be handy in this aspect. The real-time satellite data may be compared with real time in situ water data to assess changes in water level (Albright et al., 2003). Again, in validating lake level models, in-situ lake levels are supposed to validate modelled lake levels but the use of satellite altimetry data comes in to cover absence of in-situ data (Velpuri et al., 2011). Satellite data are estimated from TOPEX/Poseidon (T/P), Jason 1, 2, or 3 and ENVISAT Satellites (Velpuri et al., 2011).

Changnon et al. (1989) used climate scenarios based on three global climate model estimates that showed a doubling Carbon Dioxide ($CO_2$) in the atmosphere. Scenarios based on the extreme annual precipitation are then used to determine potential future lake recessions. Muala et al. (2014) from a case of limited in-situ data in water level monitoring, derived water level and lake surface area measurements from satellite measurements. Landsat satellite data may also be valuable in checking lake recessions. Velpuri et al. (2011) modelled lake levels using satellite altimetry data and Hui et al. (2006) specifically used multi temporal Landsat imagery to model spatial temporal change of a lake. Calmant et al. (2008) and Zhang et al. (2011a,b) have successfully made use of satellite radar and laser altimetry respectively to estimate water levels from water bodies.

Kavekar et al. (2011) used genetic programming (GP) and Artificial Neural Networks (ANN) to forecast daily water levels of a lake for a set of time intervals using observed levels where as comparisons of Auto Regressive Integrated Moving Average ARIMA models using time series analysis may also be employed (Ozen et al., 2015).

Galavi et al.(2013) noted that ARIMA models have demonstrated comparable skills to more recent Artificial Neural Networks (ANNs) in lake level forecsting. For example, Irvine and Eberhardt (1992) developed ARIMA models for forcasting Lakes Erie and Ontario levels. That study took into account short term, seasonal and long term water level dynamics in the two lakes and the ARIMA models of the form (1,0,1) , (0,1,1) were accepted.

Lake water level analysis for detecting lake recessions or booms may also be based on in-situ water levels and, in some cases, bathymetry maps (Duan, 2014). These all may suggest a possible trajectory of lake levels into the near future. Assessment of the long-term water balance of lakes provides improved knowledge of regional and global climate change and a quantification of human impacts on water resources (Sutcliffe and Petersen, 2007). Lake outflow has a direct bearing on the resultant water level. In case of lack of a gauged lake outflow, estimation of lake outflow is estimated using calibration as remote sensing techniques are only used in this aspect only in lakes that are dominated by irrigation abstraction (Velpuri et al., 2011). However, Duan (2014) stated that lake outflows may be determined from the relationship that lake inflow minus lake outflow gives change in lake storage. Many models have been developed for forecasting lake levels and surface areas' reaction to climate change (Duan, 2014). Such models can either be deterministic (assumes that variables can be well specified in times and simulated) or stochastic (assumes random variation following a probability distribution). For instance, Mason et al. (1994) developed a model that assumed a linear relationship between discharge rate and lake water level. The linear model then was able to describe the discharge – lake level relationship and went further in predicting lake morphology characteristics.

### 2.4 Development and Evaluation of the Hydrological Water Budget Model

In evaluating the model (Fig. 1) a choice of a class of a hydrological model is done followed by selecting a particular model that is then calibrated and validated for use in predictions (Xu, 2002).

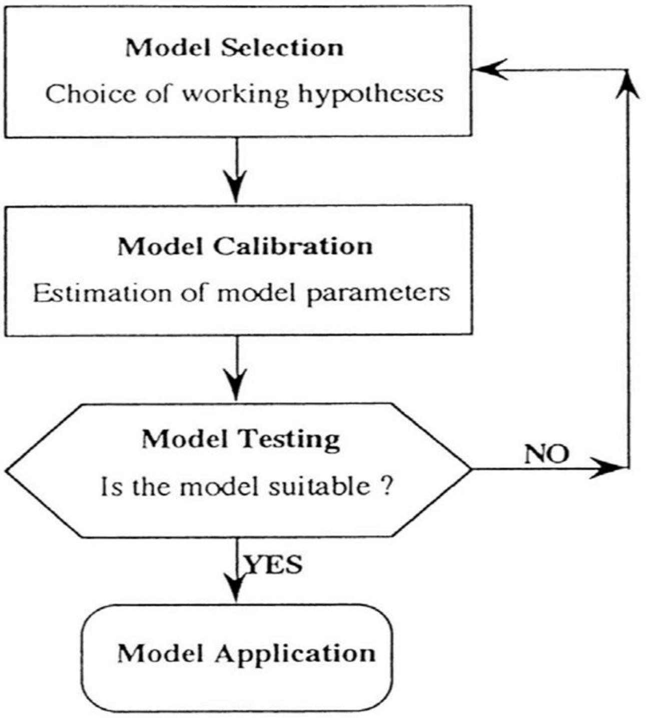


**Figure 1: Phases of Model Evaluation Flow Chart (Adapted from Xu, 2002)**

Xu (2002) stated that hydrological water budget modelling involves defining the problem at hand followed by the specification of objectives. Data is then checked before determining possible computing facilities and specification of socio – economic constraints. The hydrological water budget model is then used and one can predict at what point in the water budget the water level is going to recede or get high. Accuracy of the model is checked using various statistical analyses like the Nash-Sutcliffe Index, root mean square error to the standard deviation of observations ratio and the Percent Bias Error (PBIAS) (Moriasi et al., 2007; Xu, 2002).

# CHAPTER 3

# STUDY AREA AND METHODOLOGY

## 3.1 Introduction

The first part of the study involved getting relevant clearances from authorities in the study area. This involved engaging the Ministry of Agriculture, Irrigation and Water Development (MAIWD), Machinga District Water Development Office and local authorities around Lake Chiuta's catchment. Benefits in conducting the research were put forward and then a desk top study was conducted where literature on the subject was evaluated and reviewed to gain an in-depth knowledge of the subject in question.

## 3.2 Study area

Lake Chiuta is located in the Southern Region of Malawi (Fig. 2). Malawi is divided into 17 Water Resource Areas based on its river basins (JICA, 2014). Lake Chiuta belong to Water Resource Area Number 11. The catchment area of the lake is about 1,330 km$^2$ but the catchment area of the whole Lake Chiuta Water Resource Area is 2,464 km$^2$ (JICA, 2014). The lake is found in Machinga District in the eastern part of Malawi (JICA, 2014).

### *3.2.1 Geomorphology*

The lake lies at a mean elevation of 620masl with a maximum depth of 5m and with a pan–shaped morphology (Dulanya et al., 2012). In terms of geomorphic features of the lake, the basin belongs to the low to highland topographical division and forms the east banks of the Great East African Rift Valley (GEAR) comprising of gentle hills that range from 600 to 800 masl (MIWD, 2010). Thus the lake is located on the eastern part of the Malawi Rift of the GEAR (MIWD, 2010).

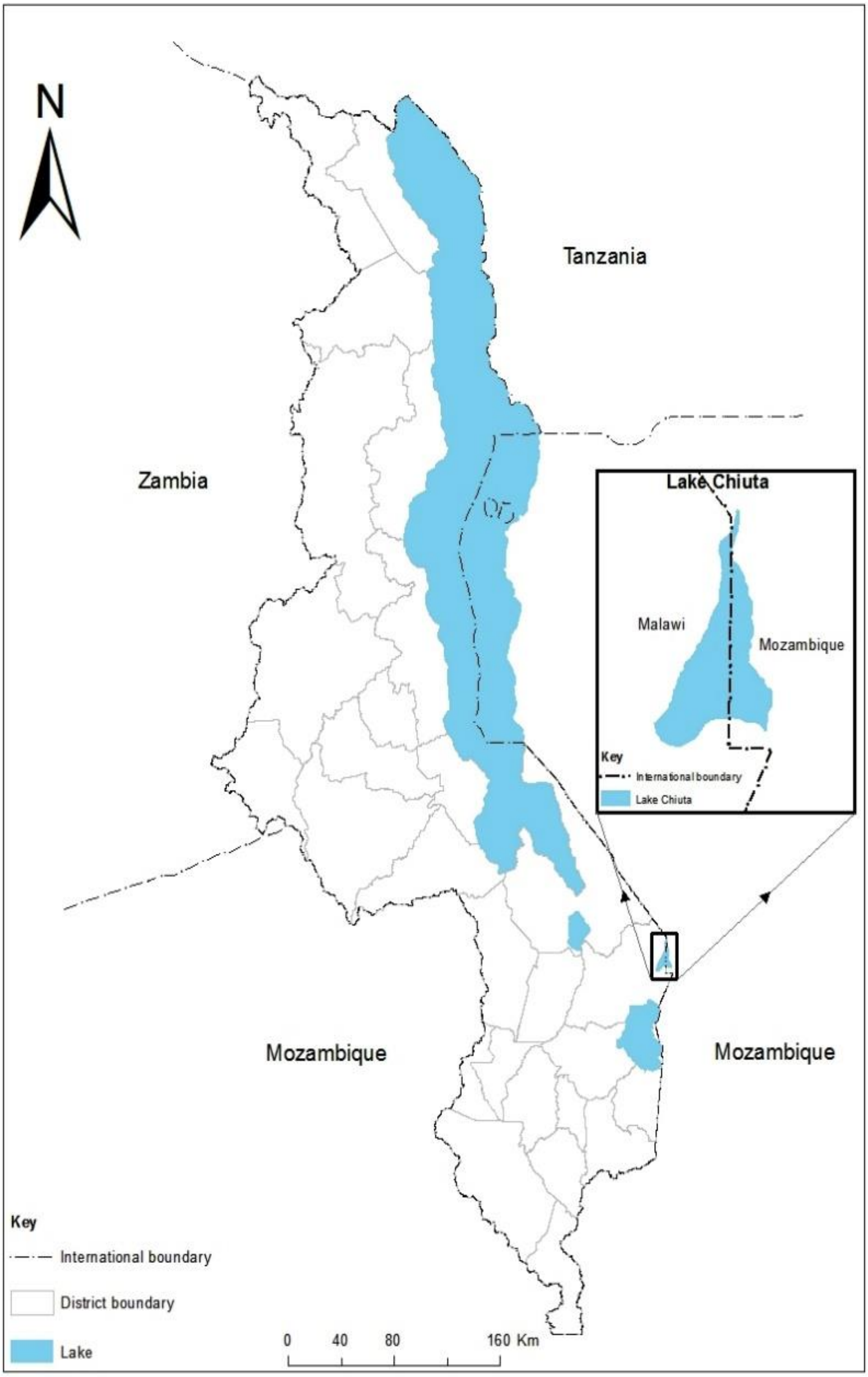


**Figure 2: Location of Lake Chiuta (Adapted from Dulanya et al. (2012)**

### *3.2.2 Hydrology*

Lake Chiuta's basin encompasses all streams draining into Lake Chiuta and the water surface area of the lake is 200km$^2$ with a larger area in Malawi and a smaller one in Mozambique as it is a shared water course between the two countries (JICA, 2014). Its total length is 204.9 km with a total volume of 0.225km$^3$ (MIWD, 2010). Hydrology of the lake is dominated by inflows from Mpili River (Dulanya et al., 2012). The lake is separated from Lake Chilwa in the south by a sand bar. During times of high levels, the lake discharges into Lake Amaramba in the neighboring Mozambique through a wetland. In dry years, this outflow ceases, resulting in a discontinuity between the two lakes. Lake Chiuta then exists as a separate single water body (JICA, 2014).

### *3.2.3 Rainfall and Climate*

Lake Chiuta's basin receives a mean annual rainfall of about 1135mm and the expected inflows into the lake amount to 248mm, resulting in a runoff coefficient of 21.85% (JICA, 2014). The area experiences two distinct seasons such as wet and dry seasons following Inter Tropical Convergence Zone (ITCZ) moving state (MIWD, 2010). The climate of the area is sub-tropical with weather variations (MIWD, 2010). The area is affected by south easterly winds in the dry season JICA, 2014)

## 3.3 Data Collection

Most rainfall stations in the lake's basin had no data. Available data was therefore collected from different sources. Rainfall data spanning a period from 1960 to 2009 was obtained for two known rainfall stations (Ngokwe EPA and Kakhomba

Agricultural Station) in the lake basin (Fig. 3). The data collected was generally of good quality as it had a lots of information without gaps.

**Figure 3: Ngokwe and Kakhomba Rainfall Stations**

Temperature data (from 1971 to 2005) used to analyse lake evapotranspiration was collected from the Department of Climate Change and Meteorological Services. Satellite altimetry data was available for October 1992 to March 2017 period from the following US Foreign Agriculture Service website:

https://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/gr_regional_chart.aspx ?regionid=safrica&reservoir_name=Chiuta.

## 3.4 Lake Hydroclimatology Evaluation and Analysis

### *3.4.1 Catchment and Over-the-Lake Rainfall*

Rainfall data sets from Ngokwe and Kankhomba Stations were averaged to come up with a mean rainfall estimate for Lake Chiuta Catchment. An arithmetic average method was used to estimate Lake Chiuta catchment rainfall. Since there was no station in the lake, rainfall data from nearby Ngokwe station was used as over-the-lake rainfall as suggested by Duan (2014). The rainfall data was analysed at various temporal scales like monthly, seasonal (wet and dry), and annually.

Precipitation Concentration Index (PCI) was estimated using equation 1. PCI graph was then plotted in R software and analysis for direction of temporal trends in the time series was conducted using the Mann-Kendall Test (Mann, 1945; Kendall, 1975) and slopes of significant trends were quantified using linear regression. Standardised anomalies from mean rainfall were quantified by dividing anomalies by climatological standard deviation. Anomaly being the difference of climatological value from the observed values. The results were plotted using R Software.

Return periods of hydrological extremes were determined through frequency analysis where extreme values were compared with the data set of the whole period and noting number of occurrence. This assisted in determining the likelihood of such extreme occurrence happening again. The analyses were conducted based on 5 and 10 – year temporal dimensions. Average Rainfall Annual Yield ($AAY$) was calculated in accordance with Drayton (1984) as follows:

$$AAY = 0.71(AAR - 690) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 9$$

Where $AAR$ is the Average Annual Rainfall.

### *3.4.2 Over-the-lake Evapotranspiration*

Over-the-lake evapotranspiration was determined using an empirical formula by the USGS and USBR as stated in equation 8. Furthermore, maximum and minimum temperature data for Mangochi Station between 1971 and 2005 were used to derive temperatures of the Lake Chiuta basin using altitude as a conversion factor. Lake Chiuta is located at a higher altitude (620masl) than Mangochi Station (482 masl) and should therefore experience relatively cooler conditions. The temperatures for Lake Chiuta were then estimated from equation 10 as follows:

$$T_{Chiuta} = T_{Mangochi} * \frac{489 m.a.s.l}{620\ m.a.s.l} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 10$$

Where $T_{Chiuta}$ is estimated temperature in Lake Chiuta and $T_{Mangochi}$ is mean temperature at Mangochi Station. Data collected for Mangochi consisted of daily maximum and minimum temperatures. Temperatures corrected for Chiuta were analysed at annual and monthly scale. In addition, the mean temperature data were also used in deriving the lake evapotranspiration and the Standardised Precipitation-Evapotranspiration Index (SPEI) for the area. R software package by Begueria and Vicente-Serrano (2015) was applied to analyse SPEI as recommended by the WMO.

### *3.4.3 Lake Runoff Modelling*

As the lake inflows could not be determined due to lack of river inflow data runoff modelling was conducted in this study. Runoff models help in understanding of how river basins may behave hydrologically under different climate change scenarios (Xu, 2002). A model can be defined as a representation of a complex system and a run off model among its various uses, may be used to study potential impacts of climate change and for generation of synthetic sequences of hydrologic data that may be useful in forecasting (Xu, 2002). There are many examples of hydrological models as classified according to their class and one such particular model that has been used in this paper is the WASMOD model. Model parameters of the WASMOD according to some studies, are easily be correlated with basin characteristics like land cover fractions and soil textures (Xu, 1999, 2002; Muller – Wohlfeil et al., 2003).

WASMOD is an acronym standing for Water and Snow Balance Modelling System and it belongs to a class of conceptual, stochastic and lumped water balance models (Xu, 2000). The WASMOD is selected to solve problems in hydrological modeling because it has a simple structure and has few parameters in line with global modeling limitations (E. Widėn – Nilsson et al, 2007). The study used the monthly Water and Snow Balance Model (WASMOD) by Xu (2001). WASMOD takes various combinations of climate data as inputs. This model structure is a lumped conceptual kind (Figure 4).

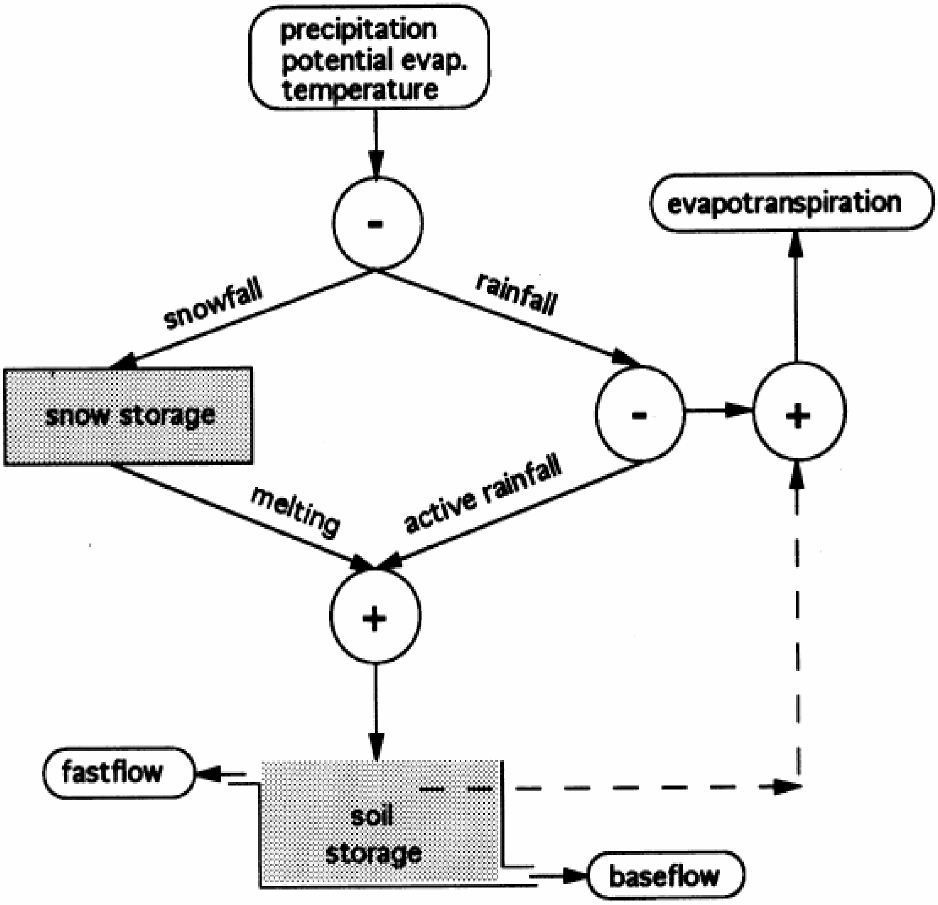


**Figure 4: WASMOD - M Model Structure (Xu et al., 1996; Xu, 2002)**

These combinations at the minimum require catchment rainfall and discharge. Other combinations of inputs include evaporation, temperature and relative humidity. Rainfall and temperature were available for Chiuta catchment but there was no gauged data for any of the inflowing rivers. As a result, the monthly area rainfall was multiplied by a run-off coefficient of 21.85% (JICA, 2014) to come up with total runoff for the catchment as surrogate for all river inflows.

The model was then calibrated and validated against the inflows using the simple split sample test. The period from 1965 to 1985 was used for calibration and 1990 to 2009 was used for validation.  There are 8 different inbuilt model types and the best model is selected based on model performance as outlined by Xu (2001). A WASMOD2 executable file was run. Since predetermined that this was a snow free catchment, the snow routine module was neglected.

Then choice of model type had to be made and in this case type 3 model was chosen since the given data as in model type 4 models had precipitation and discharge as inputs. An input file in notepad was chosen and typed on WASMOD code in capital letters from which WASMOD output a message of “Available Data for Chiuta Catchment as being available from 1960 to 2009. Three options are then available as calibration only, calibration and simulation, and simulation only.

Calibration was chosen to start from 1965 to 1985. Two choices then had to of either preliminary run or final run. Preliminary run was selected. The preliminary run according to WASMOD allows calibration and comparison of eight different versions of the model and tells one which version fits best of the catchment data after model evaluation has been conducted. Final run takes less than 1 minute, it calibrates the best (or selected) model version and provides a detailed result. After the preliminary run was done, the program ran successfully. An output file called was then opened from where a best model was chosen using the criteria suggested by (Xu, 2002).

After choosing the best model for Chiuta catchment, the above procedure was repeated but it was not ran in preliminary mode but rather in final ran mode with the best model number with a validation period of 1990 to 2009. The program ran successfully and results were looked at and plotted. At this level the model was optimized automatically resulting in optimized parameter values and the 95% confidence interval, correlation matrix of parameter values, parameter values compared against number of iterations, sum of squares of residuals compared against parameter values in the neighborhood of the optimized value and autocorrelation of residuals compared against time lag.

The model performance evaluation criteria included the Nash-Sutcliffe Index Coefficient, the Percent BIAS and the Mean Squared Error. Best model performance is noted when PBIAS ± 25 %, $RSR \leq 0.70$ and $\boldsymbol{R^2}_{NS} \geq \mathbf{0.5}$ (Moriasi et al., 2007). WASMOD did the analysis by calculating observed and calculated observations and in parameter analysis all zero values had to belong to the 95 % of the statistical interval (Xu, 2002; Xu, 1999a). The statistical interval is called the half width confidence interval (HWCI) which is the half width of 95% confidence interval (Xu, 2002). This half width of a confidence interval showed a margin of error. So WASMOD having had the upper and lower limits and having them subtracted with the mean, the half width confidence interval was obtained.

Outputs of interest from the model were the total flows, fast flow and groundwater contributions. These are stored in a file after each run and were extracted for further analysis. Return periods for extreme flows was also analysed through frequency analysis.

Calibrated model was then used in WASMOD to simulate inflows and lake levels at three different hydroclimatic scenarios in the lake's catchment as follows:

a) Scenario 1 considered 2 °C temperature increase and 10 % rainfall decrease
b) Scenario 2 considered 2 °C degrees temperature increase and no change in rainfall
c) Scenario 3 considered 2 °C temperature increase and 10% increase in rainfall

These scenarios were selected as representative of hydroclimatic change in the area to appreciate the situation of runoff in case of such expected change. The choice was governed by prevailing trends in rainfall and temperature. So three scenarios were chosen to represent a lot of hydroclimatic scenarios that may come in.

## 3.4 Lake Response to Climatic Forcing and Possible Trajectory of Lake Levels into the Near Future

### *3.4.1 Lake Level Monitoring*

After two successive years of low rainfall from 2014 to 2016, a considerable lake recession was noted in early 2016. The study conducted dry season field visits from 15th July 2016 to 8th October 2016 on a bi – weekly basis to monitor the lake level recession. As the recession progressed, level gauges that were installed in the lake from which observations were recorded were noted to be reading declining lake levels. The level gauges were installed strategically on the north, center and southern parts of the lake to have a fair view on how the lake level was dropping.

### 3.4.2 Lake Outflow into Lake Amaramba in Mozambique

Determination of lake outflows to the Amaramba used the following relationship:

$$O = P + I - E - \frac{dS}{dt} \qquad \ldots\ldots 11$$

Where $I$ are Lake Inflows; $P$ is over the lake rainfall, $E$ is over the lake evapotranspiration and *dS/dt* is change in lake storage per unit change in time (Mason et al., 1994; Neuland, 1984, Street-Perrot, 2003). Mann-Kendall trend test analysis was used in R software to note significant or insignificant trends at $\alpha=0.05$ significance level.

### 3.4.3 Lake-level Variation

Multi – temporal satellite images for Lake Chiuta from the year 1973 to 2015 have been used. The images were to be useful in understanding the Lake Chiuta's level and shore line variability in temporal timescale. Temporal resolution of the images in question consisted time line of start of rainfall season and end of the rainy season.

Lake level deviation from a datum was used to derive mean lake levels assuming a mean lake level of 5m. Mann-Kendall trend test analysis was used to note significant or insignificant trends at $\alpha=0.05$ significance level. Return periods of extreme lake levels were also analysed through frequency analysis.

### 3.4.4 Hydrological Water Budget Model Development & Evaluation

Modelled inflow, determined precipitation, modelled or determined over the lake evaporation were then aggregated into the hydrological water budget model for calibration and validation. Water level time series, lake surface area and lake water volume from open access data based on satellite measurements and the currently available satellite altimetry database providing lake levels were considered (Duan, 2014). Multi-temporal satellite images and satellite altimetry data were used to determine historical lake levels. The satellite data were then used as supporting information to calibrate and validate the hydrological water budget model for constrainment of model parameter uncertainty and to improve run off estimation. Satellite data used is from TOPEX/Poseidon (T/P), Jason 1, 2, or 3 and ENVISAT Satellites (Velpuri et al., 2011). The water budget model then took the form:

$$D_{(t)} = D_{(t-1)} + Q_{rain} + Q_{in} - Q_{eva\,p} - Q_{outflow} \ldots\ldots\ldots\ldots\ldots\ldots 12$$

Where $D_t$ is the lake level at present time (t), $D_{t-1}$ is the lake level at previous time step $(t - 1)$, $Q_{rain}$ is the over-the-lake precipitation, $Q_{in}$ are lake inflows, , $Q_{evap}$ is over-the-lake evaporation or evapotranspiration, , $Q_{outflow}$ is the lake outflow.

### ***3.4.5 Development of an early warning model***

The ARIMA model on the annual total flows took the form *(p, d, q).* This required data was without a trend and with a long stationarity without missing data (Young et al.,2015). In this model *p* is the order of the autoregressive process, *d* is the order of differencing, *q* is the order of moving average process. In case of no trend in data, the model took the form (*p, 0, q*). This study made use of Auto-Regressive Integrated Moving Average Technique (ARIMA) on the annual lake inflows. The inflows being the sum of over-the-lake rainfall and inflows from rivers. Periodicity and seasonality in the data series were removed. Autocorrelation Coefficient, lake levels from 1992 to 2017, with a gap between 2002 and 2008 were investigated. The 2002 and 2008 data gap was dealt with by evaluating subset of the monthly lake levels between years 2009 and 2017.

Assuming a 5-year serial correlation in lake levels, ARIMA (1, 0, 1) to ARIMA (5, 0, 1) models were tested on the annual inflows. This proxy stochastic model was then applied to predict lake inflows from 2009 to 2030 at a 95% Confidence Interval.

The predicted total inflows between 2010 and 2028 were verified by the following relationship:

$$Inflow = P_{Ngokwe} + RC * \overline{P}_{catchment} \quad \text{.......................................................................} 13$$

Where *Inflow* is the total inflow into the lake, $P_{Ngokwe}$ is the rainfall at Ngokwe station representing over the lake rainfall, $\overline{P}_{catchment}$ is the average rainfall over the catchment from as many observation stations as possible and RC is the catchment runoff coefficient (Muvundja et al., 2013) .

# CHAPTER 4

# RESULTS AND DISCUSSIONS

## 4.1 Hydrological parameters

## 4.2 Catchment Rainfall Regime

The trend in the rainfall pattern was negative with a slope of -0.89mm per year but this was not significant (Mann – Kendall value = -0.594, $p>0.05$) (Fig. 5). The total annual mean of rainfall in Lake Chiuta Catchment as averaged from the two rainfall stations of Kankhomba Agriculture and Ngokwe during the 1960 to 2009 was calculated to be 879.9mm much lower than the 1135mm that was reported by the JICA (2014). The 1135mm of rainfall reported by JICA (2014) was reported based on Water Department / UNDP (1993). Therefore it should be possible that the figure should be higher than what this study found out. The 1978/79 peak in rainfall could be attributed to have added a big weight to the rainfall as of 1993. The dataset's standard deviation to mean ratio percentage which is the coefficient of variability was calculated as 21.1%.

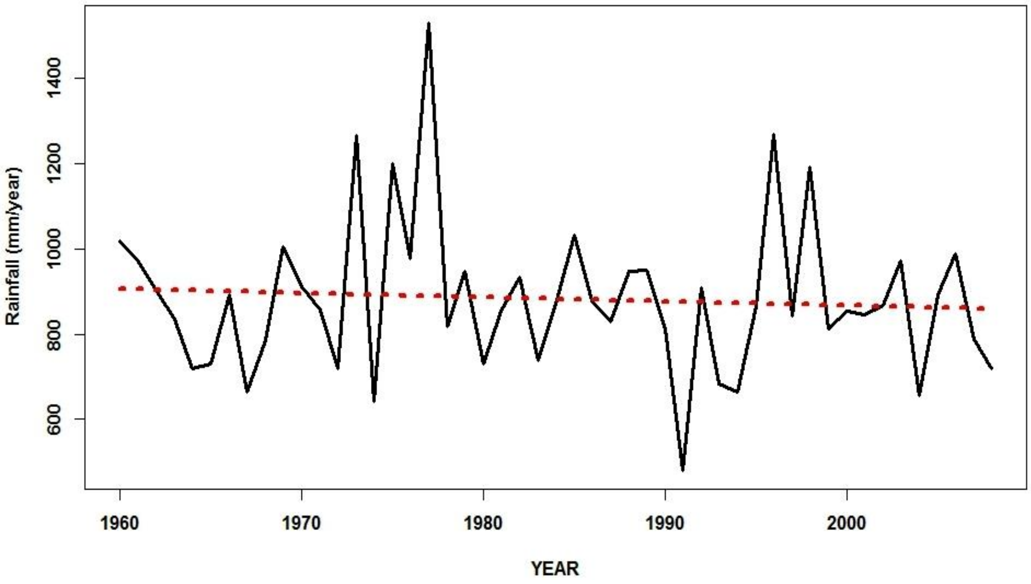


**Figure 5: Lake Chiuta Mean Annual Rainfall (1960 - 2009)**

The catchment reported an annual mean maximum rainfall in the year 1978 of 1455.4 mm, a minimum mean annual rainfall in 1981 of 515.1mm. The country in 1978 received a lot of rainfall as reported by Kumambala & Ervine (2010) with Lake Malawi levels being the highest in that period.

The corresponding departures from the mean annual rainfall indicated 1978 highest rainfall and the 1997 one as signified by the two maxima. And the 1974 and 1991 minima are also visible (Fig 6). The pattern from the year 1975 indicates that rains have normal to below normal.

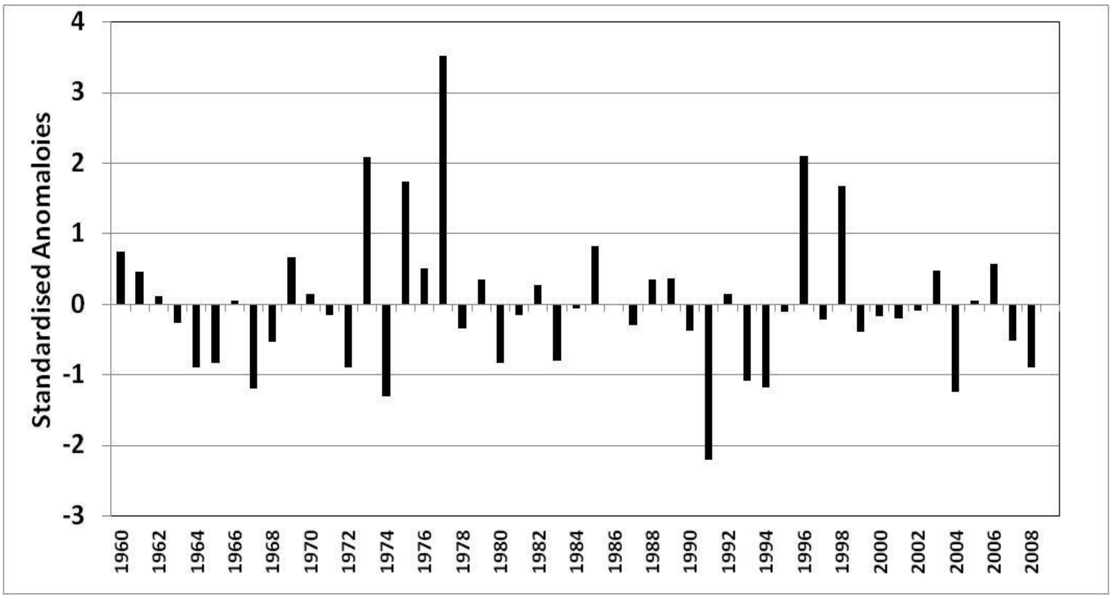


**Figure 6: Standardised anomalies from mean annual rainfall**

Most rains in Chiuta do fall from November to April (Fig. 7). The month of January is when the rains peak with rainfall of about 26.2% of the total annual mean catchment rainfall. February is second with rains of 19.6% of the total annual mean. December contributes 18.9%, March 16.5% and April 5.6% of the total annual mean catchment rainfall. The months August and September are the driest months.

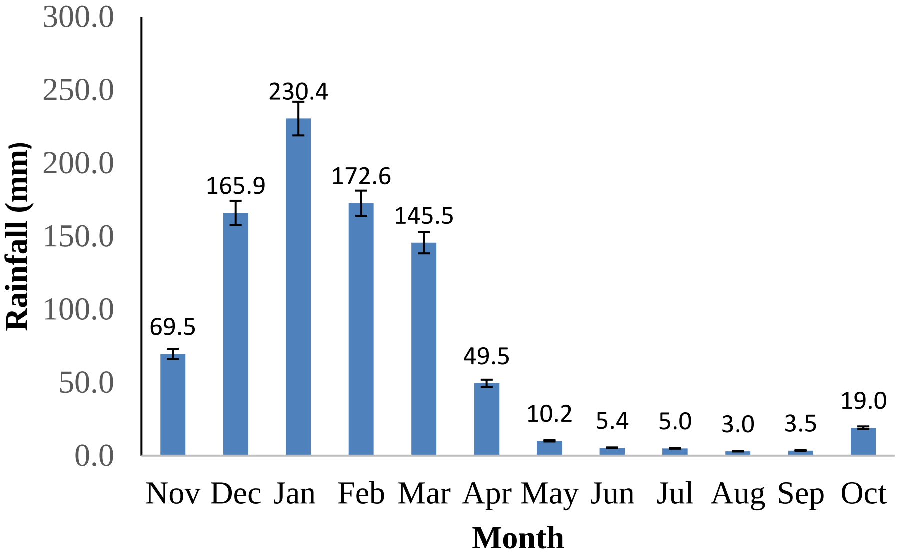


**Figure 7: Mean Lake Chiuta Catchment Rainfall Regime**

June and July contributes 0.6% of the total annual rainfall where as August contributes 0.3% and September contributes 0.4% of the total annual mean catchment rainfall. May 1.2 %, April 5.6%, October 2.2% November 7.9%. The error margin was 5%.

The 1960 to 2009 Lake Chiuta Catchment Mean Monthly Rainfall had its mean calculated to 73.3mm per month with a high coefficient of variability of 126.4%. The general trend is negative with a slope of -0.0794mm per month (Fig. 8).

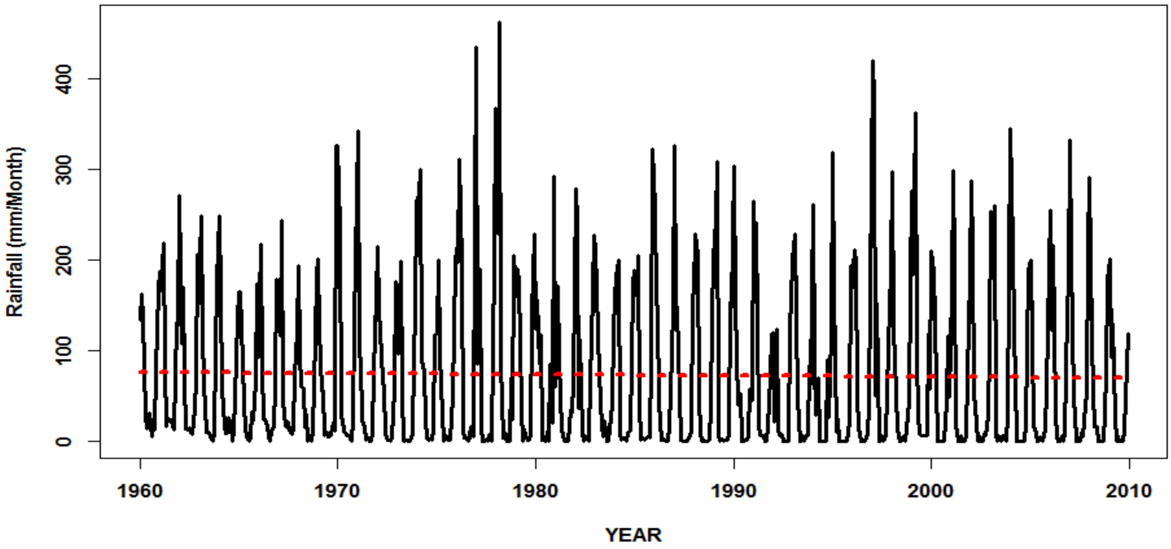


**Figure 8: Lake Chiuta Catchment Mean Monthly Rainfall**

The Mann-Kendall Trend Statistic of -2.98 was found to be significant at $\alpha$=0.05 level agreeing with the annual rainfall time series.

The mean rainfall from 1960 to 2009 wet seasons was 833.5mm and the coefficient of variability was 21.7% (Fig. 9a). Mean maximum rainfall in the wet seasons was observed in the year 1978 of 1372mm and mean minimum rainfall in the wet seasons was observed in the year 1981 of 464.6 mm just as in the general catchment rainfall analysis .A wet season stationary series trend is noted much as the trend direction and slope are positive though with a slight a slope of 0.28mm per year. The Mann - Kendal trend was found to be insignificant at α=0.05 level.

The mean rainfall from 1960 to 2009 dry seasons was calculated to be 46.1mm. The coefficient of variability was 67.83% (Fig. 9b). Mean maximum rainfall in the dry seasons was observed in the year 1961 of 118.5mm. A negative trend is noted with a slope of -1.16mm per year. The Mann-Kendall trend was found to be significant at α=0.05 level. This suggests that the catchment's dry seasons are likely to continue experiencing reduced amounts of rainfall.

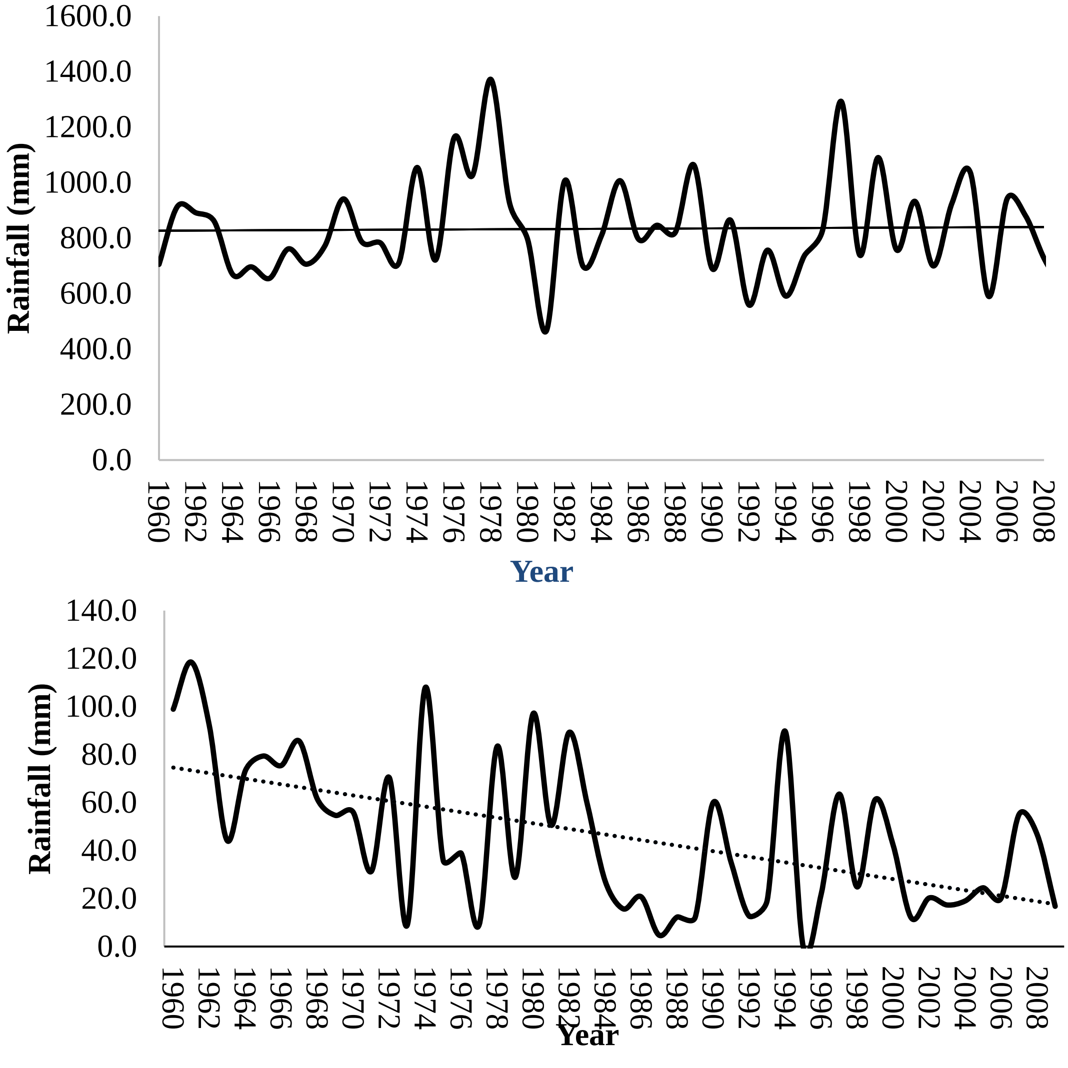


Figure 9: Wet (a) and Dry (b) Season Catchment Rainfall

As can be noted in table 2, after analysing monthly rainfall trends, positive trends were noted in the months of January and February, the January rainfall pattern had a significant slope of 1.65mm per year with a lowest coefficient of variability of 36.15%. Months of March, April, had negative and insignificant trends while May to August had negative but significant trends. September to December had negative and insignificant trends.

**Table 2: Summary Statistics for Lake Chiuta's Catchment Rainfall**

| SEASON | **MEAN (mm)** | ***CONT %** | **CV%** | **MAX (mm)** | **MIN (mm)** | **MK α=0.05** | **SLOPE** | ****S** |
|---|---|---|---|---|---|---|---|---|
| **Annual** | 879.6 | 100 | 21.1 | 1455.4 | 515.1 | -0.594 | -0.89 | I |
| **Monthly** | 73.3 | N/A | 126.4 | 121.3 | 42.9 | -2.98 | -0.08 | S |
| **Wet Season** | 833.5 | 94.76 | 21.7 | 1372 | 464.6 | 0.177 | 0.28 | I |
| **Dry Season** | 46.1 | 5.24 | 67.83 | 118.5 | 0 | -3.29 | -1.16 | S |
| **January** | 230.4 | 26.2 | 36.15 | 434.6 | 59.3 | 2.175 | 1.65 | S |
| **February** | 172.6 | 19.6 | 36.5 | 377.4 | 20.8 | 0.18 | 0.3 | I |
| **March** | 145.5 | 16.5 | 66 | 462.7 | 9.7 | -0.32 | -0.33 | I |
| **April** | 49.5 | 5.6 | 75.4 | 195.4 | 7.3 | -1.77 | -0.48 | I |
| **May** | 10.2 | 1.2 | 152.7 | 77.6 | 0 | -3.52 | -0.32 | S |
| **June** | 5.4 | 0.6 | 136.7 | 29.9 | 0 | -4.67 | -0.3 | S |
| **July** | 5 | 0.6 | 149.5 | 31.4 | 0 | -4.32 | -0.28 | S |
| **August** | 3 | 0.3 | 166.1 | 23.4 | 0 | -2.52 | 0.13 | S |
| **September** | 3.5 | 0.4 | 170.97 | 32.2 | 0 | -1.76 | -0.14 | I |
| **October** | 19 | 2.2 | 111.97 | 89.7 | 0 | -0.678 | 0.02 | I |
| **November** | 69.5 | 7.9 | 56.49 | 154.1 | 4.7 | -0.192 | -0.06 | I |
| **December** | 169.9 | 18.9 | 36.03 | 326.1 | 44.8 | 0.8 | -0.8 | I |

***Contribution to annual rainfall; **S = trend significance, S = Significance, I = Insignificant**

### 4.2.1 *Precipitation Concentration Index Analysis*

A positive PCI increasing trend with a slope of 0.11% per year was noted (Fig. 10). The trend is significant at α = 0.05 significance level based on the Mann-Kendall trend analysis test. A positive trend greater than 10% signifies an irregular rainfall distribution in Chiuta catchment (De Luis et al, 2011). PCI of between 10 % and 20% indicates strong rains in a particular season and PCI of over 20% generally is a sign non-uniform rainfall pattern with most of rains falling in a close particular time periods (De Luis et al., 2011).

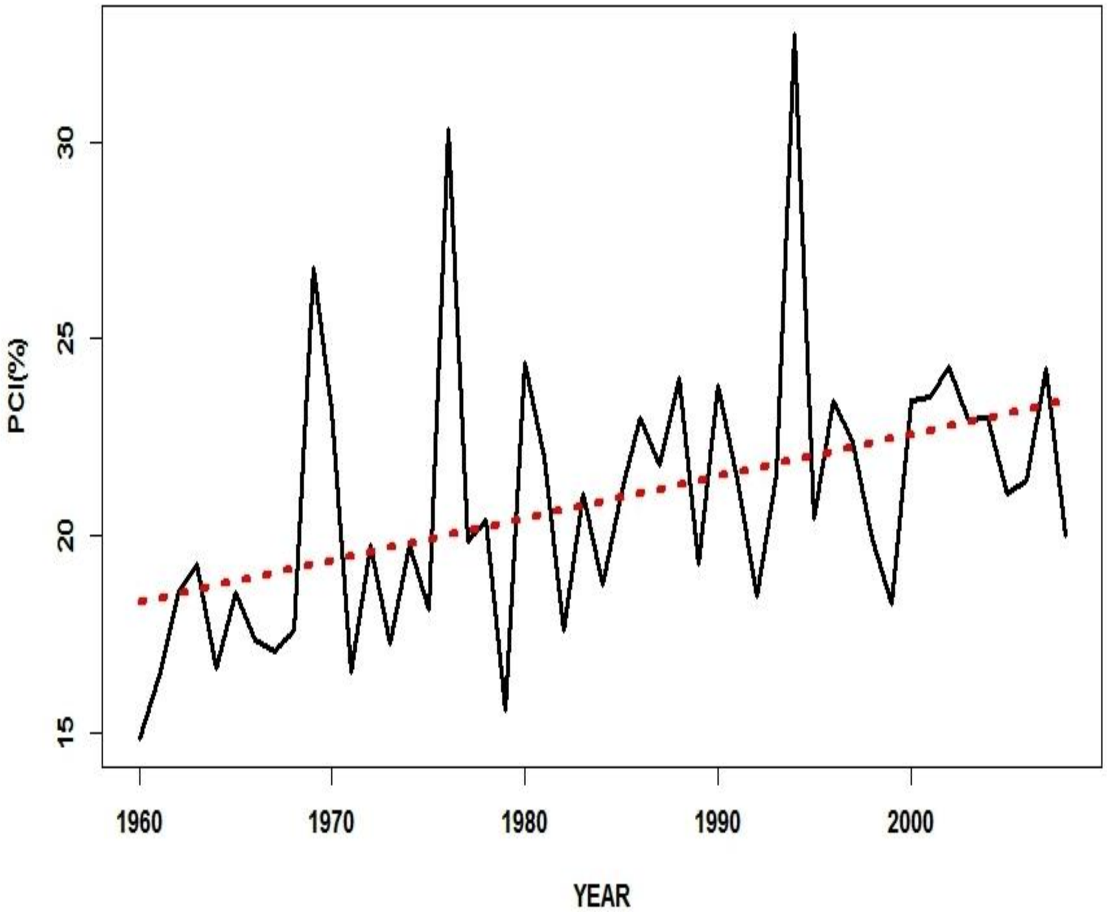


**Figure 10: Precipitation Concentration Index for Chiuta**

The mean PCI for Chiuta catchment was found to be 20.9% indicating an irregular rainfall distribution pattern with most of the rains concentrated in the months of January and February which is in conformity with Ngongondo et al., (2011). A PCI minimum of 14.9% was encountered in 1960/61 hydrological year. Still with the minimum of 14.9%, the rainfall distribution could be said that the rains were strong but concentrated in some close periods. The maximum PCI was encountered in the year 1994 at 32.7%. A drought was experienced in the area during the period 1992 to 95 and the rainfall pattern was highly irregular (MIWD, 2010).

### *4.2.2 Analysis of 5 and 10- Yearly Rainfall Extreme Events*

Table 3 shows average catchment rainfalls averaged over a period of 5 and 10-year periods. It is only in the 1975-79 period in which rainfall averaged over a 1000mm and in the 10-year period, the highest has been 1970-79 decade in which catchment rainfalls averaged 995.4mm.

**Table 3: Mean Catchment Rainfall - 5 & 10-year scale**

| | **Period** | **Mean Catchment Rainfall (mm)** |
|---|---|---|
| **5 – Year Period** | 1960 – 64 | 893.1 |
| | 1965-69 | 789.4 |
| | 1970-74 | 909.7 |
| | 1975-79 | 1081.1 |
| | 1980-84 | 819 |
| | 1985-89 | 919.8 |
| | 1990-94 | 735.4 |
| | 1995-99 | 972.2 |
| | 2000-04 | 892.4 |
| | 2005-09 | 783.7 |
| **10-year period** | 1960-69 | 841.2 |
| | 1970-79 | 995.4 |
| | 1980-89 | 869.4 |
| | 1990-99 | 853.8 |
| | 2000-09 | 838 |

Attaching return periods of extreme events, Table 4 shows that the catchment received annual rainfall below 860.42mm (T = 1). This will approach 1032.5mm every 5 years and a relatively wet season above 1455.4mm should be expected once in 50 years.

**Table 4: Return Periods for Lake Chiuta Catchment Rainfall**

| Return Period | Mean Catchment Rainfall (mm) |
|---|---|
| 50 | 1455.4 |
| 25 | 1356.2 |
| 17 | 1199.7 |
| 10 | 1151.4 |
| 8 | 1095.3 |
| 7 | 1076.3 |
| 6 | 1055.3 |
| 5 | 1032.5 |
| 1 | 860.42 |

### 4.3 Over-the-lake Rainfall Analysis

Most rains over Lake Chiuta do fall in from November to April (Fig. 11). The month of January is when the over-the-lake rains peak with rainfall of about 26.6% of the total annual mean over the lake rainfall. February is second with rains of 19.39% of the total annual mean. December contributes 18.12%, March 16.58% and April 5.79% of the total annual over-the-lake rainfall. The months August and September are the driest months. June 0.63% and July contributes 0.67% of the total annual rainfall where as August contributes 0.35% and September contributes 0.36% of the total annual mean over-the-lake rainfall. May 1.09 %, April 5.79%, October 2.45% November 7.96%. The error margin was 5 %.

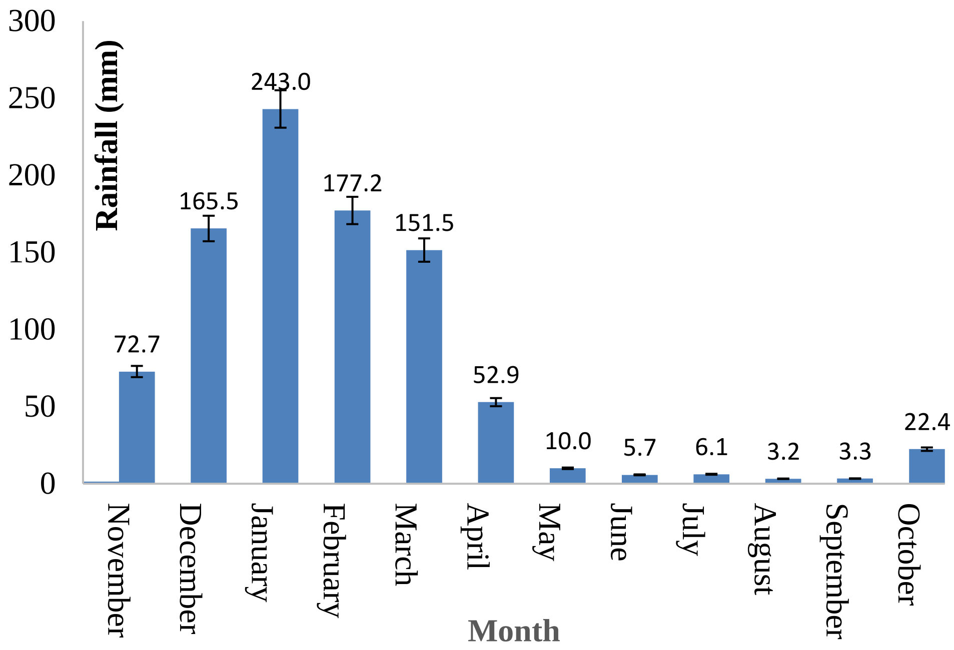


Figure 11: Mean Monthly Over-the-Lake Chiuta Rainfall

The total annual mean for over-the-lake rainfall was 913.6mm. The dataset's standard deviation to mean ratio percentage which is the coefficient of variability was calculated as 26.85%. The lake had an annual mean maximum over-the-rainfall in the year 1978 of 1714.1mm and a minimum mean annual over-the-lake rainfall in 2009 of 479.9mm (Fig. 12).

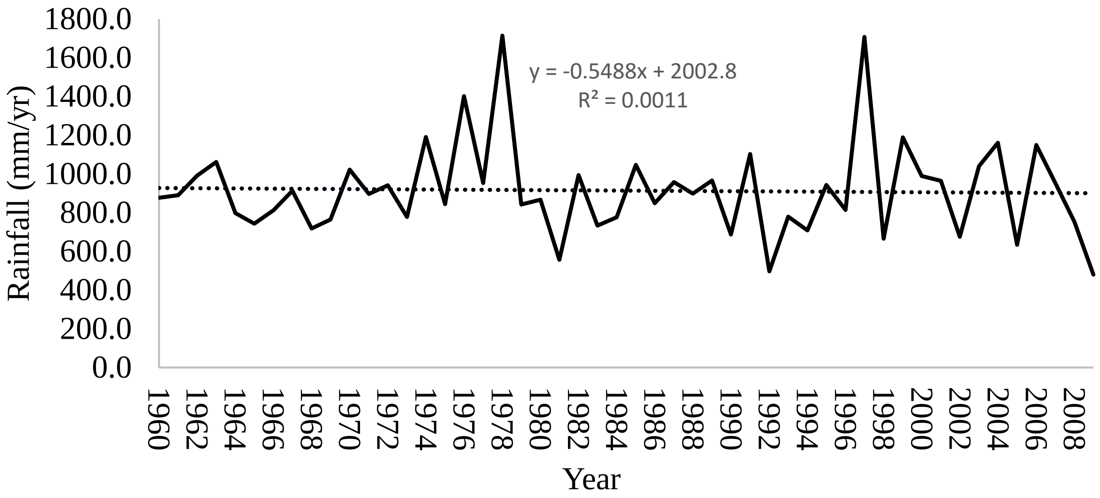


Figure 12: Annual Over-the-Lake Chiuta Rainfall (1960-2009)

The 1997 over-the-lake rainfall was high as 1707.2mm. Again, another minimum of 497.1mm in 1991/92 may be due to an El Nino event that occurred in that year (MIWD, 2010). The data set could as well be considered as having double maxima. Hydrological year 1996/97 had a very strong La Nina event. The country in 1978 received a lot of rainfalls as reported by Kumambala & Ervin (2010). Lake Malawi levels were the highest in that period as well. The trend of the mean annual over-the-lake rainfall direction of the trend was negative with a slope of -0.55mm per year. The Mann - Kendall trend was also negative (-0.2) but not significant at α=0.05 level.

The 1960 to 2009 Lake Chiuta over-the-lake mean monthly rainfall had its mean calculated to 76.1mm per month with a coefficient of variability of 26.85%. The general trend is negative with a slope of -17.6mm per month (Fig. 13). The Mann-Kendall Trend was found to be significant at α=0.05 level.

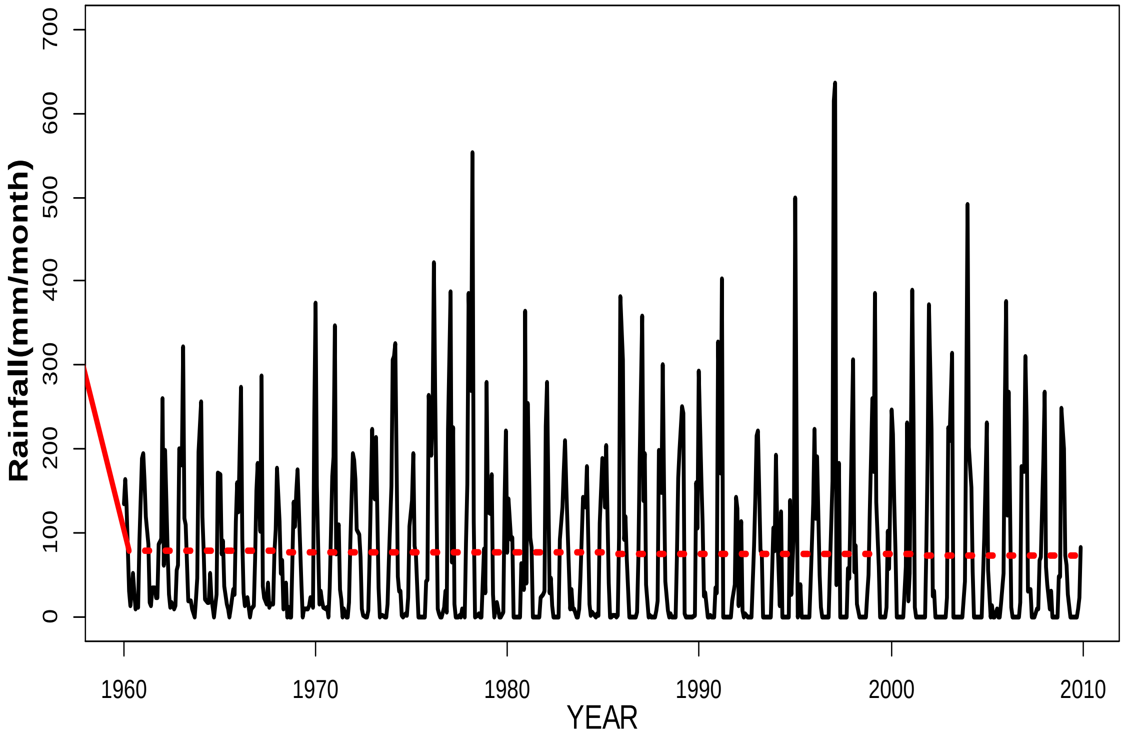
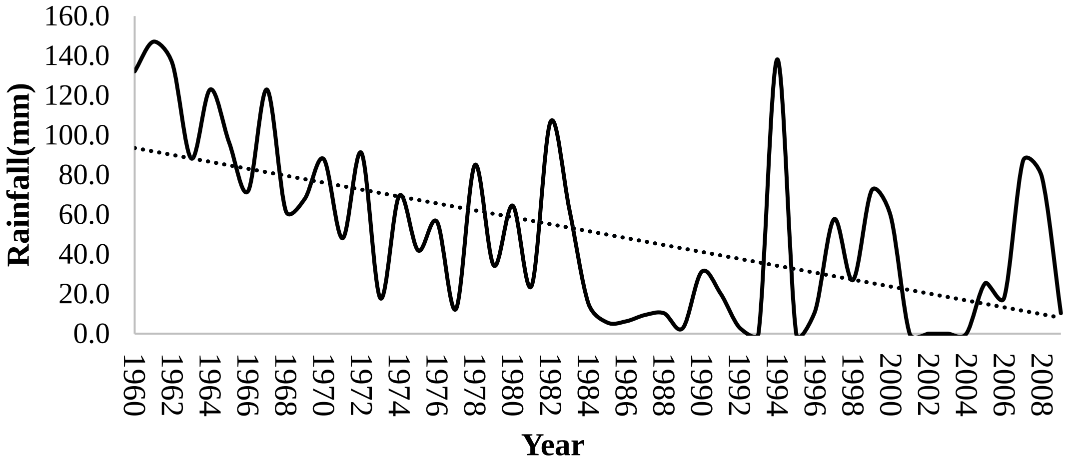


**Figure 13: Mean Monthly Over-the-Lake Chiuta Rainfall**

The rains in Lake Chiuta are highly seasonal as already discussed above. Most of the rains fall from November to April followed by a dry spell from May to October. The Wet season was taken as November to April whereas the dry season was taken as May to October. The mean lake rainfall from 1960 to 2009 dry seasons was calculated to be 50.8mm. The coefficient of variability was 86.9%. Mean maximum lake rainfall in the dry seasons was observed in the year 1961 of 147.1mm and the minimum was 0mm in 1993, 1995, 2001-04, a negative trend is noted with a slope of -1.75mm per year (Fig. 14a). The Mann-Kendall trend was found to be -4.53 which was significant at α=0.05 level.

The mean over-the-lake rainfall from 1960 to 2009 wet seasons was calculated to be 862.9mm and the coefficient of variability was 28.2%. Mean maximum over-the-lake rainfall in the wet seasons was observed in the year 1997 of 1649.5mm and Mean minimum over the lake rainfall in the wet seasons was observed in the year 2009 of 469.7 mm . A sort of stationary series trend is noted in wet seasons, the trend direction and slope are slightly positive though slight with a slope of 1.2mm per year (Fig. 14b). The Mann- Kendall trend statistic was found to be 0.8 which is insignificant at α=0.05 level.



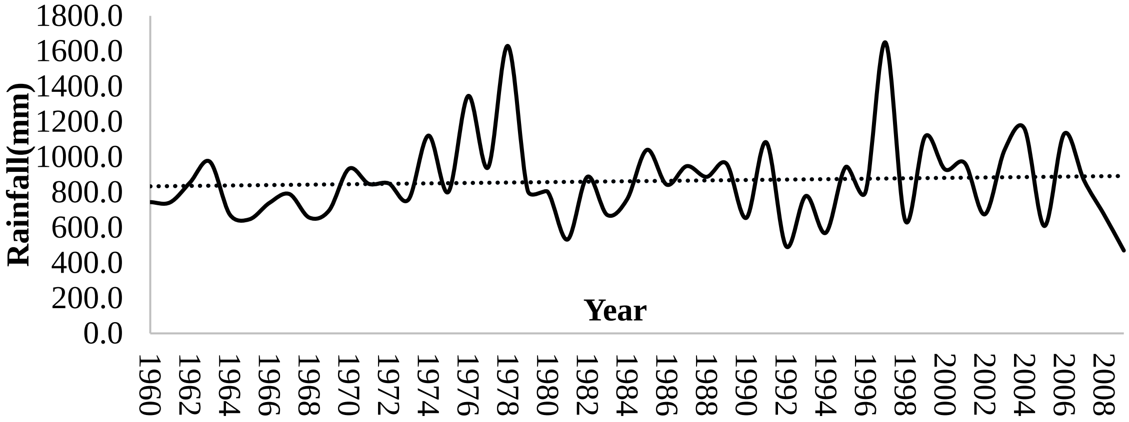


**Figure 14: Dry (a) and Wet (b) Season Over-the-Lake Rainfall**

Negative over-the-lake trends were noted in months March to December but significant trends were noted in May, June, July, August, and September certainly due Chiperoni winds influence weather patterns in May to September hence negative over the lake trend (JICA, 2014). There has been a peak in over-the-lake January rainfalls with a positive trend rise of 2.48mm per year which is a significant trend. The trend continues in February though this is not significant (Table 5).

**Table 5: Over-the-Lake Chiuta Summary Statistics**

| **Season** | **Mean (mm)** | **Stdv (mm)** | **CV (%)** | **Maximum (mm)** | **Minimum (mm)** | **MK α=0.05** | **Slope mm yr$^{-1}$** |
|---|---|---|---|---|---|---|---|
| Annual | 917.92 | 245.67 | 27 | 1749 | 449.5 | -0.22 | -0.45 |
| Dry | 50.78 | 44.13 | 87 | 147.1 | 0 | -4.53 | -1.75 |
| Wet | 868.81 | 244.06 | 28 | 691.3 | 446.5 | 0.80 | 1.19 |
| Monthly | 76.14 | 104.00 | 137 | 635.20 | 0.00 | -4.22 | -0.10 |
| Jan | 243.02 | 115.50 | 48 | 613.8 | 41.1 | 2.38 | 2.48 |
| Feb | 177.19 | 104.82 | 59 | 635.2 | 13.5 | 0.13 | 0.53 |
| Mar | 151.52 | 119.24 | 79 | 52.7 | 0 | -0.64 | -0.49 |
| Apr | 52.87 | 49.63 | 94 | 265.2 | 0 | -1.78 | -0.55 |
| May | 9.98 | 15.60 | 156 | 72 | 0 | **-3.05** | -0.32 |
| Jun | 5.75 | 9.47 | 165 | 40.2 | 0 | **-5.49** | -0.43 |
| Jul | 6.12 | 12.67 | 207 | 51.7 | 0 | **-4.68** | -0.51 |
| Aug | 3.21 | 6.89 | 215 | 35.6 | 0 | **-3.25** | -0.26 |
| Sep | 3.33 | 7.06 | 212 | 33.4 | 0 | **-3.09** | -0.25 |
| Oct | 22.40 | 28.62 | 1.28 | 231 | 0 | -1.32 | 0.02 |
| Nov | 72.74 | 47.94 | 0.66 | 138.2 | 0 | -0.27 | 0.04 |
| Dec | 165.51 | 76.38 | 0.46 | 382.1 | 20.2 | -1.20 | -0.81 |

## 4.4 Runoff Modelling

### *4.4.1 Model Automatic Optimization*

Table 6 is an output from preliminary run of the WASMOD Model. The best model for a given catchment is the one with highest $R^2$ value, lowest #S (the number of seasons with significant residuals value), NO = 0 or the lowest (Xu, 2002). In this case the best model according to the stated criteria was taken as model number 7 which was then calibrated for a period 1965 to 1985 and simulated further from a period 1990 to 2009. Model number 7 was chosen because it had an $R^2$ value of 0.912 (Most important model parameter (Xu, 2002)) that was the highest amongst the 8 models.

**Table 6: Selection of the Best WASMOD Model**

| Model | 1E | B1 | B2 | $R^2$ | #S | NO | NSI |
|---|---|---|---|---|---|---|---|
| **1** | 1 | 1 | 1 | 0.776 | 0 | 0 | 0 |
| **2** | 1 | 1 | 2 | 0.772 | 0 | 0 | 0 |
| **3** | 1 | 2 | 1 | 0.872 | 0 | 0 | 0 |
| **4** | 1 | 2 | 2 | 0.764 | 0 | 0 | 0 |
| **5** | 2 | 1 | 1 | 0.851 | 0 | 1 | 0 |
| **6** | 2 | 1 | 2 | 0.783 | 1 | 1 | 1 |
| **7** | 2 | 2 | 1 | 0.912 | 0 | 3 | 1 |
| **8** | 2 | 2 | 2 | 0.859 | 0 | 0 | 0 |

Where, Model is the number of model versions; 1E is the choice of two evapotranspiration equations; B1 is the choice of slow flow equations; B2 is the choice of fast flow equations; $R^2$ is the model quality measure; #S is the number of seasons with significant residual; NO is the number of non – optimized parameters; NSI is the number of non – significant parameters.

#### *4.4.1.1 $R^2$ value (calibrated on the whole period 1965 - 1985)*

The $R^2$ value measures the quality of the model (Xu, 1999). This compares the residual variance and the initial variance of the process (Xu, 2001). For the best model number, the $R^2$ value was calculated as 0.912. This means that the residual variance differed with the initial variance by a figure of 0.912. At this point, it can be said that the best model has been successfully automatically optimized in WASMOD.

#### *4.4.1.2 Model Parameter Analysis (Optimized model parameter values and the 95% confidence interval)*

Table 7 shows results of the model optimized parameter values and the 95% confidence interval. An analysis of the model parameters basically was done to determine if all model parameters were statistically significant and correlated with each other and check which model parameter is more sensitive than the other. Zero values had to belong to the 95% confidence interval (Xu, 2002). This means that what has been shown in table 7 are 95% probabilities of having a true null hypothesis.

**Table 7: Model Residual Analysis**

| No | Parameter | Scale | Scaled Parameter | Scaled-HWCI | 100*HWCI |
|---|---|---|---|---|---|
| **A(1)** | 0.000507 | 100 | 0.507 | 0.034 | 67.148 UP |
| **A(2)** | 0.000000 | 1000 | 0.000263 | 0.000 | 118.51 UP |
| **A(3)** | 0.000166 | 100 | 0.0166 | 0.010 | 60.843 UP |
| **A(4)** | 3.3 | .100 | 0.33 | 0.121 | 36.647 D |
| **A(5)** | 28.5 | .010 | 0.285 | 0.229 | 80.48 D |
| **A(6)** | 62.32 | .10 | 0.6232 | 0.074 | 11.934 D |

Initial parameter values for the run scaled were A (1) = 0.250; A (2) = 0.230; A (3) = 0.206. Model parameters of the best model were statistically significant and are well optimized.

#### *4.4.1.3 Correlation matrix of parameter values*

Table 8 indicates a correlation matrix of the model’s parameter values. Correlation coefficient between two parameters is very near +1 or -1 implying that the model could be found with a smaller number of parameters and with the same explanatory power. Correlation coefficients between model parameters indicated that easy optimization will be achieved (Xu, 2002). Relative error was -0.513.

**Table 8: Model Parameter Analysis**

| | **A(1)** | **A(2)** | **A(3)** | **A(4)** | **A(5)** | **A(6)** |
|---|---|---|---|---|---|---|
| **A(1)** | 1 | 0.8072 | 0.9277 | -0.5239 | 0.0827 | -0.2748 |
| **A(2)** | 0.8672 | 1 | 0.8879 | -0.4862 | 0.2399 | -0.1375 |
| **A(3)** | 0.9277 | 0.8879 | 1 | -0.6127 | -0.0337 | 0.0274 |
| **A(4)** | -0.5239 | -0.4862 | --0.6127 | 1 | 0.3484 | 0.1041 |
| **A(5)** | 0.0827 | 0.2399 | -0.0337 | 0.3484 | 1 | 0.1894 |
| **A(6)** | -0.2748 | 0.1375 | 0.0274 | 0.1041 | 0.1894 | 1 |

#### *4.4.1.4 Iterations before model optimization*

After running model number 7 in the final run mode, calibrating and simulating the model, results were analyzed and plotted (Fig. 15). This plot is showing the number of iterations that could be done just before the optimized value is obtained or parameter stabilization is obtained.

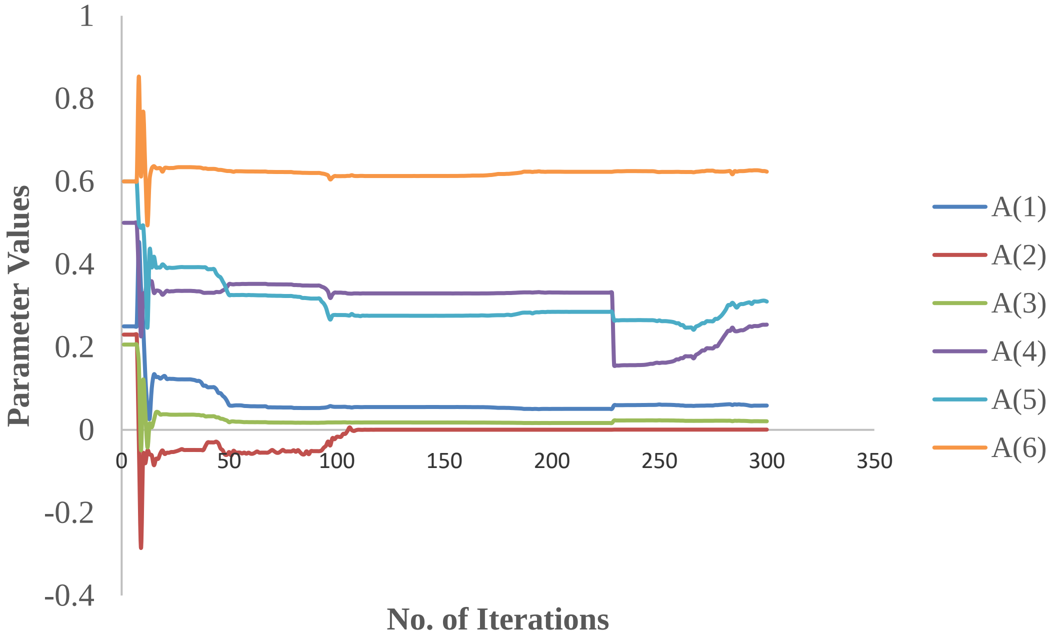


**Figure 15: Model Parameters vs Model Iterations Plot**

For the parameters, between 1 and 10 iterations, the parameter values had a random and an undefined behavior after that the number of iterations stabilized to up to 300 iterations. These iterations seek to minimize some differences between characteristics of modelled, calculated, simulated and calculated flows as discharges or runoff (Xu, 2002).

#### *4.4.1.5 Parameter Sensitivity*

Plot of sum of squares (SSQ) of residuals against each parameter in the neighborhood of the optimized value presented model parameter sensitivity (Fig. 16). The parameter plotted was parameter number A (4). The curve has a parabolic aspect that is centered around the minimum and according to the shape of the parabola, it can be deduced qualitatively that the global minimum was obtained when the sum of squares of residual was at about 115 and the parameter optimized value was at 0.28. This trend is in conformity with Kizza et al. (2011).

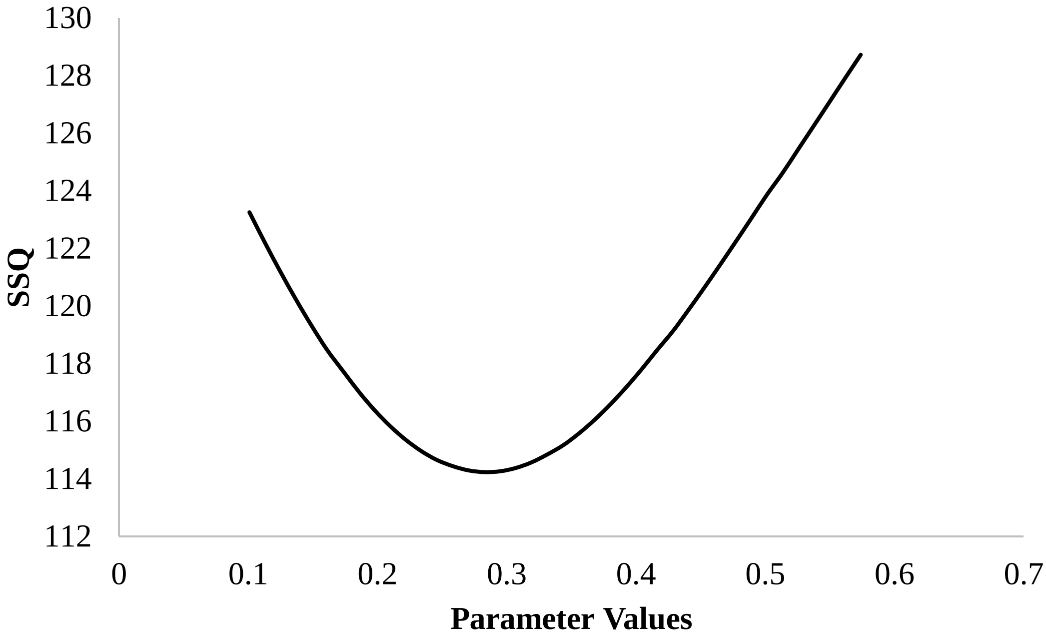


**Figure 16: Sum of Squares of Residuals vs Parameter Values in the Neighborhood of the Optimized Value**

#### *4.4.1.6 Residual autocorrelation against time lag*

Correlation measures a straight-line relationship. The residuals have a random pattern with a decreasing trend though not significant at α = 0.05 (Fig. 17). The residual autocorrelation is insignificant and there is homoscedasticity in the residuals. In residual analysis, checks are made in the model for absence of trend and homoscedasticity that shows a sequence of random variables or errors to be the same (Xu and Halldin, 1995). Residuals must be random with no trend as well as having the residual correlation to be insignificant and having the residuals to be homoscedastic. Again (Xu 2002) stated that independence of residuals can be checked by plots of autocorrelations and time lag and the corresponding half width of a 95% confidence interval. This meant that model would simulate flows in a satisfactory manner.

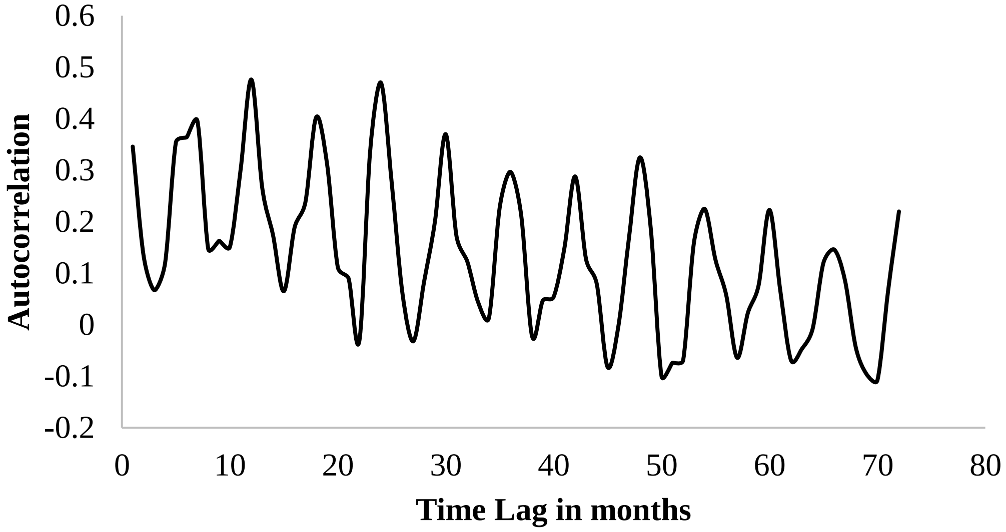


**Figure 17: Autocorrelation of Residuals vs Time Lag Plot**

### *4.4.2 Model Calibration 1965 - 85*

Comparison of observed run off and model calibrated runoff shows that the model has ably fitted in and has the same pattern as the observed plot indicating that the model is able to reproduce calibrated inflows from observed in flows (Fig 18). Observed and calibrated mean monthly calibrated inflows also have the same pattern like that of the observed flows (Fig.19).

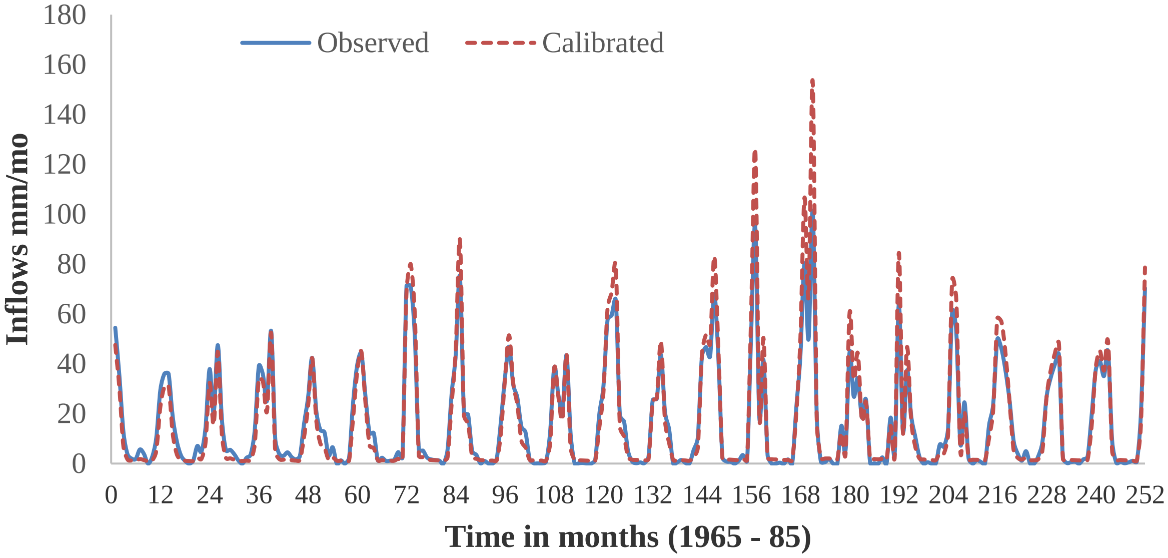


**Figure 18: Observed & Calibrated Inflows (1965 - 1985)**

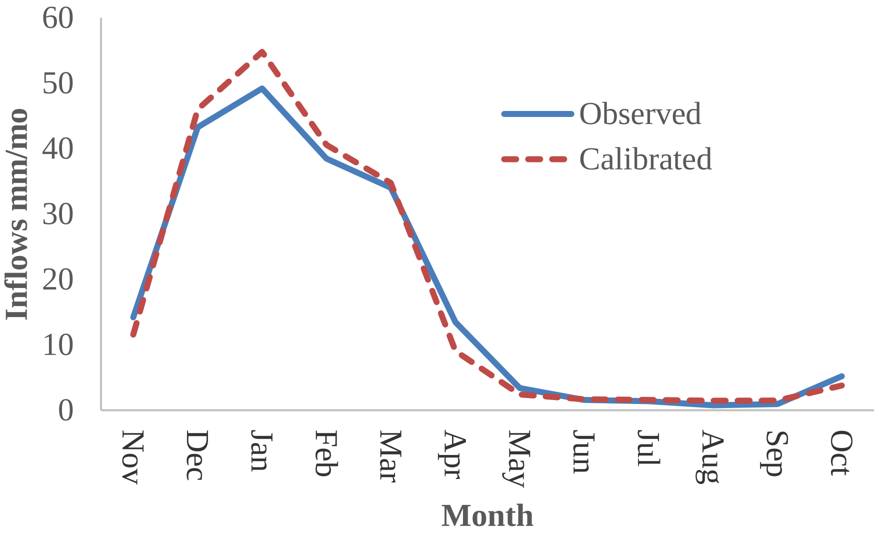


**Figure 19: Observed & Calibrated Mean Monthly Inflows (1965 - 1985)**

### *4.4.3 Model Simulation 1990 – 2009*

Comparison of observed run off and model simulated runoff shows that the model has the same pattern as the observed plot indicating that the model would reproduce accurate inflows (Fig. 20). Mean monthly observed and simulated inflows have the same pattern like that of the observed flows (Fig 21).

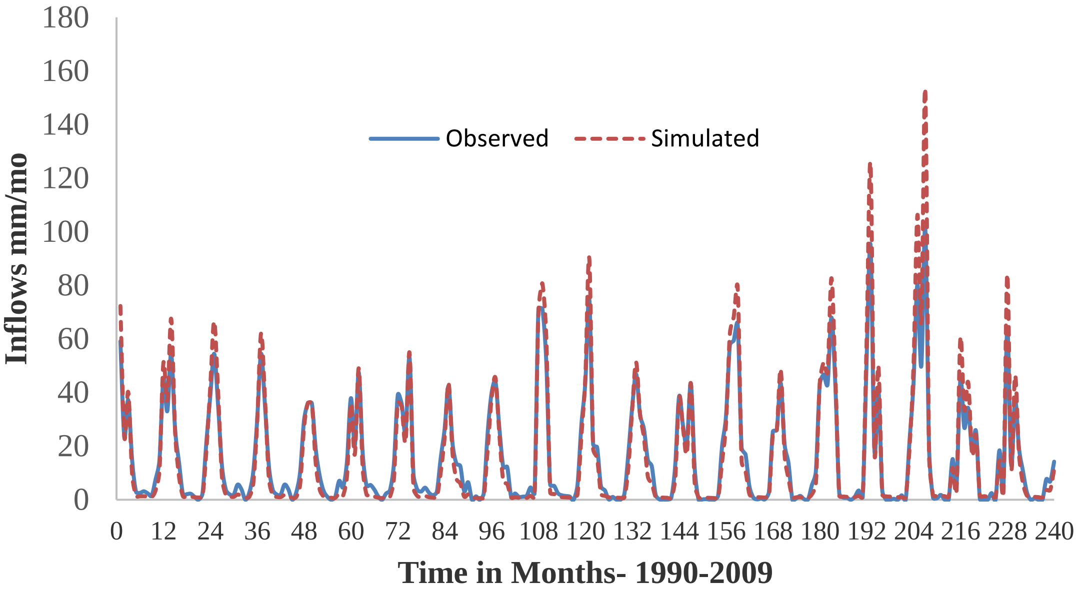


**Figure 20: Observed and Simulated Inflows (1990 - 2009)**

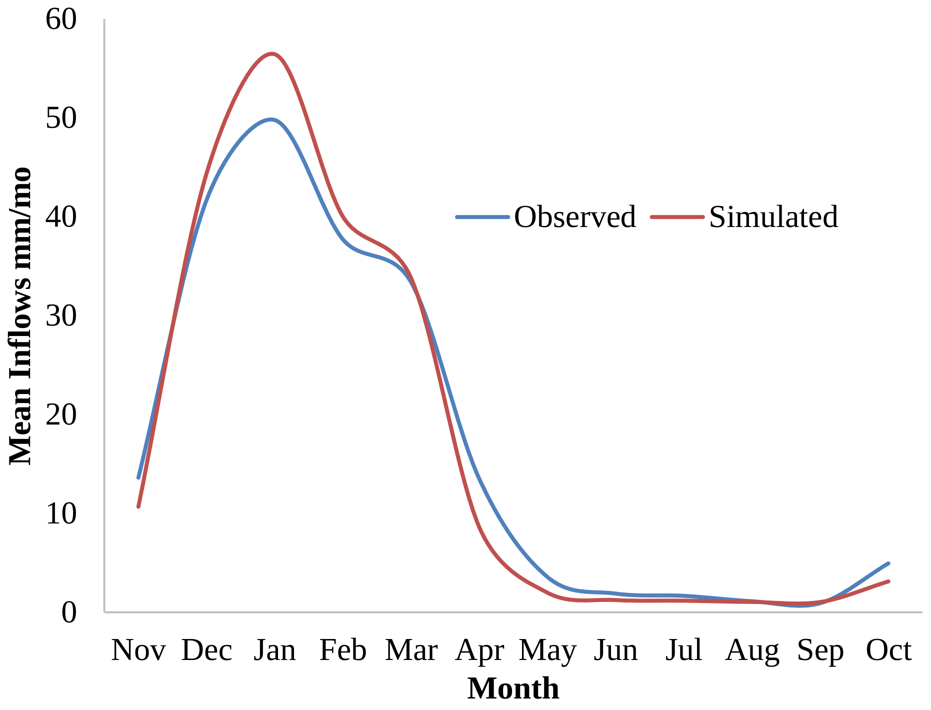
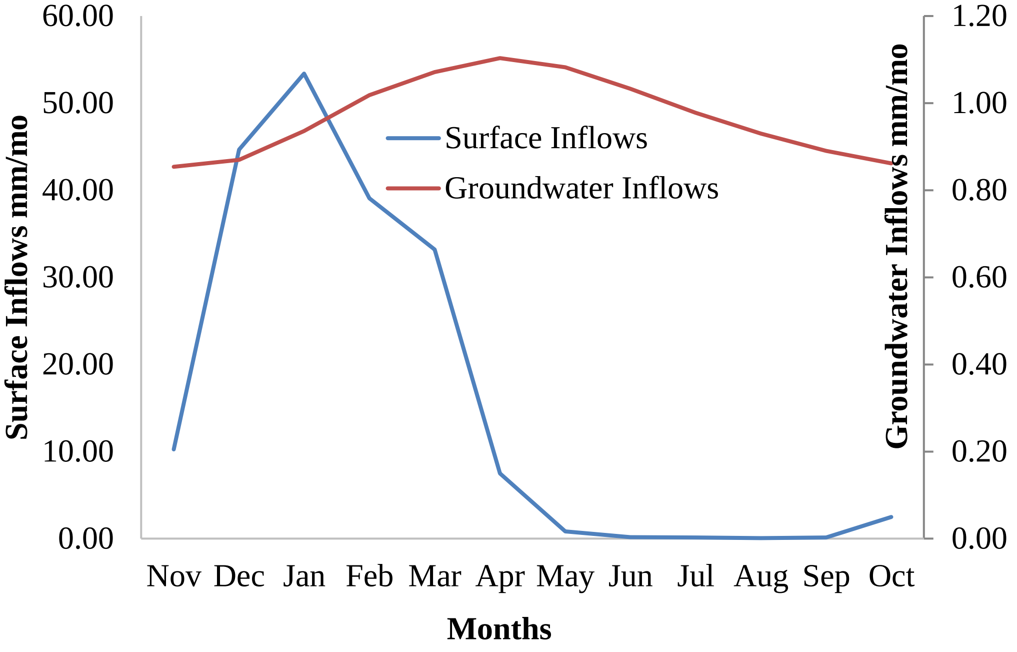


**Figure 21: Mean Monthly Observed and Simulated Inflows (1990 -2009)**

### *4.4.4 Calibrated and Simulated Groundwater & Surface water Inflows*

Model calibrated and simulated groundwater flows into the lake indicate that surface water has a much significant contribution to the lake's water budget than groundwater inflows (Fig. 22). Even in times of low or no surface flows, the little groundwater flow has no effect on the final Lake Chiuta level. JICA (2014) reported that the Lake Chiuta itself is underlain by a fractured basement that has discontinuous planes like joints, cracks, fractures, geological faults in the basement rock mass. This characteristic may cause groundwater flux not to flow into the massive rock body but may only flow along the adjoining discontinuous planes (JICA, 2014).Laminar flow theory does not apply to a fractured basement due to random flow and in this case groundwater flow depends mainly on joint development and clearance hence water yields may be low (JICA, 2014).



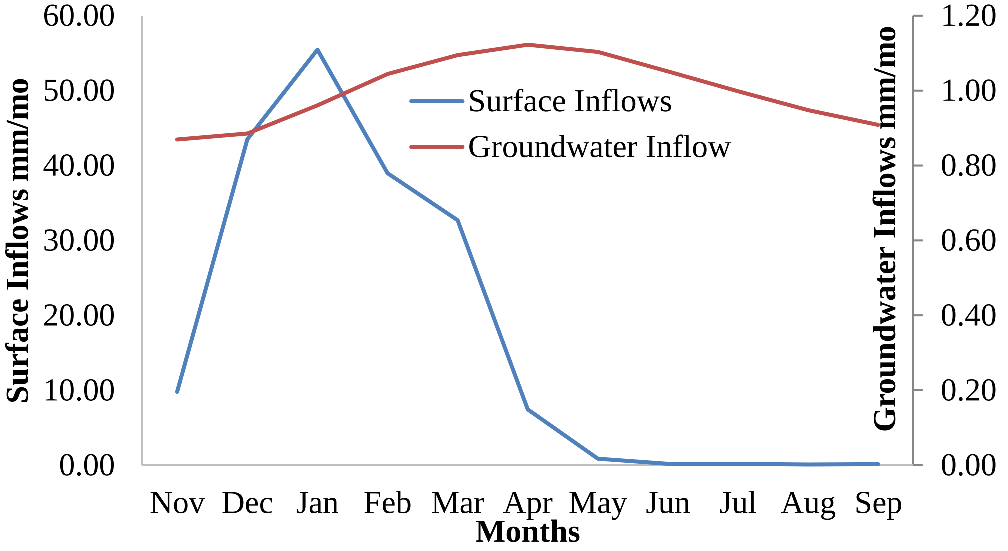


**Figure 22: Surface/ Groundwater Calibrated (a) and Simulated (b) Inflows**

However, the catchment of Lake Chiuta itself has a colluvium kind of orientation that may transmit groundwater flow as laminar flow between particles (JICA, 2014). However this colluvium formation is underlain by a basement complex Gneisses resulting in low infiltration and percolation capacities hence low soil moisture storage (MIWD, 2010).

During the field work in the area, it was noted that some water wells that were drilled in the area for human use had clayey sediments that may return some moisture though with poor percolation and infiltration as well. Based on the above, groundwater inflow was therefore be disregarded in the overall water balance model. Now with disregard of ground water inflow, groundwater has also been disregarded in the lake's hydrological water budget as in Duan (2014).

### *4.4.5 Runoff Model Summary and model test results*

Presented in table 9 are the figures for the calibrated model. The calibration show a mean observed inflow of 16.03mm/month (192.36mm/ year) against a mean simulated inflow of 16.221mm/month (194.65mm/year). Nash-Sutcliff coefficient of the calibrated model was found to be 1.00, PBIAS was 1.12% and RSR was 0.0094 As stated by Moriasi et al. (2007) if NS > 0.5, RSR<0.7 and PBIAS is within 25% of the mean the model can be deemed acceptable which is the case with this analysis (Mc Cuen,2006; Ngongondo et al., 2006).

**Table 9: WASMOD - M Model Summary**

| | Mean | Standard Deviation | Coefficient of Variation (CV) |
|---|---|---|---|
| **Precipitation(mm)** | 74.62 | 92.964 | 1.246 |
| **Potential Evaporation (mm)** | 62.32 | 20.151 | 0.323 |
| **Actual Evaporation (mm)** | 56.35 | 19.513 | 0.346 |
| **Observed Runoff (mm)** | 16.03 | 20.312 | 1.246 |
| **Model Calculated Runoff (mm)** | 16.221 | 24.26 | 1.496 |
| **Fast Run Off (mm)** | 15.361 | 24.25 | 1.579 |
| **Slow Run Off (mm)** | 0.860 | 0.245 | 0.285 |

Model simulation shows a mean observed inflow of 15.12mm/month (181.44mm/ year) against a mean simulated inflow of 14.07mm/month (168.84mm/year) (Table 10).

**Table 10: WASMOD - M Model Test Results**

| | Mean | Standard Deviation | Coefficient of Variation (CV) |
|---|---|---|---|
| **Precipitation (mm)** | 69.186 | 82.059 | 1.186 |
| **Evaporation (mm)** | 56.104 | 18.893 | 0.337 |
| **Observed Runoff (mm)** | 15.117 | 17.93 | 1.186 |
| **Model Calculated Runoff (mm)** | 14.067 | 20.307 | 1.433 |
| **Fast Run Off (mm)** | 13.258 | 20.307 | 1.532 |
| **Slow Run Off (mm)** | 0.809 | 0.159 | 0.197 |

Nash-Sutcliff coefficient of the model was found to be 0.97, PBIAS was -6.95% RSR was 0.059 as indicated in table 11. It can therefore be concluded that the model simulations of inflows into Lake Chiuta are acceptable.

**Table 11: WASMOD - M Model Evaluation Results**

| | **PBIAS (%)** | **Nash-Sutcliff ®** | **RSR** |
|---|---|---|---|
| **Calibration** | 1.19 | 1.00 | 0.0094 |
| **Simulation** | -6.95 | 0.97 | 0.059 |

Observed flows are lower in the simulation (134.62mm/ yr.) than in the calibration period but still it can be concluded that the simulations of inflows into Lake Chiuta area acceptable when compared to Drayton et al., (1984). Average Annual Yield (AAY) was calculated as 134.83mm which is not far away from flows in the calibrated and simulated WASMOD.

### *4.4.6 Analysis of Lake Inflows Return Periods*

Lake Chiuta inflows are taken as a sum of over the lake rainfall and surface inflows. Surface inflows having been derived from rainfall using a runoff coefficient of 21.85%, were added to over the lake rainfall to get the total lake inflows. Inflows have then been averaged below in both 5 years and 10-year time periods and shown in table 12. Lake inflows peaked in 1975-79 period and in the decade 1970-79 period.

**Table 12: Mean Inflows' 5 & 10 year scale**

| | **Period** | **Mean Lake Inflows (mm/yr)** |
|---|---|---|
| **5 – Year Period** | 1960 – 64 | 1118.3 |
| | 1965-69 | 962.6 |
| | 1970-74 | 1163.9 |
| | 1975-79 | 1387.2 |
| | 1980-84 | 964.4 |
| | 1985-89 | 1144 |
| | 1990-94 | 915.6 |
| | 1995-99 | 1276.1 |
| | 2000-04 | 1160.8 |
| | 2005-09 | 965.3 |
| **10-year period** | 1960-69 | 1040.5 |
| | 1970-79 | 1275.6 |
| | 1980-89 | 1054.2 |
| | 1990-99 | 1095.9 |
| | 2000-09 | 1063.1 |

The Lake inflows showed a negative trend with a slope of -0.74mm per year though the trend was not significant at α = 0.05 as the Mann-Kendall trend statistic was found to be -0.32 (Fig. 23).

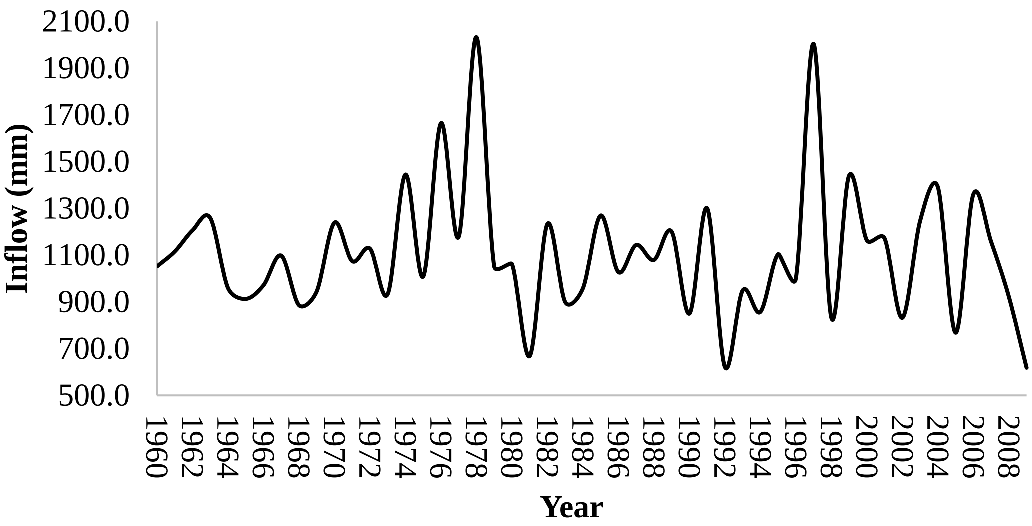


**Figure 23: Total Lake Inflows**

The highest mean inflow was in 1978 when mean inflows peaked 2032.1mm/yr. (Fig 24). The chance of having this exceeded in this 50-year interval (1960-2009) is taken as once in 50 years. The return period of having 2032.1mm/year inflow exceeded was then taken as 50 years.

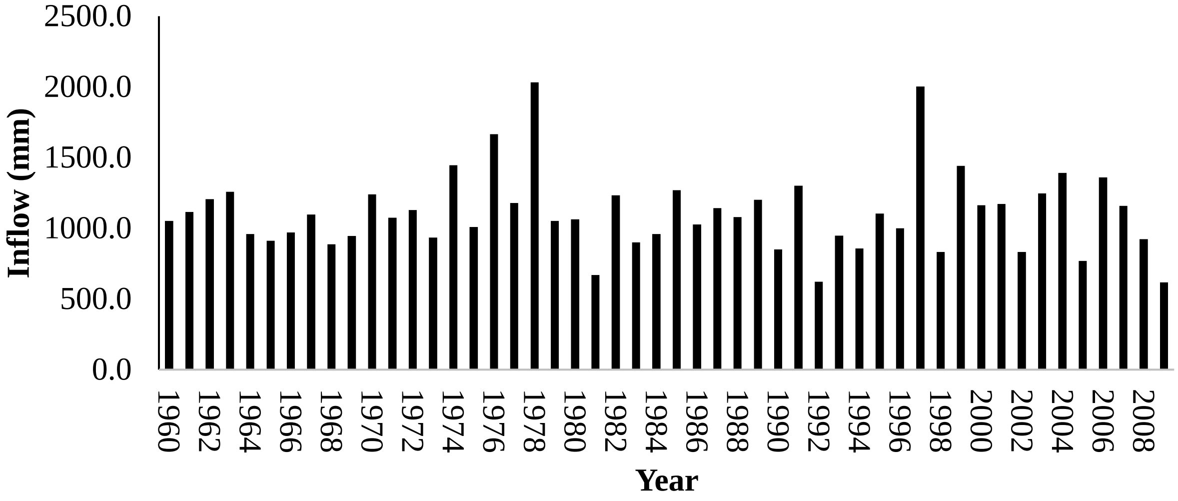


**Figure 24: Lake Inflows' Return Periods Assessment**

The second maximum in inflows was experienced in 1997 of 2003.5mm/year and it has only been exceeded twice in this 50-year interval. Therefore, the likelihood of having this exceeded in a 50-year interval is once in 25 years. The return period is then taken as 25 years. Similar analyses were conducted and the table 13 shows return periods inflows.

**Table 13: Lake Inflows' Return Periods**

| Return Period | Lake Inflow (mm/yr) |
|---|---|
| 50 | 2032.1 |
| 25 | 2003.5 |
| 10 | 1440.5 |
| 5 | 1259 |
| 1 | 1049 |

## 4.5 Lake Evapotranspiration

The empirical formula for calculating evapotranspiration being a function of temperature necessitated an analysis of the catchment's temperature regime.

### *4.5.1 Lake Chiuta Catchment Temperature Regime*

The 1969 to 2008 mid-range temperatures for Chiuta had a mean of 23.5 °C. Mean maximum temperature was 23.69 and mean minimum temperatures were calculated as 13.62. The coefficient of variability was calculated as 2.03%. An increasing positive trend with a slope is 0.02 °C per year (Fig. 25). The Mann - Kendall trend statistic of 3.96 was found to be significant at $\alpha=0.05$

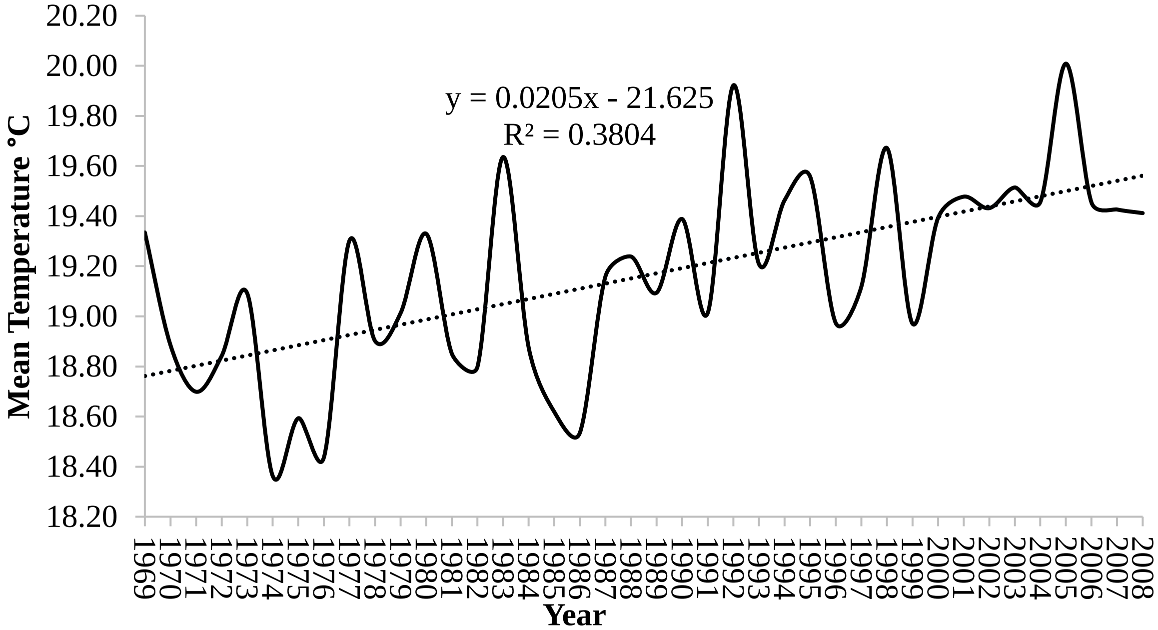


**Figure 25: Temperature Regime for Lake Chiuta (1969 - 2008)**

From the year 1992 temperatures in Chiuta rose (Dawson, 1970). This positive trend in temperature is likely to have an impact on the Lake Chiuta level and the overall hydological water budget of the catchment.

#### *4.5.1.1 Summary Statistics of Lake Chiuta Temperatures*

Table 13 summarizes the temperature regime of Lake Chiuta. The coefficients of variation are all less than 10 % indication low variability and most Mann-Kendall trends were found to be significant. All but three trends were positive, signifying that temperatures in Lake Chiuta basin have been increasing.

**Table 14: Summary Statistics for Chiuta Temperatures**

| SEASON | MEAN | CV | MAX | MIN | MK | SLOPE | TS |
|---|---|---|---|---|---|---|---|
| **Annual** | 23.5 | 2.03 | 23.69 | 13.62 | 3.96 | 0.02 | Significant |
| **Monthly** | 23.5 | 8.46 | 24.73 | 13.62 | 4.11 | 0.03 | Significant |
| **January** | 19.87 | 4.65 | 21.18 | 17.59 | 2.47 | 0.04 | Significant |
| **February** | 20.17 | 2.89 | 21.50 | 19.13 | 1.41 | 0.01 | Insignificant |
| **March** | 20.14 | 2.49 | 21.19 | 19.03 | 2.13 | 0.014 | Significant |
| **April** | 19.31 | 2.92 | 20.40 | 18.01 | 1.37 | 0.012 | Insignificant |
| **May** | 17.80 | 3.83 | 19.41 | 16.59 | 0.84 | 0.0007 | Insignificant |
| **June** | 16.12 | 4.02 | 17.36 | 14.63 | 3.17 | 0.03 | Significant |
| **July** | 16.13 | 6.52 | 18.79 | 13.62 | 2.73 | 0.03 | Significant |
| **August** | 17.26 | 3.25 | 18.49 | 15.91 | 2.82 | 0.02 | Significant |
| **September** | 19.32 | 2.57 | 20.40 | 18.36 | 3.12 | 0.019 | Significant |
| **October** | 21.22 | 3.23 | 22.46 | 19.69 | 2.04 | 0.02 | Significant |
| **November** | 21.78 | 3.80 | 23.69 | 20.11 | 2.3 | 0.03 | Significant |
| **December** | 20.81 | 3.07 | 21.95 | 19.71 | 2.3 | 0.02 | Significant |

### *4.5.2 Over-the-lake Evapotranspiration and Standardised Precipitation Evapotranspiration Index*

Evapotranspiration pattern indicates a positive trend (slope 0.094) and a significant Mann-Kendall trend statistic of 3.94 (Fig. 26). The coefficient of variability was 1.36 % indication low variability. Mean evapotranspiration was calculated as 130.87cm per year. Maximum evapotranspiration was 134.74 cm/year in 2005 this might be due to mean temperatures that reached to a maximum of 24.7 °C and the minimum evapotranspiration was 127.21cm/year in 1974 due to drop in temperatures in that year (JICA, 2014).

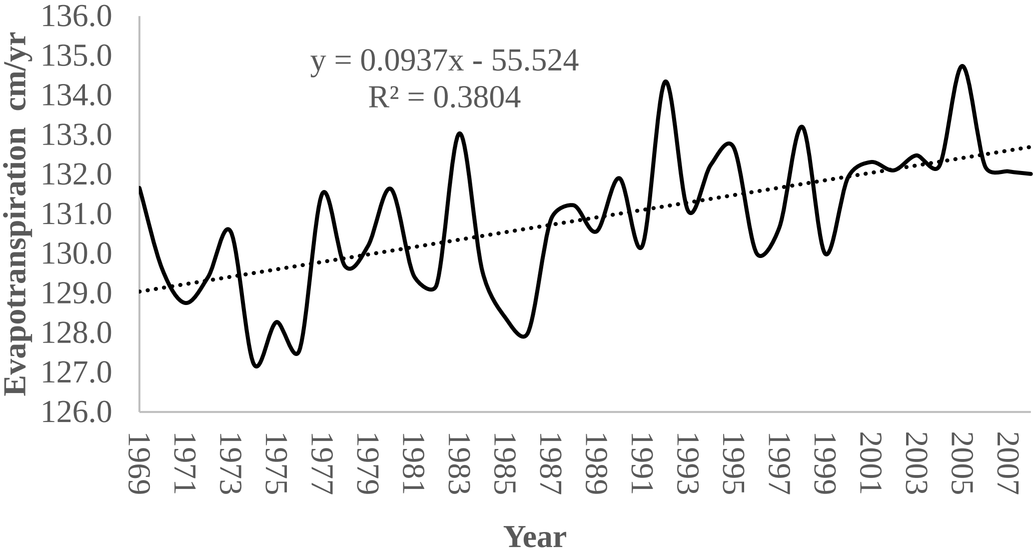


**Figure 26: Lake Chiuta Evapotranspiration Pattern**

Negative SPEI periods do indicate rainfall deficit and positive SPEI periods do indicate rainfall surplus (Fig. 27). It can also be observed that there has been a proliferation of warming with reduced amounts of rainfall. The water balance deficits are the red regions which dominate except for the 1997 and 2003 La Nina periods. The predominant blue regions are signifying water balance surplus with the wet period of 1977 to 79 having the highest water balance surplus.

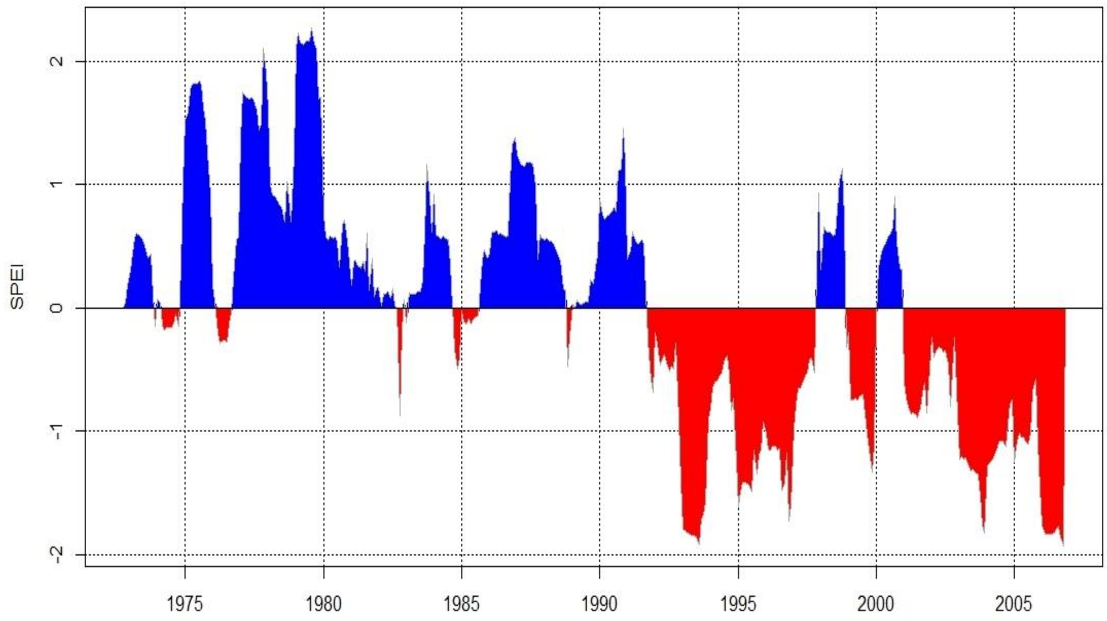


**Figure 27: Lake Chiuta SPEI Plot**

## 4.6 Lake Response to Climate Forcing

### *4.6.1 Oceanic Nino Index*

Lake Chiuta it being in Southern Africa is highly likely to be affected by two large scale climate indices that play significant role in rainfall variability over eastern and southern Africa. These two large scale climate indices are the Southern Oscillation Index (SOI) and Indian Ocean Dipole Mode Index (DMI). Figure 28 shows Oceanic El Nino Index. It may then be stated that that Southern Oscillation Index (SOI) patterns augers well with the monthly rainfall one.

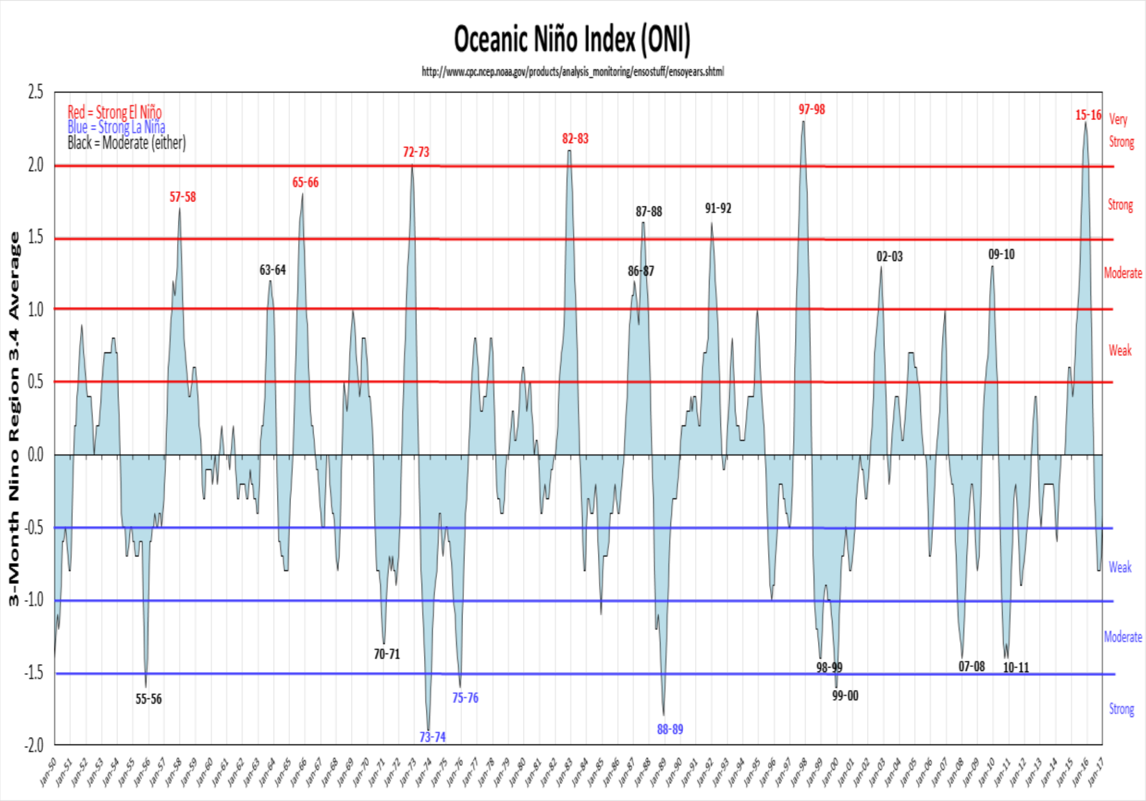


**Figure 28: Oceanic Nino Index**

Extents to which Lake Chiuta reached in the wet and dry seasons of 2016 respectively mainly due to catalytic climate forcing on the lake, indicated recession (Fig. 29) and (Fig. 30). It can be noted that the recession in the dry season was very high and most parts of the lake were dry. The extent of the lake level as captured from satellite imagery suggested that the lake level might have on a trajectory of 1973 level when the level was at its lowest. Probably the lake level reached the 1979 recession.

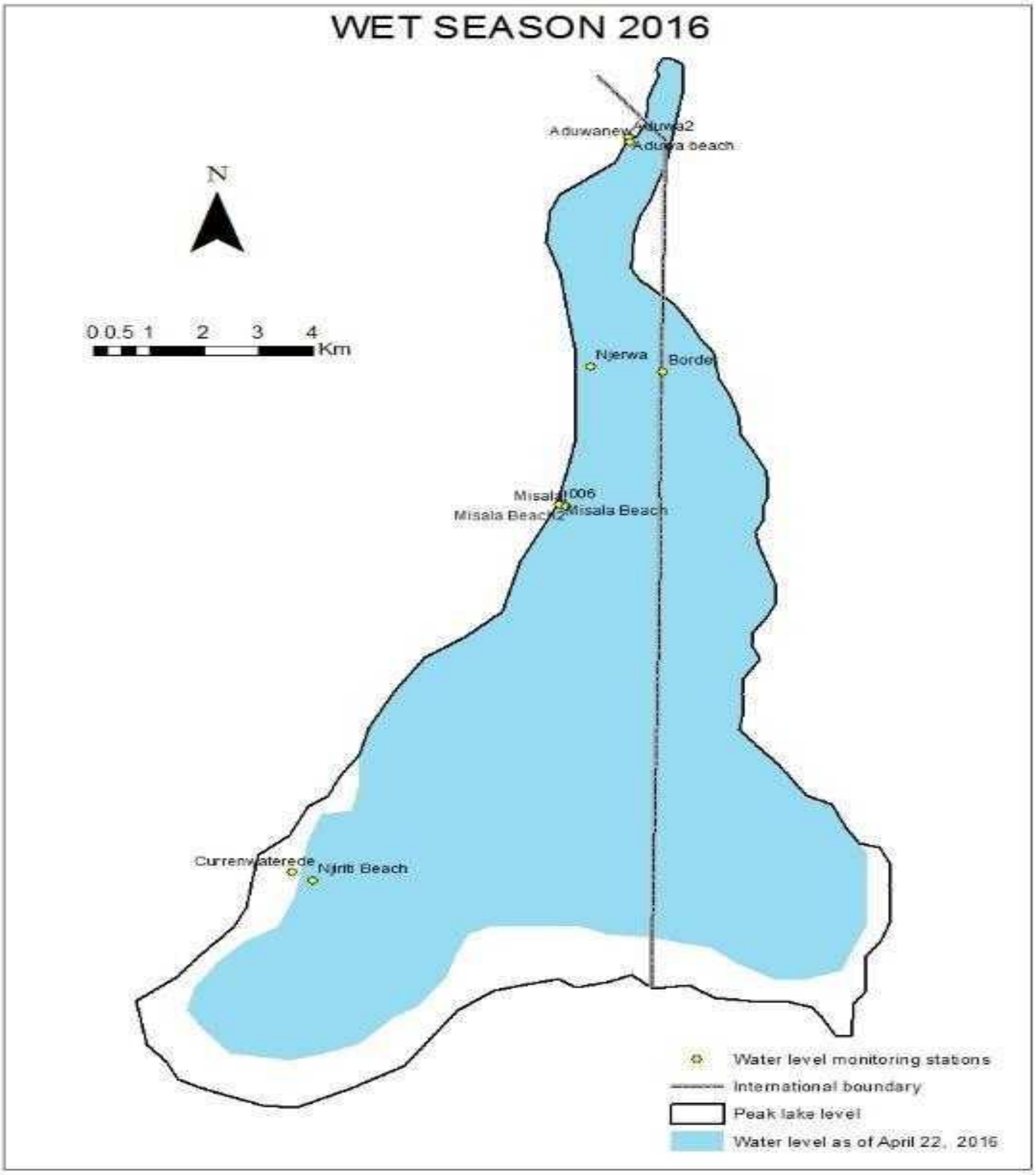


Figure 29: Lake Chiuta 2016 Wet Season Extent

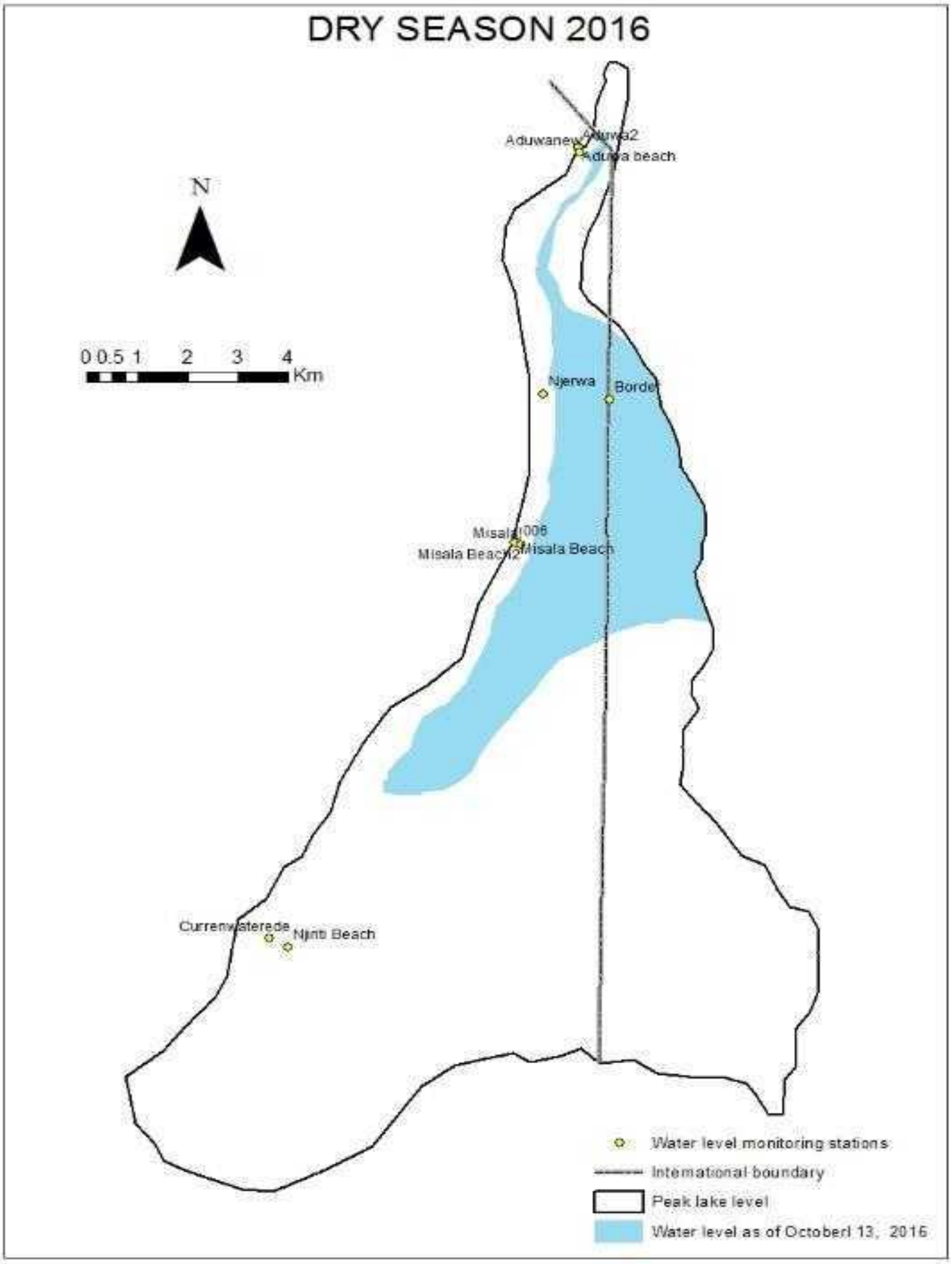


**Figure 30: Lake Chiuta 2016 Dry Season Extent**

Lake level changes monitored from the three level pegs (fig. 31) showed declining lake levels (fig. 32). The mean lake level depth had a significant drop with a negative slope decreasing trend of 0.004m per day translating to 4mm lake level drop daily. On average the Lake has lost about 239mm (fig. 32) from 15th July 2016 to 9th October 2016.

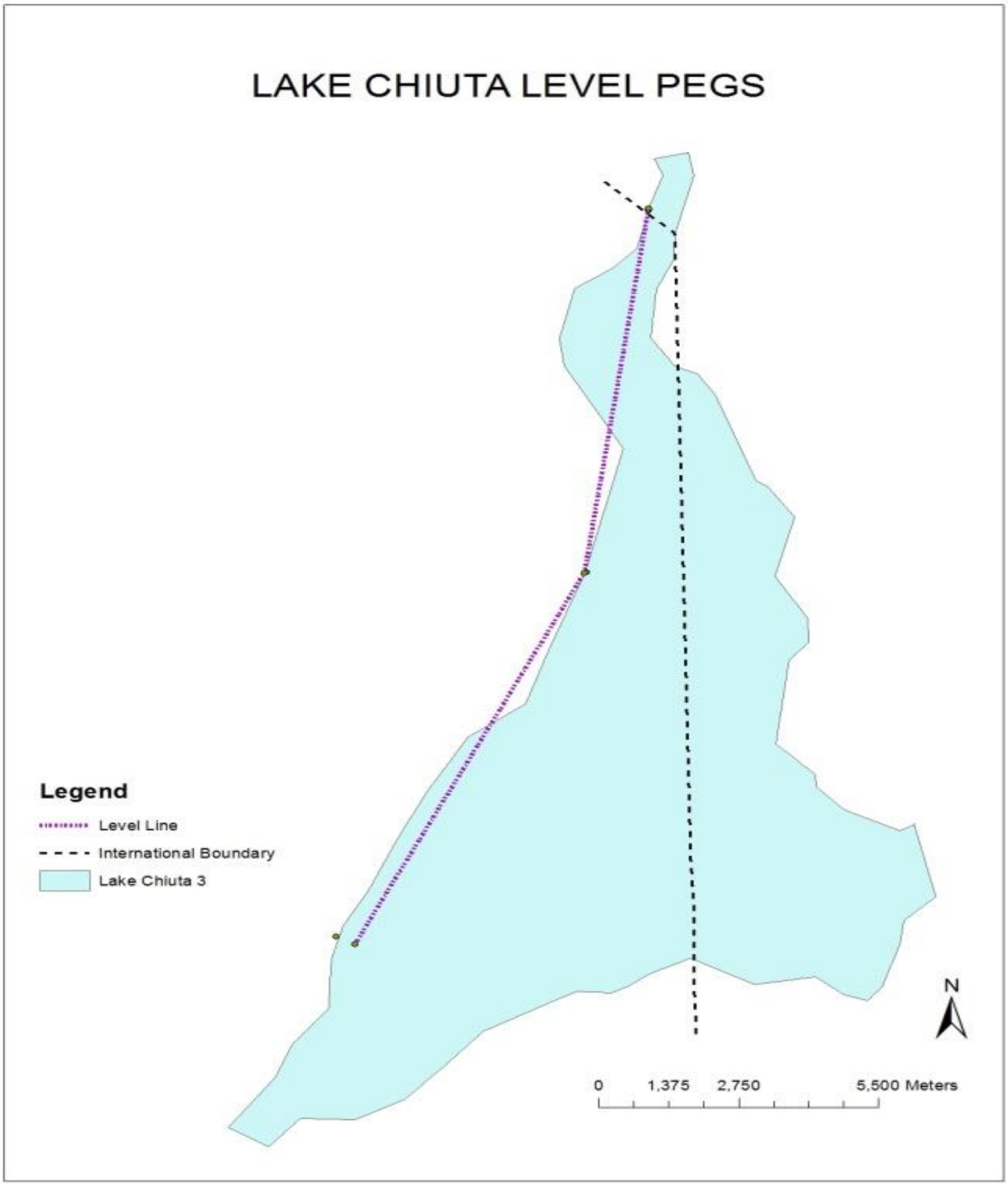


Figure 31: Lake Chiuta Level Pegs

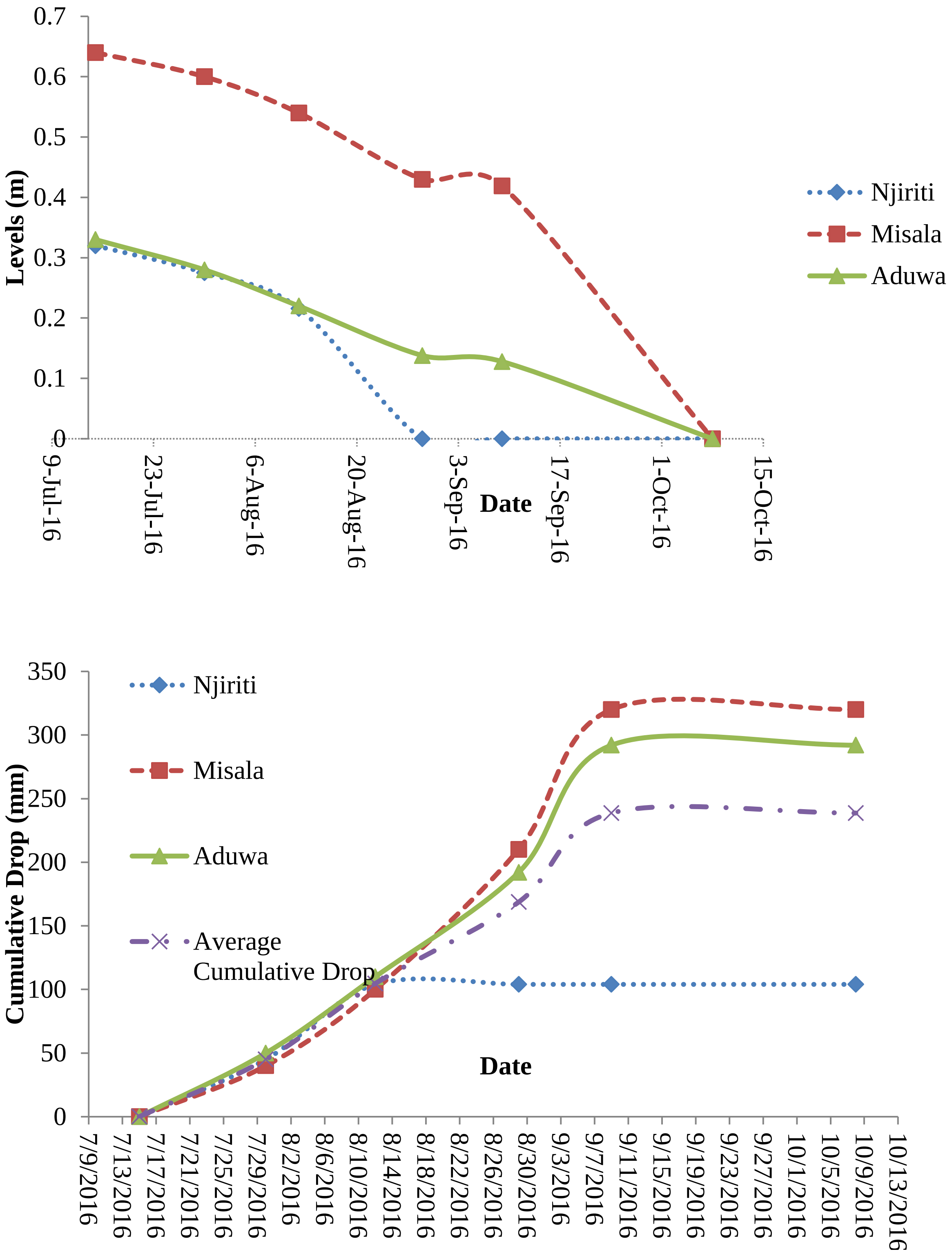
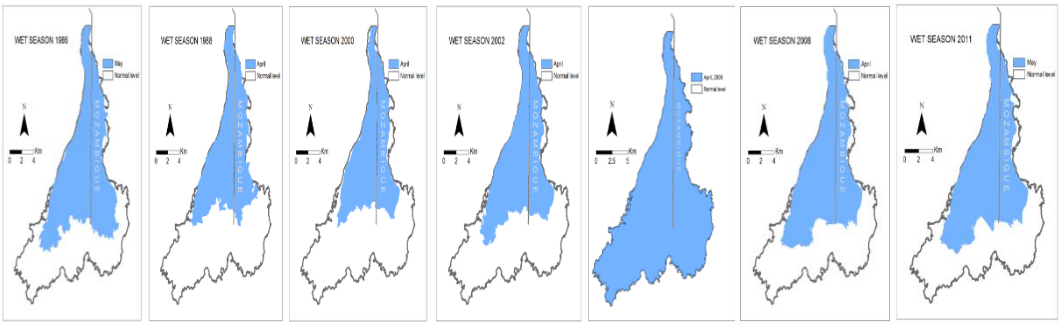


**Figure 32: Lake Chiuta Level (a) and Cumulative Drop (b)**

## 4.7 Possible Trajectory of Lake Levels Into the near Future

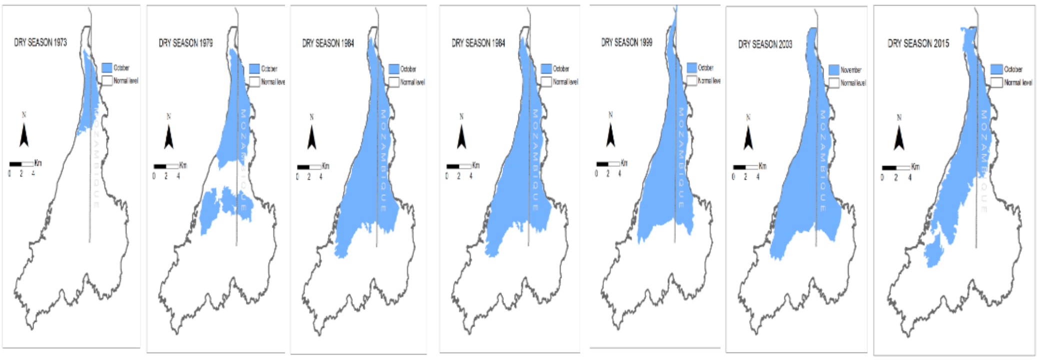
### *4.7.1 Historic Lake Chiuta Variation*

*From* the available lake satellite images, the lowest lake area of 13.76 km$^{2}$ was experienced during the dry season of 1972/73 and normal lake area was experienced in 2003 (Fig. 33). It is only in 2003 when the lake surface area reached 200 km$^{2}$. At its minimum level in 1973 the lake surface shrunk to as low as 14km$^{2}$. From 1973 to date, the lake area has only surpassed surface area of 120km$^{2}$ only once in 2003 (Dulanya et al., 2012).



1986 1988 2000 2002 2003 2008 2011

**Wet Season**



1973 1979 1981 1984 1999 2003 2015

**Dry Season**

**Figure 33: Lake Chiuta Wet and Dry Season Level Variations**

The period from the year 1988 to 2013, the wet season lake area extent has been fluctuating between 120 km$^2$ and 80km$^2$ representing about 40% to 60% of the normal Lake area respectively (Fig 34). This means that on average the lake has lost about 80km$^2$ which represents 40% lake extent loss in recent times. The period from the dry season lake extent has been fluctuating between 50 km$^2$ in 1979 and 85 km$^2$ in 1984. Concentrating on the year when the lake filled up to the 200km$^2$ extent in 2003 mainly on the hydrological inputs to the Lake's water budget; the catchment had a mean rainfall of 924.7mm in the wet season and 17.3mm in the dry season and the total mean rainfall in the Lake Chiuta catchment was 942mm.

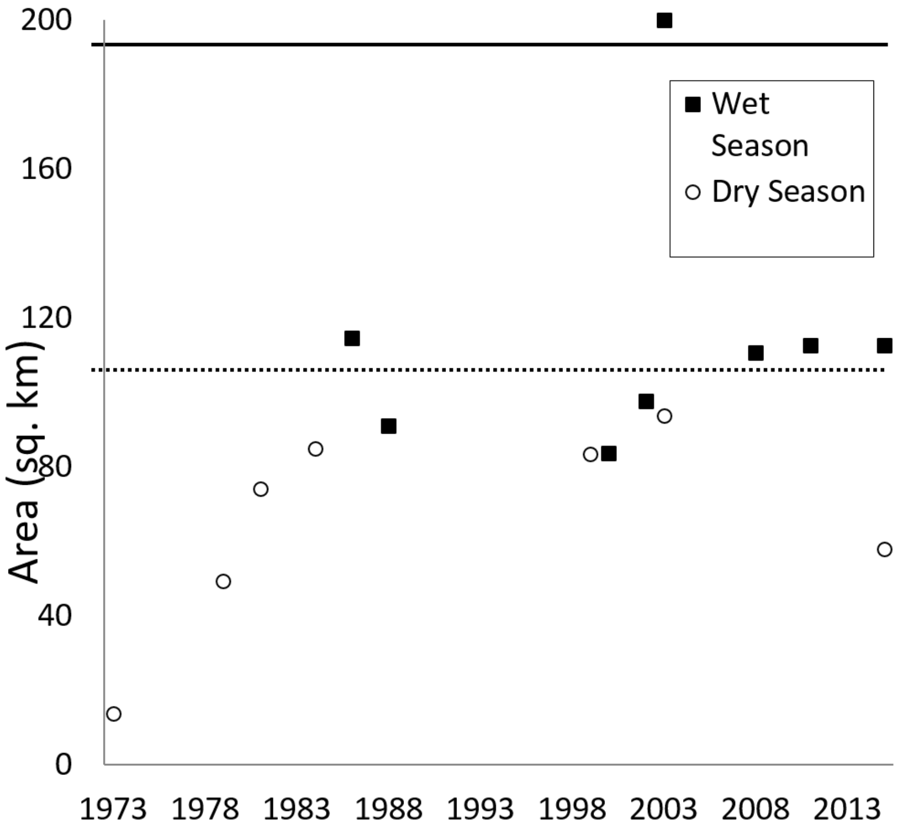


**Figure 34: Lake Area vs Year Plot (Wet & Dry Seasons)**

The study employed a run off coefficient of 21.85% and applying the same to the mean catchment rainfall, then run off from the catchment into the Lake was calculated as 21.85% × 942mm = 205.83mm.

Over-the-lake rainfall represented from the nearby Ngokwe (used in the absence of lake rain gauges (Duan, 2014)) reported a total rainfall of 1040.5 and with trace amounts of rainfall in the dry season. Lake Chiuta may have filled to capacity of 200 km$^2$ any particular year if the above determined hydrological inputs area exceeded. That is if the sum inflow 205.53mm and over the lake rainfall 1040.5mm which is 1246.3mm is exceeded not considering negligible groundwater flow and abstractions that may have been there from lake inflow rivers (Fig 35).

Using the same approach, the lake should have exceeded the 200 km$^2$ mark in 1963, 1974, 1976, 1978, 1982, 1991, 1997, 1999, 2004 and 2006 season should have experienced the largest lake. The time the lake experienced lowest lake area extent in 1973 of 14km$^2$, the catchment received a mean rainfall of 718mm with over the lake rainfall of 776.8mm (Dulanya et al., 2012). Using the same analysis as with the upper limit of inflow, the total inflow was 933.7mm which is 74.9% of the total inflow that may be required for a normal 200km$^2$ lake area (Fig. 35).

The average evaporative demand in that sea was about 1087 mm a thing that might have depleted the waters from Chiuta resulting in the significant recession that was experienced then (Drayton, 1984). Using the same approach, the lake should have exceeded the 14 km$^2$ mark in 1965, 1968, 1981, 1983, 1990, 1992, 1994, 1994, 1998, 2002, 2005 and 2009 should have experienced the lowest lake areas as noted but that was not so as may be due to the flows not being enough to achieve such an extent or high evaporation rates.

The 1973 lake recession may not be the only extreme one as the results suggests but rather in 1981 when the catchment received lowest rainfall of 515.1 mm, with over the lake rainfall of 555.9 mm, resulting in a total inflow of 668.4mm (Fig. 35). Positive trend increase of over the lake evapotranspiration and decreasing rainfall trends, the deficits are likely to become more severe on the lake.

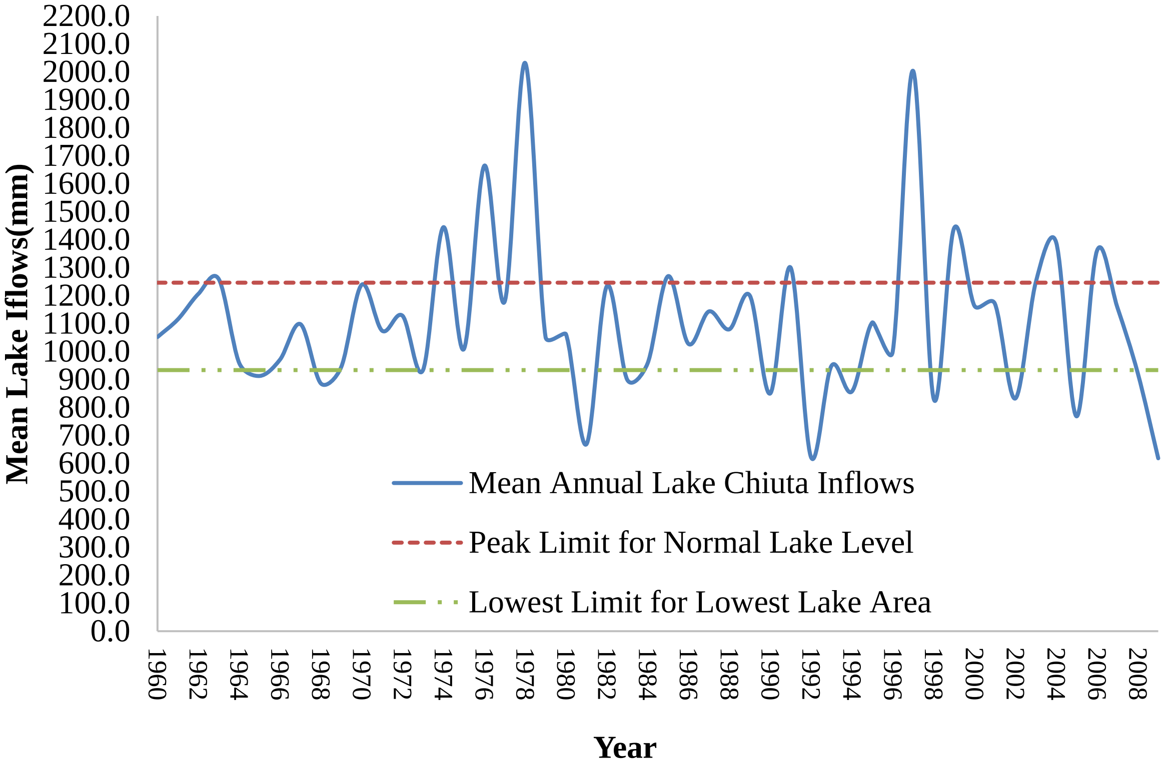


**Figure 35: Mean Lake Inflows Analyses with High and Low Lake Extents**

### *4.7.2 Lake Outflow into Amaramba*

At temporal dimensions, Lake Chiuta connects with Lake Amaramba in Mozambique when conditions permit. That is when Lake Chiuta experiences high levels, discharge occurs and when the lake recedes there is a discontinuity between the two lakes aided by a wetland and flow in Chiuta may be downstream with the prevalence of North

Easterlies. Lake Chiuta's outflow or discharge into Lake Amaramba is of paramount importance in terms of Lake Chiuta's water balance analysis. Flow into the Amaramba will occur if the RHS of equation 11 is positive if not flow into Amaramba will not occur. The temporal change in storage was calculated from predetermined lake levels that were derived from satellite altimetry which was lake level at time $t_0$ less lake level at the immediate next time $t_1$.  Amaramba outflows plotted against decadal time scale in months from April 1992 indicated a negative trend in this time scale with a slope of -0.0026mm/month though the trend is not significant as per Mann-Kendall trend analysis test (Figure 36). Mean monthly outflows peaked in 1997 with outflows of 639.mm in January and 634mm in February.

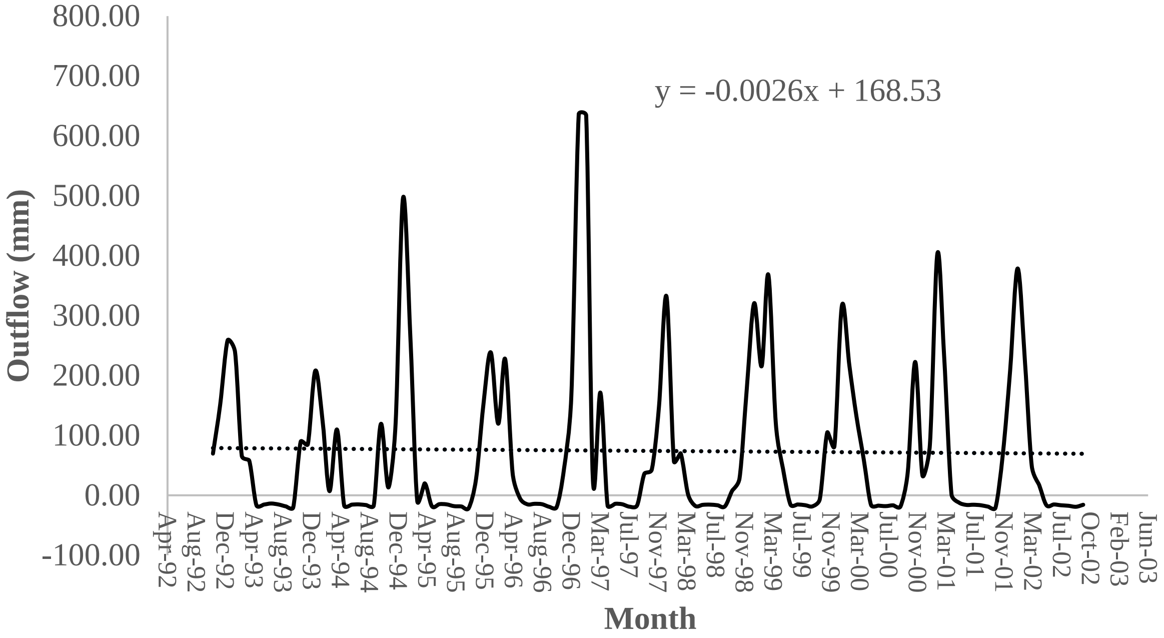


**Figure 36: Estimated Lake Chiuta Outflows into Lake Amaramba**

Groundwater outflow and Amaramba outflow and lake evaporation should be thought to constitute the gross outflow flux from Lake Chiuta. However, having noted that ground water inflows were minimal into Chiuta, it was also deduced that groundwater outflows would also have a minimal effect due to Lake Chiuta's underlain basement, so the groundwater outflow flux was taken out of the gross Lake Chiuta outflow. The mean lake outflow into Amaramba in this decadal time scale was calculated to be 74.19mm/month.

### *4.7.3 Lake Level Deviations from Datum*

Lake Chiuta levels has been varying from 23rd November 1992 to 31st March 2017 (Fig.37). The horizontal line y = 0 for all x is representing the datum level. Most of the levels in Lake Chiuta from 1992 to 1997 have been deviating below the datum zero level. Data is from 1992 because that is the time Topex/Poseidon and Jason 1, 2 & 3 satellite missions has been in existence in monitoring lake levels across the globe. There was a break from 2002 to 2008 when monitoring recommenced. The lake level deviations have had a positive trend with a slope of 2 $\times 10^{-6}$ m per day which is 0.002mm per day though not significant trends at $\alpha = 0.05$ as per Mann-Kendall trend statistic that was found to be 0.45. The maximum deviation from the zero-level datum was observed on 7th January 1996 and was -3.9m. The maximum deviation above the zero-level datum was observed on 15th July 1997 and was 1.86m

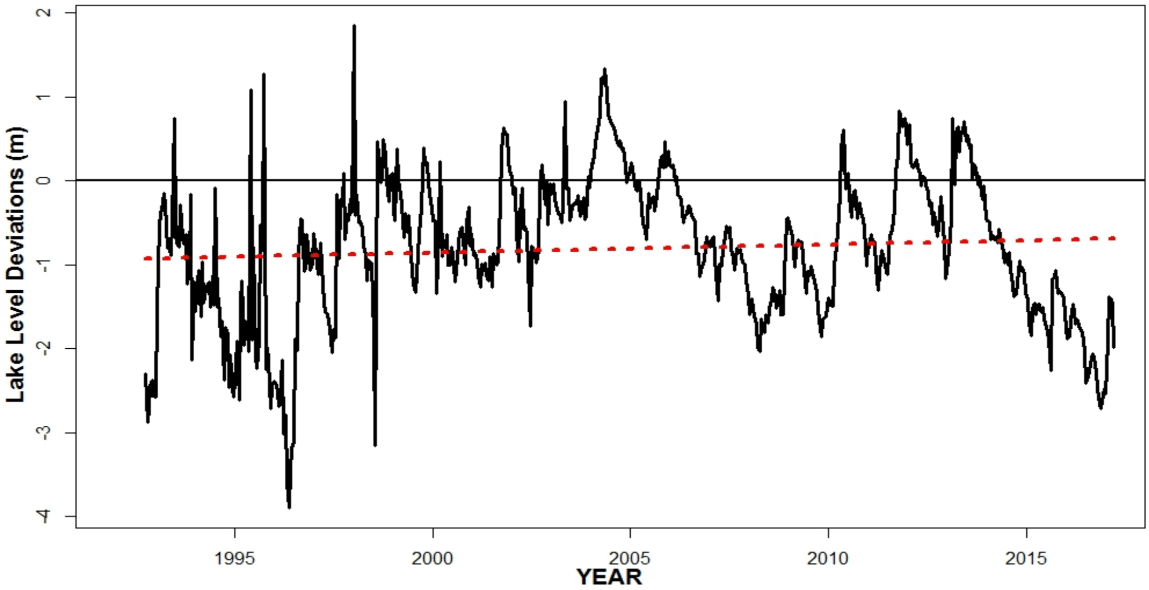


**Figure 37: Lake Level Deviations from Datum**

The area has experienced El Nino and La Nina weather patterns from 1992 to 2011 (Dulanya et al, 2012). The El Nino (mainly from 2014 to 2015) that results in less rains in the Southern Hemisphere than the rains in the Northern Hemisphere (JICA, 2014), has been responsible for the recessions experienced by the lake. A deviation of -2.68m is noted in this aspect as observed on 12th December 2016. According the UN University World Risk (2016), the country had a La Nina weather pattern, a pattern that induced lots of rainfall in the Southern Region and less rains in the Northern Hemisphere. This La Nina weather pattern resulted in rains that had an impact on the lake as the lake level is rising.

Lake levels derived from satellite altimetry data and a mean lake depth of 5m have are shown a positive trend though the trend is not significant at $\alpha = 0.05$ significance level based on the Mann-Kendall trend statistic of 0.46. The slope is $2 \times 10^{-6}$ m per day which is 0.002mm per day. Level peak was 5.31 m (Fig 38).

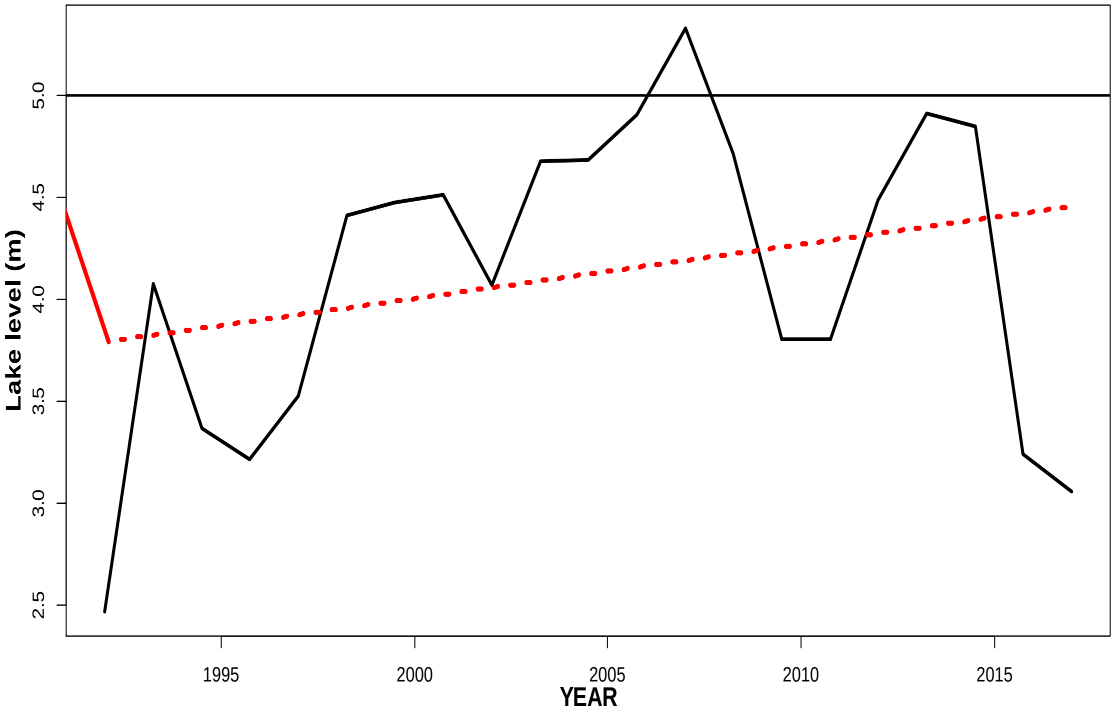


**Figure 38: Lake Chiuta Levels Derived from Satellite Altimetry**

### *4.7.4 Lake Level Return Period Analysis*

Considering return period in extreme levels, figure 39 of mean annual levels was considered to determine return periods. The highest mean level was in 2009 when mean level peaked 5.31m. Therefore, the chance of having this exceeded in this 20year interval (1992-2017) is once in 20 years. Therefore, the return period of having 5.31m level exceeded was taken as 20 years.

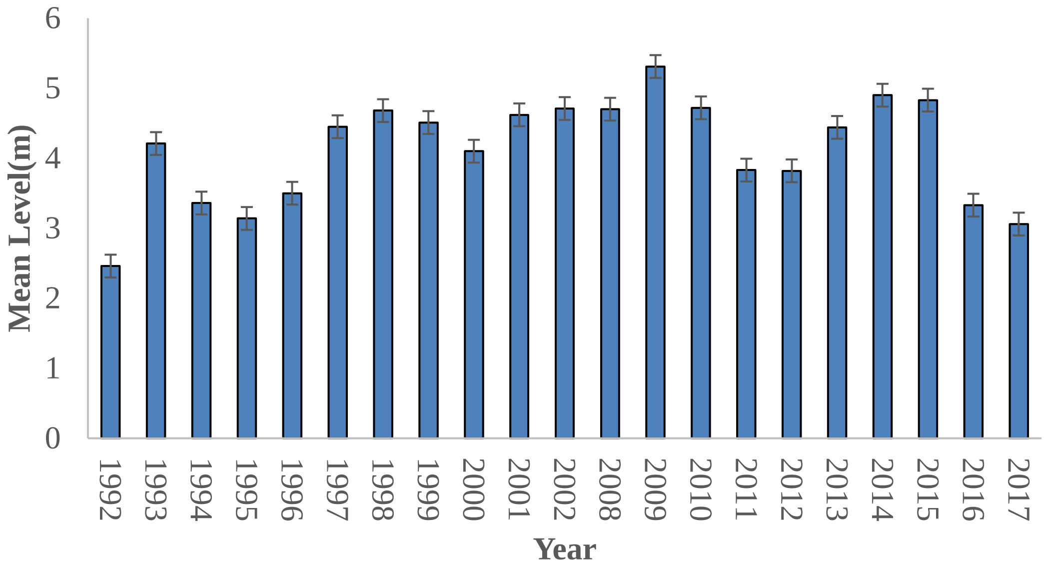


**Figure 39: Lake Chiuta Mean Levels' Return Periods Assessment**

The second maximum in mean level was experienced in 2014 of 4.9m and it has only been exceeded twice in this 20-year interval. Therefore, the likelihood of having this exceeded in a 20-year interval is once in 10 years. The return period is then taken as 10 years. Similar analyses were conducted and the table 15 shows return periods of the lake level events as determined above.

**Table 15: Lake Chiuta Mean Lake Levels Return Periods**

| Return Period | Mean Lake Level(m) |
|---|---|
| 20 | 5.31 |
| 10 | 4.9 |
| 5 | 4.83 |
| 1 | 3.82 |

### 4.8 Lake Chiuta Hydrological Model Development

Simulated lake levels took the same pattern as calibrated lake levels (Fig.40). Nash-Sutcliff coefficient of the model was found to be 0.99, PBIAS was -0.25% and RSR was 0.0013 therefore as stated by Moriasi et al. (2007) if NS > 0.5, RSR<0.7 and PBIAS is within 25% of the mean the model can be deemed acceptable which is the case with this analysis (Mc Cuen ,2006; Ngongondo et al., 2006).

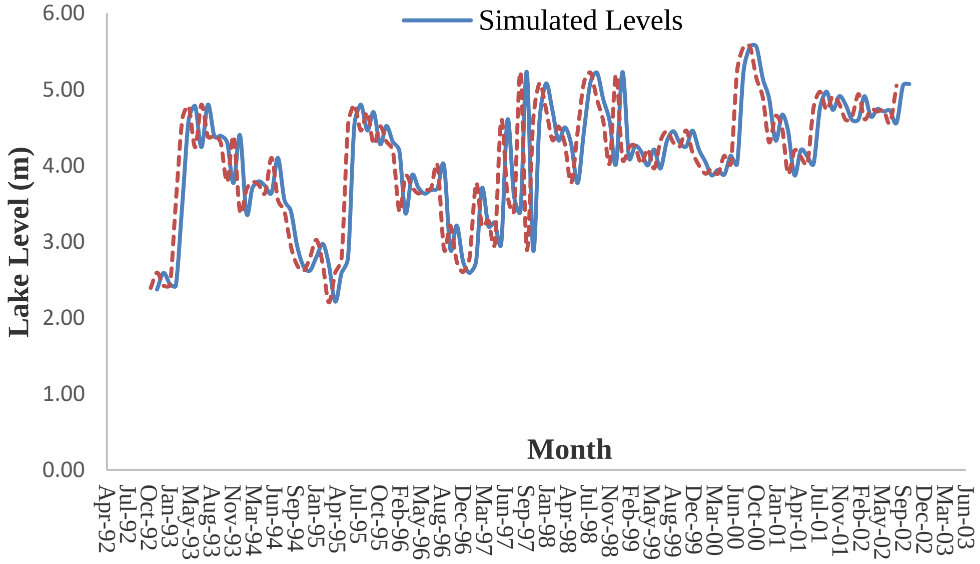


**Figure 40: Lake Chiuta Level Calibration and Simulation (1992 - 2002)**

Calibrated WASMOD run with hydroclimatic scenarios simulated mean inflows as shown in table 16.

**Table 16: Simulated Runoffs under Changed Climate Conditions**

| Scenario | Mean Monthly Simulated Runoff (mm) |
|---|---|
| 1 | 12.3 |
| 2 | 14.7 |
| 3 | 18.23 |

Mean monthly inflows simulated from calibrated WASMOD form changed hyydroclimatic scenarios are as indicated in figure 41. In scenario 1, the simulated flows are less than the calibrated flows due to 10 percent rainfall decrease that will result in reduced runoff .

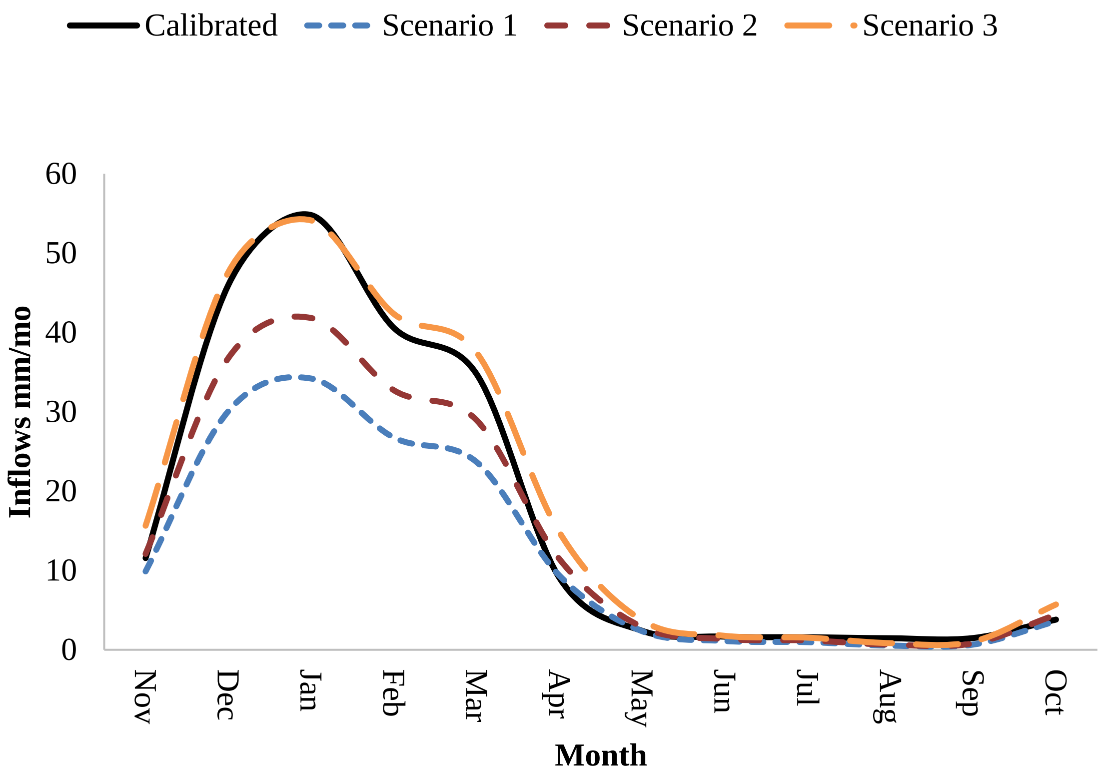


**Figure 41: Calibrated Mean Monthly Inflows & Changed Climatic Scenarios**

In scenario 2, the simulated inflows are also less than calibrated flows much. It may be suggested that much as in this scenario there was no rainfall change, but increase of 2 degrees celcius in temperature might result in increment in surface inflow evepotranspiration resulting in reduced runoff. In scenario 3, the simulated flows are slightly higher than the calibrated flows. 10 percent increase in rainfall might result in increase runoff but may be countered by the 2 degrees celcius temperature increment that may induce high evaporative tendencies on the surface flows.

Changed climatic scenarios compared against annual lake mean inflow thresholds for lake level recessions indicated that lake inflows of up to 1246. 3 mm per annum or more will result in level boom and inflows of 933.7mm or below would result in serious lake level recession (Fig 42).

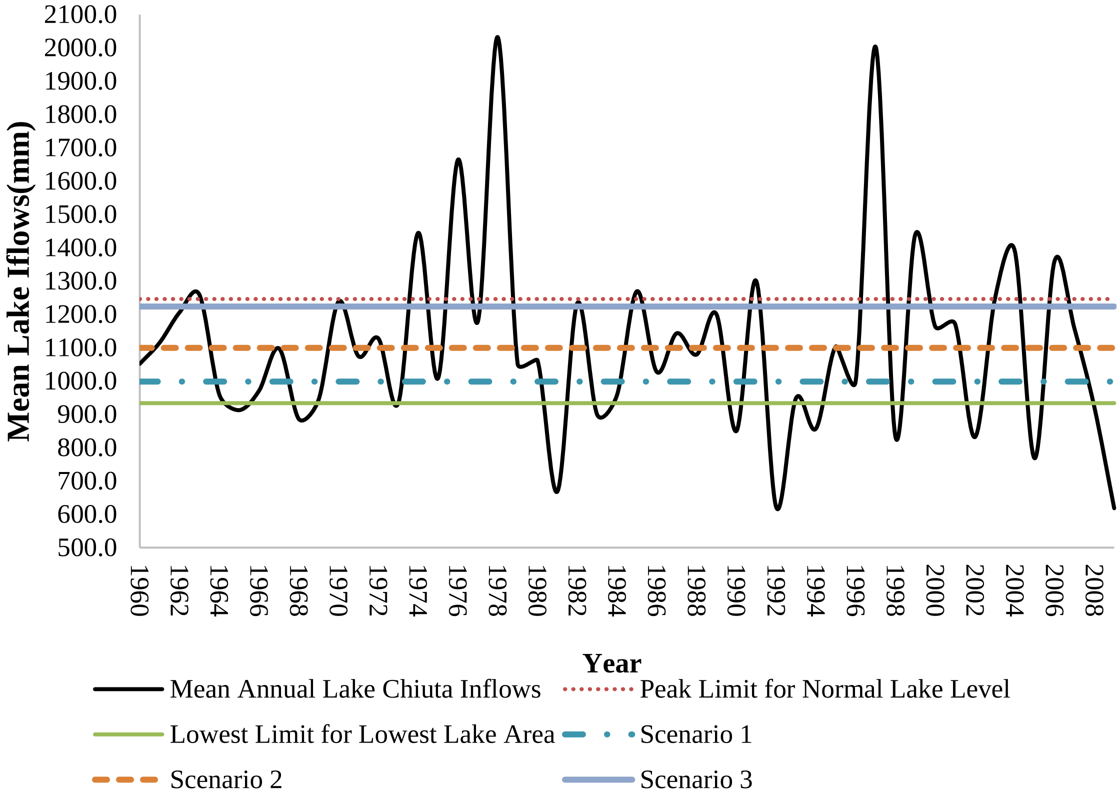


**Figure 42: Climatic Change Scenarios**

This comes in when the catchment receives rainfall of below 1040.5mm and 942mm respectively. As already analysed, such rainfall of about 1040.5mm is likely to be experienced in the catchment at least once in every five years. So any rainfall of less that 1040.5mm should raise an alarm of low lake level and any rainfall of above 1040.5 mm should indicate lake normal water level or lake boom. The two inflow thresholds having been compared with inflows simulated from three hydroclimatic scenarios showed that for scenario 1 of 10% rainfall decrease and 2 degrees temperature increase, the flows would be on a path following low inflow threshold therefore any flows of this magnitude would be used to trigger an alarm of a lake recession. Scenario 2 simulated inflows from no rainfall increase and 2 degrees temperature increase would put lake inflows to be between the two thresholds but the resultant lake level would not be as expected lake normal level due to lake evaporative losses from temperature increase of 2 degrees. Scenario 3 inflows put the lake level to follow  a lake boom trajectory mainly due to rainfall increase by 10%. The lake evaporation not being much to affect lake level rise. So any lake inflows as in scenario 3 may be used to raise an alarm for lake level booms.

Simulated lake levels based in different hydroclimatic scenarios are shown in figure 43. Scenario 1 simulated lower lake levels than the calibrated lake levels. This is due to the rainfall decrease by 10% coupled with the temperature increase of 2 degrees. Rainfall decrease  and temperature increase would result in reduced lake inflows and lake evaporative losses respectively and as a result the lake would lose its level. In scenario 1 levels would fluctuate between 3.78m and 1.5m. Scenario two, with no rainfall increase but 2 degree temperature increase would result in lake losses mainy due to lake evaporation.

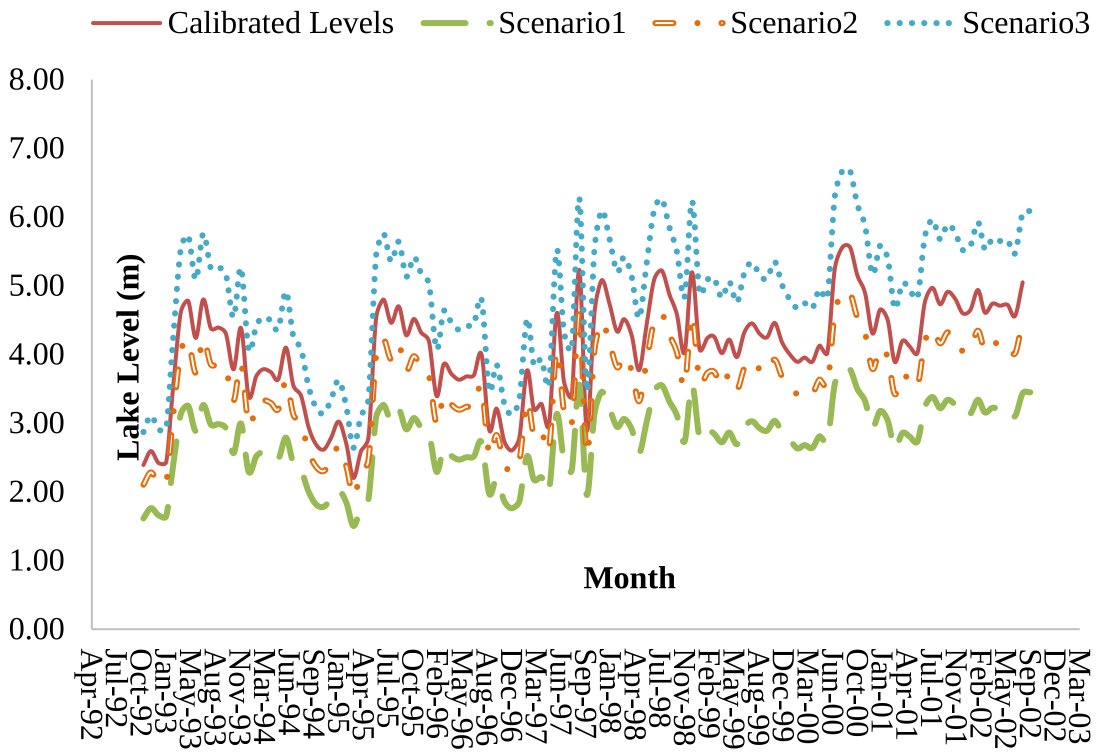


**Figure 43: Lake Level Scenario Simulations (1992 – 2002)**

Much as lake inflows might not deviate a lot from the calibrated inflows, the lake level will be dropping due to increased evaporative losses but the level recession is lower than that of scenario 2. Lake level fluctuate between 4.89m and 2.28m in this scenario. Scenario 3 with 10% rainfall increase and 2 degrees temperature increase, would result in lake level rise above calibrated levels. Levels would fluctuate between 6.67m and 2.64m. The increase of rainfall by 10 percent would result in incease inflows and much as lake evaporative losses from temperatures increase would consume lake level, the lake inflow are much higher to counter evaporative lake losses resulting in lake boom.

### *4.8.1 Development of an early warning model*

Significant autocorrelation up to around 5 years or lag 60 is noted having used and investigated autocorrelation coeficient (ACF), the monthly lake levels from 1992 to

2017 (with a gap between 2002 and 2008) (Fig. 44). Lake levels are serially correlated up to 5 years. Lake levels are serially correlated up to 5 years. The gap effect between 2002 and 2008 was dealt with by evaluating a subset of the monthly lake levels between 2009 and 2017.

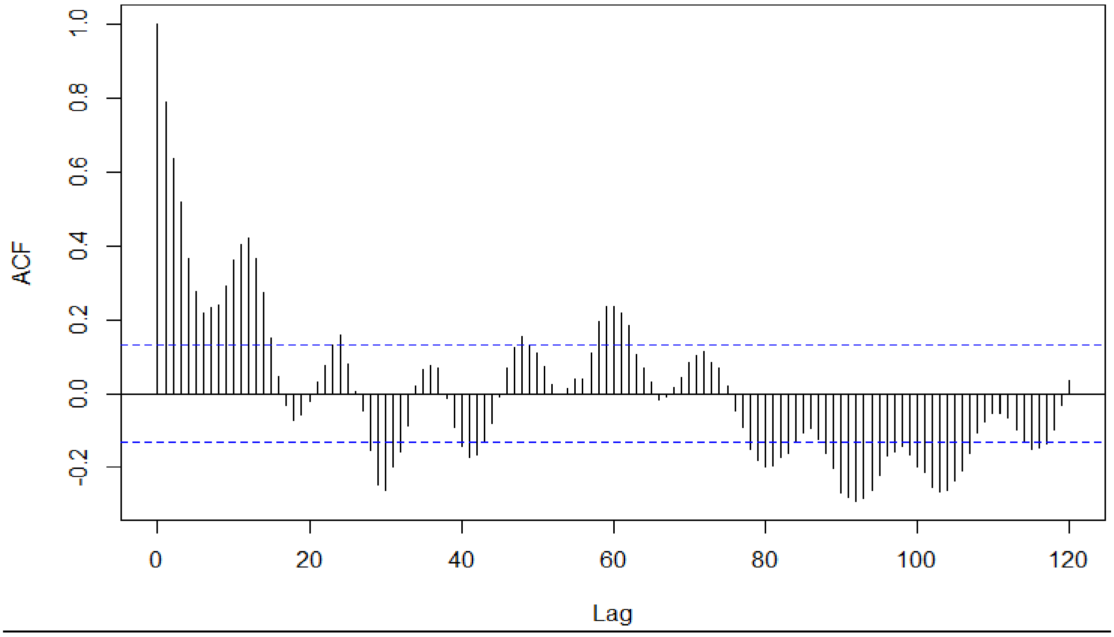


**Figure 44: Autocorrelation Function (ACF) of Monthly Lake Levels (The Dotted Line is the 95% Confidence Interval)**

This study has found that the rainfall regime in Lake Chiuta exhibited no significant trend during 1960 to 2009. Since the inflow is the sum of catchment runoff (derived from rainfall) and over-the-lake rainfall, the total inflow could be one the best indicators of the behavior of the lake as a proxy to lake level variations, taking into consideration the effect of serial correlation. The main assumption of this technique is that lake evaporative losses will continue increasing as found that evaporative losses exhibited a significant positive rising trend.

The best model was found to be an ARIMA (5, 0, 1). The results of the residuals of the simulated inflows, the ACF of the residuals and the Ljung-Box p-values are shown in figure 45. The residual of simulated inflows are supposed to be random, the ACF should not be significant after the first lag while the Ljung-Box statistic should be p>0.05 at all lags (Fig. 45). These three conditions were satisfied by an ARIMA (5, 0, 1) model.

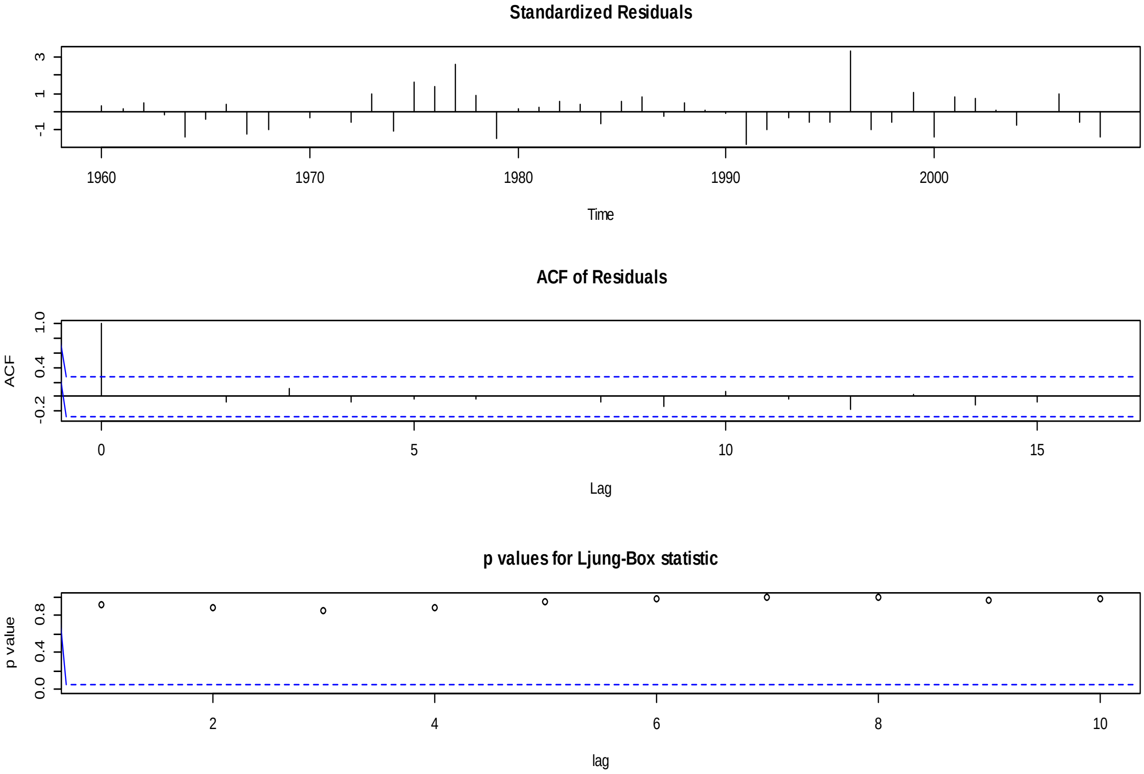


**Figure 45: Standardised Residuals (a), ACF Residuals & Ljung-Box Statistic for Lake Inflows**

The simulations suggest that most of the inflows during the period will be between 983 mm and 1329 mm. This means that the lake may approach filling up only once (1329 mm) (Fig. 46). As already discussed , for the lake to reach its full extent, the lake should encounter inflows of  1246mm, therefore the simulation shows that full lake extent would only be reached once in this forecast The forecast is from 2009 to 2030 at a 95% statistical confidence interval. Lake flows of less than 1246mm should then be an indicator for a recession alarm.

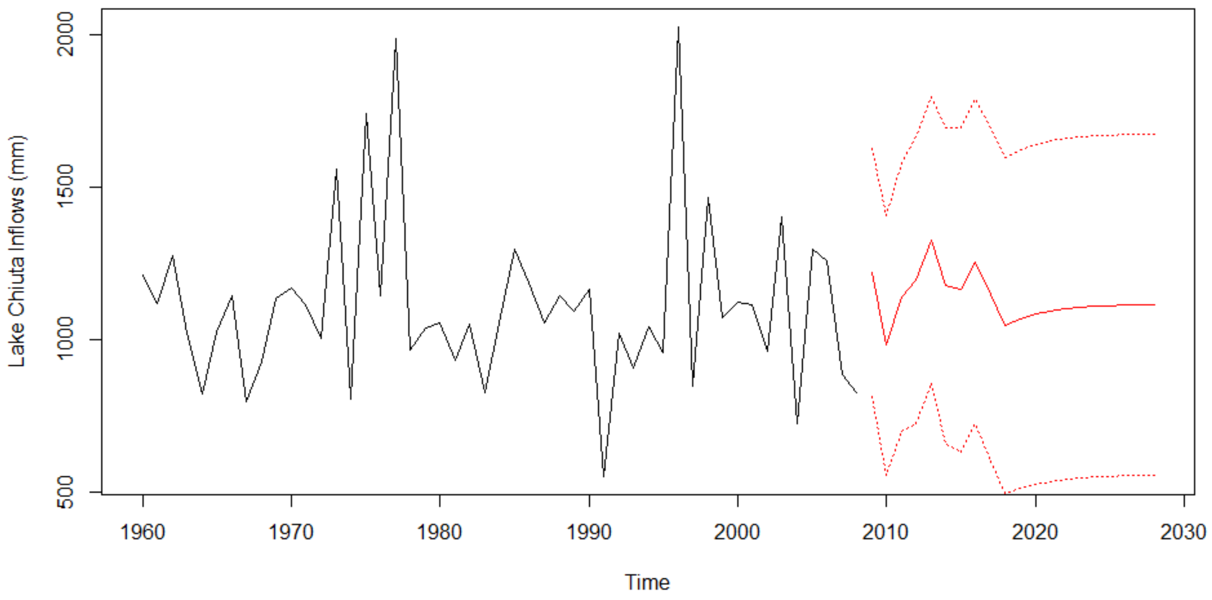


**Figure 46: Forecasted Lake Chiuta Levels up to 2029 (Dotted Lines are Upper Limits of the 95% Confidence Interval). (The Historical Total Annual Inflows and the Actual Forecasted Annual Inflows are shown in Appendix 7 & 8**

Since the climate of the lake is seasonal with a marked rainy period, most of the total inflow should be expected by the end of the rain season. If the total inflow does not exceed 1246 mm and the initial minima lake level in the preceding December was less than 4 m, an alarm for possible recession can be raised.

# CHAPTER 5

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusion

This study has investigated the hydroclimatology of Lake Chiuta in Southern Malawi and an early warning lake level model has been presented. Specifically, the climate regime of the area has been analysed together with the lake response through lake area and levels. A combination of meteorological data, satellite products and modeling tools were applied for the purpose. Lake Chiuta has undergone serious recession in recent times. Lake level in 2015/16 season can be likened to that of 1979. The lake, as noted from historical imagery was at its maximum in 1989 and 2003 and its minimum in 1973. The results show that a large part of the inflows are composed of over-the-lake rainfall, with contributions from river discharge. For the lake to fill up, a total inflow of 1246 mm is required annually, although this may change if the evaporative demands keep increasing. The rainfall regime using 1960 – 2009 data set has had no significant trend but with a negative slope. Rainfall variations in the catchment have had an impact on the resultant water level. Chiuta temperatures have had a significant rising trend which has had an effect on lake evapotranspiration which also has shown a significant rising trend. Lake Chiuta rainfall – runoff relationship is highly affected by rainfall resulting high and low-level stands. Decreasing the rainfall trends, reduced run off, increased lake evapotranspiration, has depleted lake levels. As a result, the basin has basically been under a water deficit for the past 50 years, and this is exemplified by Lake Chiuta area and lake levels, which have mostly been below their respective normal area of 200 $km^2$ and 5 m during the period. When the lake is full, its surface area is 200 $km^2$ however looking at the lake's historical imagery the lake surface area hasn't reached $120km^2$ in the recent times signifying that about $80km^2$ lake area has been lost which 40% lake area reduction.

Groundwater inflow and outflow flux has been disregarded in the final model as its impact has been noted to be very minimal. Satellite data from TOPEX/POSEIDON and Jason 1, 2 & 3 has been used to validate the final model The Hydrological Water Budget. Application of an ARIMA (5, 1, 0) model, as an early warning mechanism, on the inflows suggests that the lake may fill up once between 2008 and 2029, but this is largely dependent upon the rainfall in a season

## 5.2 Study Limitations

Lack of data from all inflowing rivers proved to be a main limiting factor. Lack of a real time weather monitoring station resulted in temperature data estimation using an altitude correction factor. This as well might not have yielded accurate results as opposed to the data that could have been got from a real time weather monitoring station.

## 5.3 Recommendations

i) All inflows rivers in Chiuta should be gauged so that gauging flows can be collected on a daily basis to have real time inflow measurements. Only Mpiri was found to be gauged but data collected from the gauge could not be traced in research.

ii) Number of rain gauging stations should be increased in the catchment to improve rainfall estimation.

iii) The lake should be installed with at least three permanent level gauges to be stationed at the northern, central and southern tips of the lake where daily lake stages may be measured and compared. A flow gauge should also be installed in the lake outflow point into Lake Amaramba for daily measurement of Chiuta outflow into Amaramba.

iv) A real time weather monitoring station to be provided in the Lake basin to have more accurate climatological parameters thereby improving lake evaporation estimations

v) Further research on the lake may look at how the lake level is impacting on the water quality and fish population.

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# APPENDICES

## Appendix 1: CHIUTA MEAN CATCHMENT RAINFALL (1960 – 2009)

| | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 133.3 | 188.0 | 270.7 | 151.4 | 249.3 | 165.1 | 92.9 | 163.3 | 194.0 | 201.6 | 326.2 |
| Feb | 162.4 | 166.4 | 107.9 | 249.3 | 161.7 | 164.6 | 217.4 | 115.9 | 96.6 | 122.1 | 236.4 |
| Mar | 134.8 | 218.4 | 170.4 | 120.3 | 57.8 | 86.5 | 80.8 | 243.2 | 61.5 | 55.7 | 25.7 |
| Apr | 29.0 | 82.0 | 67.4 | 64.0 | 16.9 | 41.0 | 24.1 | 45.0 | 57.5 | 56.1 | 23.9 |
| May | 13.3 | 16.6 | 13.5 | 9.4 | 9.1 | 15.3 | 25.3 | 17.3 | 14.8 | 5.9 | 11.1 |
| Jun | 19.8 | 26.2 | 11.7 | 9.5 | 8.4 | 5.0 | 17.3 | 14.2 | 29.9 | 10.7 | 7.6 |
| Jul | 31.4 | 23.4 | 14.4 | 10.2 | 25.8 | 0.0 | 5.7 | 20.6 | 0.0 | 4.9 | 6.5 |
| Aug | 5.1 | 23.4 | 10.9 | 4.8 | 17.6 | 5.2 | 0.0 | 11.9 | 5.8 | 5.3 | 5.4 |
| Sep | 17.6 | 16.9 | 7.0 | 0.0 | 0.0 | 32.2 | 10.7 | 7.8 | 0.0 | 6.9 | 0.0 |
| Oct | 11.7 | 12.0 | 34.6 | 10.4 | 12.3 | 21.8 | 16.4 | 13.7 | 11.0 | 21.1 | 25.3 |
| Nov | 78.0 | 131.4 | 68.1 | 98.2 | 47.3 | 65.7 | 61.0 | 72.0 | 114.3 | 10.9 | 128.4 |
| Dec | 167.7 | 127.8 | 206.7 | 176.6 | 135.4 | 173.4 | 178.8 | 121.4 | 181.9 | 326.1 | 200.7 |

| | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 343.0 | 214.5 | 126.7 | 264.0 | 119.0 | 214.0 | 434.6 | 367.5 | 159.6 | 123.2 | 59.3 |
| Feb | 94.5 | 145.4 | 96.3 | 271.8 | 199.7 | 196.9 | 84.3 | 228.3 | 190.4 | 156.6 | 171.4 |
| Mar | 90.1 | 121.3 | 198.6 | 299.6 | 95.2 | 311.3 | 190.3 | 462.7 | 175.8 | 84.4 | 88.1 |
| Apr | 23.1 | 68.0 | 54.0 | 89.3 | 62.9 | 195.4 | 15.7 | 85.0 | 35.5 | 116.8 | 49.5 |
| May | 16.1 | 57.4 | 0.0 | 77.6 | 0.0 | 10.9 | 0.0 | 3.5 | 0.0 | 1.0 | 13.2 |
| Jun | 0.5 | 8.4 | 0.6 | 22.9 | 2.3 | 3.8 | 0.0 | 2.5 | 13.7 | 0.5 | 0.0 |
| Jul | 4.8 | 0.6 | 1.0 | 3.9 | 6.6 | 3.1 | 1.6 | 8.2 | 5.8 | 0.0 | 2.4 |
| Aug | 0.0 | 0.4 | 0.0 | 0.7 | 1.0 | 0.0 | 0.0 | 0.0 | 1.2 | 11.4 | 0.0 |
| Sep | 0.0 | 0.3 | 0.0 | 2.1 | 0.7 | 5.4 | 7.6 | 0.0 | 1.0 | 0.0 | 0.0 |
| Oct | 9.9 | 3.5 | 7.4 | 0.9 | 25.3 | 15.8 | 0.0 | 69.4 | 7.3 | 84.3 | 35.0 |
| Nov | 77.4 | 57.8 | 91.3 | 13.5 | 48.0 | 4.7 | 102.4 | 23.8 | 139.6 | 19.9 | 31.3 |
| Dec | 158.2 | 176.1 | 142.2 | 116.3 | 196.6 | 238.7 | 198.3 | 204.8 | 229.2 | 292.5 | 65.0 |

| | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 279.1 | 210.9 | 156.9 | 188.3 | 257.7 | 326.7 | 166.5 | 202.7 | 304.2 | 264.7 | 120.1 |
| Feb | 242.0 | 170.3 | 181.2 | 160.5 | 159.1 | 155.2 | 228.1 | 244.1 | 149.8 | 153.5 | 20.8 |
| Mar | 35.8 | 114.8 | 200.3 | 204.4 | 140.7 | 144.0 | 204.5 | 308.8 | 94.6 | 240.7 | 124.0 |
| Apr | 112.3 | 40.4 | 10.0 | 41.2 | 42.3 | 52.2 | 48.7 | 7.3 | 39.7 | 17.8 | 14.0 |
| May | 9.4 | 17.9 | 0.9 | 1.5 | 0.7 | 0.4 | 9.6 | 0.0 | 52.9 | 7.5 | 5.6 |
| Jun | 0.0 | 5.2 | 2.7 | 3.0 | 0.7 | 0.9 | 0.1 | 2.5 | 0.0 | 5.7 | 7.0 |
| Jul | 6.2 | 22.7 | 3.2 | 0.6 | 2.1 | 0.0 | 1.6 | 0.0 | 0.0 | 5.9 | 0.0 |
| Aug | 3.0 | 0.0 | 0.0 | 2.2 | 0.0 | 0.0 | 0.0 | 0.9 | 1.0 | 0.0 | 0.0 |
| Sep | 0.0 | 0.0 | 8.0 | 5.1 | 0.1 | 0.0 | 0.0 | 1.5 | 0.5 | 0.0 | 0.0 |
| Oct | 70.7 | 13.8 | 12.5 | 3.4 | 17.3 | 3.5 | 1.0 | 7.3 | 5.6 | 15.9 | 0.0 |
| Nov | 109.1 | 39.6 | 89.1 | 90.4 | 52.3 | 9.5 | 38.0 | 154.1 | 57.0 | 70.7 | 125.5 |
| Dec | 227.8 | 122.1 | 171.9 | 322.3 | 144.6 | 158.6 | 134.3 | 147.1 | 44.8 | 117.1 | 154.3 |

|  | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 200.5 | 261.2 | 318.5 | 168.6 | 419.9 | 297.3 | 276.0 | 210.5 | 164.4 | 287.8 | 254.0 |
| Feb | 228.3 | 87.0 | 167.8 | 211.4 | 377.4 | 122.6 | 183.1 | 187.3 | 298.6 | 207.9 | 198.4 |
| Mar | 135.9 | 28.9 | 9.7 | 196.7 | 49.7 | 89.8 | 362.1 | 132.1 | 194.3 | 52.1 | 259.5 |
| Apr | 45.7 | 69.7 | 25.2 | 50.3 | 152.5 | 13.9 | 93.1 | 63.3 | 18.5 | 20.8 | 7.5 |
| May | 0.0 | 0.0 | 0.0 | 15.1 | 0.0 | 5.9 | 30.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| Jun | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 8.2 | 0.0 | 0.0 | 5.9 | 5.4 |
| Jul | 5.9 | 0.0 | 0.0 | 0.0 | 5.5 | 0.0 | 5.5 | 0.0 | 5.7 | 0.0 | 0.0 |
| Aug | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.5 | 5.9 | 0.0 | 0.0 | 0.0 | 6.1 |
| Sep | 7.5 | 0.0 | 0.0 | 0.0 | 5.5 | 0.0 | 5.4 | 0.0 | 0.0 | 8.9 | 5.8 |
| Oct | 5.9 | 89.7 | 0.0 | 6.7 | 52.5 | 13.5 | 6.1 | 42.2 | 6.2 | 5.4 | 0.0 |
| Nov | 83.5 | 26.5 | 21.2 | 38.7 | 104.5 | 43.3 | 118.8 | 115.5 | 73.7 | 27.7 | 28.5 |
| Dec | 62.6 | 117.5 | 193.8 | 165.3 | 188.8 | 172.4 | 57.0 | 48.9 | 183.0 | 103.2 | 176.8 |

|  | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|
| Jan | 344.7 | 199.7 | 254.4 | 332.8 | 290.7 | 200.9 |
| Feb | 215.0 | 111.0 | 122.5 | 203.3 | 112.6 | 92.5 |
| Mar | 119.7 | 16.4 | 215.9 | 45.4 | 54.7 | 129.8 |
| Apr | 67.0 | 14.2 | 29.6 | 31.6 | 15.8 | 26.7 |
| May | 0.0 | 0.0 | 5.6 | 0.0 | 15.4 | 0.0 |
| Jun | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.6 |
| Jul | 0.0 | 4.8 | 0.0 | 0.0 | 0.0 | 0.0 |
| Aug | 0.0 | 0.0 | 5.5 | 10.3 | 0.0 | 0.0 |
| Sep | 0.0 | 6.0 | 0.0 | 5.2 | 0.0 | 0.0 |
| Oct | 19.0 | 13.6 | 9.0 | 39.6 | 31.3 | 11.1 |
| Nov | 101.3 | 57.0 | 140.9 | 52.9 | 76.4 | 47.4 |
| Dec | 189.2 | 191.4 | 178.7 | 213.9 | 176.8 | 119.0 |

# Appendix 2: LAKE CHIUTA WATER BALANCE

LAKE CHIUTA WATBAL SIMULATION

| Date | Over the Lake Rainfall | Modelled Inflow | Over the lake evapotranspiration | Amaramba Outflows | Lake Level | Modelled Lake Level (m) |
|---|---|---|---|---|---|---|
| Nov-92 | 85.82 | 6.02 | 21.99 | 71.01 | 2370 | |
| Dec-92 | 143.37 | 28.64 | 21.24 | 153.29 | 2590 | 2.37 |
| Jan-93 | 216.37 | 62.06 | 19.81 | 260.54 | 2440 | 2.59 |
| Feb-93 | 222.33 | 37.93 | 20.09 | 239.43 | 2420 | 2.44 |
| Mar-93 | 79.07 | 7.93 | 19.82 | 65.69 | 3500 | 2.42 |
| Apr-93 | 76.34 | 1.59 | 19.79 | 57.95 | 4600 | 3.50 |
| May-93 | 0.00 | 1.09 | 18.28 | -16.59 | 4780 | 4.60 |
| Jun-93 | 0.00 | 0.99 | 15.86 | -15.35 | 4240 | 4.78 |
| Jul-93 | 0.00 | 1.79 | 15.90 | -13.62 | 4800 | 4.24 |
| Aug-93 | 0.00 | 1.26 | 16.56 | -15.18 | 4380 | 4.80 |
| Sep-93 | 0.00 | 0.71 | 19.34 | -18.40 | 4390 | 4.38 |
| Oct-93 | 0.00 | 1.01 | 21.77 | -19.98 | 4300 | 4.39 |
| Nov-93 | 105.95 | 5.66 | 21.53 | 90.74 | 3770 | 4.30 |
| Dec-93 | 79.17 | 27.1 | 21.76 | 87.66 | 4400 | 3.77 |
| Jan-94 | 192.72 | 36.14 | 20.49 | 209.37 | 3370 | 4.40 |
| Feb-94 | 105.65 | 35.88 | 20.20 | 121.34 | 3700 | 3.37 |
| Mar-94 | 13.89 | 13.52 | 20.53 | 6.31 | 3790 | 3.70 |
| Apr-94 | 125.59 | 3.86 | 19.69 | 109.67 | 3730 | 3.79 |
| May-94 | 0.00 | 1.25 | 17.82 | -16.95 | 3640 | 3.73 |
| Jun-94 | 0.00 | 0.84 | 16.96 | -15.44 | 4100 | 3.64 |
| Jul-94 | 0.00 | 0.74 | 16.03 | -15.00 | 3550 | 4.10 |
| Aug-94 | 0.00 | 0.72 | 17.46 | -16.12 | 3400 | 3.55 |
| Sep-94 | 0.00 | 2.32 | 19.67 | -16.75 | 2940 | 3.40 |
| Oct-94 | 138.19 | 1.61 | 20.58 | 119.67 | 2670 | 2.94 |
| Nov-94 | 27.09 | 8.87 | 22.67 | 14.81 | 2620 | 2.67 |
| Dec-94 | 105.26 | 35.88 | 21.46 | 121.72 | 2800 | 2.62 |
| Jan-95 | 499.27 | 16.92 | 20.03 | 497.53 | 2970 | 2.80 |
| Feb-95 | 229.47 | 49.04 | 20.12 | 259.26 | 2700 | 2.97 |
| Mar-95 | 0.00 | 12.03 | 20.79 | -9.65 | 2210 | 2.70 |
| Apr-95 | 37.84 | 1.95 | 19.56 | 20.03 | 2590 | 2.21 |
| May-95 | 0.00 | 1.84 | 18.33 | -18.20 | 2790 | 2.59 |
| Jun-95 | 0.00 | 1.22 | 15.74 | -14.69 | 4530 | 2.79 |
| Jul-95 | 0.00 | 0.77 | 16.20 | -14.94 | 4800 | 4.53 |
| Aug-95 | 0.00 | 0.66 | 18.49 | -17.90 | 4460 | 4.80 |
| Sep-95 | 0.00 | 0.82 | 19.85 | -18.41 | 4700 | 4.46 |
| Oct-95 | 0.00 | 1.15 | 22.46 | -21.23 | 4280 | 4.70 |
| Nov-95 | 42.43 | 7.73 | 22.50 | 29.45 | 4520 | 4.28 |
| Dec-95 | 134.09 | 36.23 | 20.62 | 152.00 | 4310 | 4.52 |
| Jan-96 | 223.02 | 34.61 | 19.81 | 240.22 | 4190 | 4.31 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Feb-96 | 117.67 | 21.81 | 19.46 | 119.65 | 3370 | 4.19 |
| Mar-96 | 191.26 | 54.89 | 19.03 | 226.82 | 3870 | 3.37 |
| Apr-96 | 50.15 | 4.51 | 18.01 | 36.53 | 3710 | 3.87 |
| May-96 | 11.35 | 1.41 | 17.26 | -4.48 | 3630 | 3.71 |
| Jun-96 | 0.00 | 1.15 | 16.11 | -14.88 | 3680 | 3.63 |
| Jul-96 | 0.00 | 1.41 | 15.28 | -14.06 | 3700 | 3.68 |
| Aug-96 | 0.00 | 0.95 | 16.88 | -14.66 | 4000 | 3.70 |
| Sep-96 | 0.00 | 0.79 | 19.73 | -19.06 | 2900 | 4.00 |
| Oct-96 | 0.00 | 1.06 | 21.31 | -19.49 | 3210 | 2.90 |
| Nov-96 | 58.06 | 10.38 | 23.69 | 46.91 | 2740 | 3.21 |
| Dec-96 | 162.14 | 23.47 | 21.11 | 166.79 | 2590 | 2.74 |
| Jan-97 | 613.80 | 43.55 | 19.99 | 638.36 | 2740 | 2.59 |
| Feb-97 | 635.20 | 17.42 | 19.13 | 634.14 | 3700 | 2.74 |
| Mar-97 | 38.13 | 7.85 | 20.62 | 25.01 | 3200 | 3.70 |
| Apr-97 | 184.03 | 6.12 | 18.95 | 171.15 | 3250 | 3.20 |
| May-97 | 0.00 | 1.18 | 16.63 | -16.98 | 2970 | 3.25 |
| Jun-97 | 0.00 | 2.02 | 17.20 | -14.12 | 4600 | 2.97 |
| Jul-97 | 0.00 | 0.72 | 15.86 | -14.78 | 3600 | 4.60 |
| Aug-97 | 0.00 | 0.71 | 17.90 | -18.84 | 3400 | 3.60 |
| Sep-97 | 0.00 | 0.61 | 19.67 | -16.52 | 5230 | 3.40 |
| Oct-97 | 57.67 | 0.83 | 20.73 | 36.32 | 2880 | 5.23 |
| Nov-97 | 47.12 | 18.87 | 22.40 | 45.45 | 4600 | 2.88 |
| Dec-97 | 131.26 | 37.65 | 20.32 | 151.47 | 5080 | 4.60 |
| Jan-98 | 307.06 | 45.47 | 20.75 | 334.29 | 4720 | 5.08 |
| Feb-98 | 53.86 | 24.2 | 20.97 | 57.25 | 4330 | 4.72 |
| Mar-98 | 84.25 | 6.84 | 21.19 | 69.89 | 4500 | 4.33 |
| Apr-98 | 14.77 | 5.95 | 19.90 | 1.04 | 4280 | 4.50 |
| May-98 | 0.00 | 0.89 | 17.92 | -17.58 | 3770 | 4.28 |
| Jun-98 | 0.00 | 0.94 | 16.18 | -15.74 | 4450 | 3.77 |
| Jul-98 | 0.00 | 0.74 | 16.13 | -15.35 | 5090 | 4.45 |
| Aug-98 | 0.00 | 0.7 | 17.63 | -16.41 | 5220 | 5.09 |
| Sep-98 | 0.00 | 0.69 | 19.44 | -18.26 | 4870 | 5.22 |
| Oct-98 | 26.99 | 1.48 | 21.61 | 7.82 | 4580 | 4.87 |
| Nov-98 | 51.13 | 0.88 | 22.41 | 28.71 | 4020 | 4.58 |
| Dec-98 | 127.54 | 70.01 | 21.95 | 178.79 | 5230 | 4.02 |
| Jan-99 | 259.86 | 80.74 | 19.75 | 324.24 | 4100 | 5.23 |
| Feb-99 | 174.45 | 60.59 | 19.60 | 217.69 | 4260 | 4.10 |
| Mar-99 | 384.84 | 2.7 | 19.77 | 367.91 | 4180 | 4.26 |
| Apr-99 | 136.63 | 2.17 | 18.61 | 119.96 | 4000 | 4.18 |
| May-99 | 60.12 | 1.18 | 17.48 | 44.15 | 4210 | 4.00 |
| Jun-99 | 0.00 | 0.99 | 16.11 | -15.38 | 3960 | 4.21 |
| Jul-99 | 0.00 | 0.89 | 16.01 | -15.13 | 4320 | 3.96 |
| Aug-99 | 0.00 | 0.8 | 17.40 | -16.30 | 4450 | 4.32 |
| Sep-99 | 0.00 | 0.7 | 19.09 | -18.18 | 4300 | 4.45 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Oct-99 | 12.23 | 2.02 | 20.38 | -5.84 | 4250 | 4.30 |
| Nov-99 | 102.62 | 23.85 | 21.79 | 107.85 | 4460 | 4.25 |
| Dec-99 | 58.16 | 45.73 | 21.67 | 85.69 | 4210 | 4.46 |
| Jan-00 | 246.27 | 90.18 | 20.09 | 320.74 | 4050 | 4.21 |
| Feb-00 | 217.45 | 19.15 | 19.80 | 217.11 | 3870 | 4.05 |
| Mar-00 | 137.32 | 15.83 | 20.22 | 132.53 | 3940 | 3.87 |
| Apr-00 | 77.31 | 2.18 | 19.62 | 59.59 | 3880 | 3.94 |
| May-00 | 0.00 | 1.48 | 17.51 | -15.89 | 4130 | 3.88 |
| Jun-00 | 0.00 | 0.94 | 16.89 | -17.08 | 4020 | 4.13 |
| Jul-00 | 0.00 | 0.9 | 18.63 | -17.94 | 5240 | 4.02 |
| Aug-00 | 0.00 | 0.79 | 17.50 | -16.58 | 5560 | 5.24 |
| Sep-00 | 0.00 | 0.73 | 19.59 | -18.29 | 5560 | 5.56 |
| Oct-00 | 59.14 | 0.91 | 21.58 | 38.96 | 5140 | 5.56 |
| Nov-00 | 231.03 | 11.89 | 20.78 | 224.88 | 4880 | 5.14 |
| Dec-00 | 20.25 | 33.84 | 20.49 | 36.04 | 4330 | 4.88 |
| Jan-01 | 52.69 | 51.28 | 19.96 | 86.58 | 4670 | 4.33 |
| Feb-01 | 390.12 | 32.1 | 19.98 | 403.36 | 4460 | 4.67 |
| Mar-01 | 231.71 | 23.22 | 19.98 | 234.00 | 3870 | 4.46 |
| Apr-01 | 12.43 | 8.68 | 19.57 | 1.13 | 4200 | 3.87 |
| May-01 | 0.00 | 6.01 | 17.99 | -12.18 | 4120 | 4.20 |
| Jun-01 | 0.00 | 1.06 | 16.32 | -15.92 | 4020 | 4.12 |
| Jul-01 | 0.00 | 0.86 | 16.36 | -15.60 | 4760 | 4.02 |
| Aug-01 | 0.00 | 0.79 | 17.58 | -16.42 | 4970 | 4.76 |
| Sep-01 | 0.00 | 0.73 | 19.51 | -18.81 | 4730 | 4.97 |
| Oct-01 | 0.00 | 0.71 | 21.58 | -20.58 | 4910 | 4.73 |
| Nov-01 | 85.62 | 7.71 | 23.17 | 72.05 | 4800 | 4.91 |
| Dec-01 | 192.43 | 38.11 | 21.73 | 211.48 | 4600 | 4.80 |
| Jan-02 | 372.73 | 26.66 | 20.41 | 380.27 | 4610 | 4.60 |
| Feb-02 | 223.21 | 17.51 | 20.32 | 220.76 | 4910 | 4.61 |
| Mar-02 | 25.91 | 43.5 | 20.34 | 48.30 | 4640 | 4.91 |
| Apr-02 | 30.21 | 5.97 | 19.38 | 16.51 | 4740 | 4.64 |
| May-02 | 0.00 | 0.92 | 17.47 | -16.46 | 4710 | 4.74 |
| Jun-02 | 0.00 | 0.84 | 16.27 | -15.15 | 4720 | 4.71 |
| Jul-02 | 0.00 | 0.77 | 16.88 | -16.46 | 4560 | 4.72 |
| Aug-02 | 0.00 | 0.7 | 18.15 | -17.31 | 5050 | 4.56 |
| Sep-02 | 0.00 | 0.65 | 19.63 | -18.94 | 5070 | 5.05 |
| Oct-02 | 0.00 | 0.73 | 21.70 | -15.55 | 5200 | 5.07 |

CALIBRATION

| Date | Over the Lake Rainfall | Observed Inflow | Over the lake evapotranspiration | Amaramba Outflows | Lake Level | Calibrated Lake Level |
|---|---|---|---|---|---|---|
| Nov-92 | 85.82 | 27.43 | 21.99 | 71.01 | 2370 | |
| Dec-92 | 143.37 | 33.72 | 21.24 | 153.29 | 2590 | 2.39 |
| Jan-93 | 216.37 | 43.80 | 19.81 | 260.54 | 2440 | 2.59 |
| Feb-93 | 222.33 | 49.87 | 20.09 | 239.43 | 2420 | 2.42 |
| Mar-93 | 79.07 | 29.70 | 19.82 | 65.69 | 3500 | 2.43 |
| Apr-93 | 76.34 | 9.99 | 19.79 | 57.95 | 4600 | 3.52 |
| May-93 | 0.00 | 0.00 | 18.28 | -16.59 | 4780 | 4.61 |
| Jun-93 | 0.00 | 0.00 | 15.86 | -15.35 | 4240 | 4.78 |
| Jul-93 | 0.00 | 1.28 | 15.90 | -13.62 | 4800 | 4.24 |
| Aug-93 | 0.00 | 0.00 | 16.56 | -15.18 | 4380 | 4.80 |
| Sep-93 | 0.00 | 1.64 | 19.34 | -18.40 | 4390 | 4.38 |
| Oct-93 | 0.00 | 1.29 | 21.77 | -19.98 | 4300 | 4.39 |
| Nov-93 | 105.95 | 18.24 | 21.53 | 90.74 | 3770 | 4.30 |
| Dec-93 | 79.17 | 13.68 | 21.76 | 87.66 | 4400 | 3.78 |
| Jan-94 | 192.72 | 57.07 | 20.49 | 209.37 | 3370 | 4.38 |
| Feb-94 | 105.65 | 19.01 | 20.20 | 121.34 | 3700 | 3.39 |
| Mar-94 | 13.89 | 6.31 | 20.53 | 6.31 | 3790 | 3.68 |
| Apr-94 | 125.59 | 15.24 | 19.69 | 109.67 | 3730 | 3.78 |
| May-94 | 0.00 | 0.00 | 17.82 | -16.95 | 3640 | 3.74 |
| Jun-94 | 0.00 | 0.00 | 16.96 | -15.44 | 4100 | 3.64 |
| Jul-94 | 0.00 | 0.00 | 16.03 | -15.00 | 3550 | 4.10 |
| Aug-94 | 0.00 | 0.00 | 17.46 | -16.12 | 3400 | 3.55 |
| Sep-94 | 0.00 | 0.00 | 19.67 | -16.75 | 2940 | 3.40 |
| Oct-94 | 138.19 | 19.61 | 20.58 | 119.67 | 2670 | 2.94 |
| Nov-94 | 27.09 | 5.78 | 22.67 | 14.81 | 2620 | 2.69 |
| Dec-94 | 105.26 | 25.67 | 21.46 | 121.72 | 2800 | 2.62 |
| Jan-95 | 499.27 | 69.59 | 20.03 | 497.53 | 2970 | 2.79 |
| Feb-95 | 229.47 | 36.67 | 20.12 | 259.26 | 2700 | 3.02 |
| Mar-95 | 0.00 | 2.13 | 20.79 | -9.65 | 2210 | 2.69 |
| Apr-95 | 37.84 | 5.50 | 19.56 | 20.03 | 2590 | 2.20 |
| May-95 | 0.00 | 0.00 | 18.33 | -18.20 | 2790 | 2.59 |
| Jun-95 | 0.00 | 0.00 | 15.74 | -14.69 | 4530 | 2.79 |
| Jul-95 | 0.00 | 0.00 | 16.20 | -14.94 | 4800 | 4.53 |
| Aug-95 | 0.00 | 0.00 | 18.49 | -17.90 | 4460 | 4.80 |
| Sep-95 | 0.00 | 0.00 | 19.85 | -18.41 | 4700 | 4.46 |
| Oct-95 | 0.00 | 0.00 | 22.46 | -21.23 | 4280 | 4.70 |
| Nov-95 | 42.43 | 4.64 | 22.50 | 29.45 | 4520 | 4.28 |
| Dec-95 | 134.09 | 42.35 | 20.62 | 152.00 | 4310 | 4.52 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Jan-96 | 223.02 | 36.85 | 19.81 | 240.22 | 4190 | 4.31 |
| Feb-96 | 117.67 | 46.20 | 19.46 | 119.65 | 3370 | 4.19 |
| Mar-96 | 191.26 | 42.98 | 19.03 | 226.82 | 3870 | 3.39 |
| Apr-96 | 50.15 | 10.99 | 18.01 | 36.53 | 3710 | 3.86 |
| May-96 | 11.35 | 3.31 | 17.26 | -4.48 | 3630 | 3.72 |
| Jun-96 | 0.00 | 0.00 | 16.11 | -14.88 | 3680 | 3.63 |
| Jul-96 | 0.00 | 0.00 | 15.28 | -14.06 | 3700 | 3.68 |
| Aug-96 | 0.00 | 0.00 | 16.88 | -14.66 | 4000 | 3.70 |
| Sep-96 | 0.00 | 0.00 | 19.73 | -19.06 | 2900 | 4.00 |
| Oct-96 | 0.00 | 1.47 | 21.31 | -19.49 | 3210 | 2.90 |
| Nov-96 | 58.06 | 8.46 | 23.69 | 46.91 | 2740 | 3.21 |
| Dec-96 | 162.14 | 36.12 | 21.11 | 166.79 | 2590 | 2.74 |
| Jan-97 | 613.80 | 91.76 | 19.99 | 638.36 | 2740 | 2.60 |
| Feb-97 | 635.20 | 82.46 | 19.13 | 634.14 | 3700 | 2.79 |
| Mar-97 | 38.13 | 10.85 | 20.62 | 25.01 | 3200 | 3.76 |
| Apr-97 | 184.03 | 33.31 | 18.95 | 171.15 | 3250 | 3.20 |
| May-97 | 0.00 | 0.00 | 16.63 | -16.98 | 2970 | 3.28 |
| Jun-97 | 0.00 | 0.00 | 17.20 | -14.12 | 4600 | 2.97 |
| Jul-97 | 0.00 | 1.21 | 15.86 | -14.78 | 3600 | 4.60 |
| Aug-97 | 0.00 | 0.00 | 17.90 | -18.84 | 3400 | 3.60 |
| Sep-97 | 0.00 | 1.20 | 19.67 | -16.52 | 5230 | 3.40 |
| Oct-97 | 57.67 | 11.48 | 20.73 | 36.32 | 2880 | 5.23 |
| Nov-97 | 47.12 | 22.83 | 22.40 | 45.45 | 4600 | 2.89 |
| Dec-97 | 131.26 | 41.25 | 20.32 | 151.47 | 5080 | 4.60 |
| Jan-98 | 307.06 | 64.96 | 20.75 | 334.29 | 4720 | 5.08 |
| Feb-98 | 53.86 | 26.79 | 20.97 | 57.25 | 4330 | 4.74 |
| Mar-98 | 84.25 | 19.62 | 21.19 | 69.89 | 4500 | 4.33 |
| Apr-98 | 14.77 | 3.03 | 19.90 | 1.04 | 4280 | 4.51 |
| May-98 | 0.00 | 1.28 | 17.92 | -17.58 | 3770 | 4.28 |
| Jun-98 | 0.00 | 0.00 | 16.18 | -15.74 | 4450 | 3.77 |
| Jul-98 | 0.00 | 0.00 | 16.13 | -15.35 | 5090 | 4.45 |
| Aug-98 | 0.00 | 1.20 | 17.63 | -16.41 | 5220 | 5.09 |
| Sep-98 | 0.00 | 0.00 | 19.44 | -18.26 | 4870 | 5.22 |
| Oct-98 | 26.99 | 2.95 | 21.61 | 7.82 | 4580 | 4.87 |
| Nov-98 | 51.13 | 9.45 | 22.41 | 28.71 | 4020 | 4.58 |
| Dec-98 | 127.54 | 37.68 | 21.95 | 178.79 | 5230 | 4.03 |
| Jan-99 | 259.86 | 60.31 | 19.75 | 324.24 | 4100 | 5.19 |
| Feb-99 | 174.45 | 40.01 | 19.60 | 217.69 | 4260 | 4.08 |
| Mar-99 | 384.84 | 79.13 | 19.77 | 367.91 | 4180 | 4.24 |
| Apr-99 | 136.63 | 20.35 | 18.61 | 119.96 | 4000 | 4.26 |
| May-99 | 60.12 | 6.57 | 17.48 | 44.15 | 4210 | 4.02 |
| Jun-99 | 0.00 | 1.80 | 16.11 | -15.38 | 3960 | 4.22 |
| Jul-99 | 0.00 | 1.21 | 16.01 | -15.13 | 4320 | 3.96 |
| Aug-99 | 0.00 | 1.28 | 17.40 | -16.30 | 4450 | 4.32 |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| Sep-99 | 0.00 | 1.19 | 19.09 | -18.18 | 4300 | 4.45 |
| Oct-99 | 12.23 | 1.34 | 20.38 | -5.84 | 4250 | 4.30 |
| Nov-99 | 102.62 | 25.97 | 21.79 | 107.85 | 4460 | 4.25 |
| Dec-99 | 58.16 | 12.44 | 21.67 | 85.69 | 4210 | 4.46 |
| Jan-00 | 246.27 | 46.00 | 20.09 | 320.74 | 4050 | 4.17 |
| Feb-00 | 217.45 | 40.93 | 19.80 | 217.11 | 3870 | 4.00 |
| Mar-00 | 137.32 | 28.86 | 20.22 | 132.53 | 3940 | 3.89 |
| Apr-00 | 77.31 | 13.83 | 19.62 | 59.59 | 3880 | 3.95 |
| May-00 | 0.00 | 0.00 | 17.51 | -15.89 | 4130 | 3.89 |
| Jun-00 | 0.00 | 0.00 | 16.89 | -17.08 | 4020 | 4.13 |
| Jul-00 | 0.00 | 0.00 | 18.63 | -17.94 | 5240 | 4.02 |
| Aug-00 | 0.00 | 0.00 | 17.50 | -16.58 | 5560 | 5.24 |
| Sep-00 | 0.00 | 0.00 | 19.59 | -18.29 | 5560 | 5.56 |
| Oct-00 | 59.14 | 9.22 | 21.58 | 38.96 | 5140 | 5.56 |
| Nov-00 | 231.03 | 25.24 | 20.78 | 224.88 | 4880 | 5.15 |
| Dec-00 | 20.25 | 10.69 | 20.49 | 36.04 | 4330 | 4.89 |
| Jan-01 | 52.69 | 35.92 | 19.96 | 86.58 | 4670 | 4.30 |
| Feb-01 | 390.12 | 65.25 | 19.98 | 403.36 | 4460 | 4.65 |
| Mar-01 | 231.71 | 42.45 | 19.98 | 234.00 | 3870 | 4.49 |
| Apr-01 | 12.43 | 4.05 | 19.57 | 1.13 | 4200 | 3.89 |
| May-01 | 0.00 | 0.00 | 17.99 | -12.18 | 4120 | 4.20 |
| Jun-01 | 0.00 | 0.00 | 16.32 | -15.92 | 4020 | 4.11 |
| Jul-01 | 0.00 | 1.25 | 16.36 | -15.60 | 4760 | 4.02 |
| Aug-01 | 0.00 | 0.00 | 17.58 | -16.42 | 4970 | 4.76 |
| Sep-01 | 0.00 | 0.00 | 19.51 | -18.81 | 4730 | 4.97 |
| Oct-01 | 0.00 | 1.36 | 21.58 | -20.58 | 4910 | 4.73 |
| Nov-01 | 85.62 | 16.10 | 23.17 | 72.05 | 4800 | 4.91 |
| Dec-01 | 192.43 | 39.98 | 21.73 | 211.48 | 4600 | 4.81 |
| Jan-02 | 372.73 | 62.89 | 20.41 | 380.27 | 4610 | 4.60 |
| Feb-02 | 223.21 | 45.43 | 20.32 | 220.76 | 4910 | 4.64 |
| Mar-02 | 25.91 | 11.38 | 20.34 | 48.30 | 4640 | 4.94 |
| Apr-02 | 30.21 | 4.53 | 19.38 | 16.51 | 4740 | 4.61 |
| May-02 | 0.00 | 0.00 | 17.47 | -16.46 | 4710 | 4.74 |
| Jun-02 | 0.00 | 1.29 | 16.27 | -15.15 | 4720 | 4.71 |
| Jul-02 | 0.00 | 0.00 | 16.88 | -16.46 | 4560 | 4.72 |
| Aug-02 | 0.00 | 0.00 | 18.15 | -17.31 | 5050 | 4.56 |
| Sep-02 | 0.00 | 1.95 | 19.63 | -18.94 | 5070 | 5.05 |
| Oct-02 | 0.00 | 1.19 | 21.70 | -15.55 | 5200 | 5.07 |
|  |  |  |  |  |  | 0.78 |

## Appendix 3: CHIUTA MEAN TEMPERATURE

| Year | Temperature | Year | Temperature |
|---|---|---|---|
| 1969 | 19.33 | 1990 | 19.39 |
| 1970 | 18.89 | 1991 | 19.01 |
| 1971 | 18.70 | 1992 | 19.92 |
| 1972 | 18.84 | 1993 | 19.21 |
| 1973 | 19.09 | 1994 | 19.46 |
| 1974 | 18.36 | 1995 | 19.56 |
| 1975 | 18.59 | 1996 | 18.97 |
| 1976 | 18.44 | 1997 | 19.12 |
| 1977 | 19.30 | 1998 | 19.67 |
| 1978 | 18.90 | 1999 | 18.97 |
| 1979 | 19.01 | 2000 | 19.39 |
| 1980 | 19.33 | 2001 | 19.48 |
| 1981 | 18.85 | 2002 | 19.43 |
| 1982 | 18.80 | 2003 | 19.51 |
| 1983 | 19.64 | 2004 | 19.46 |
| 1984 | 18.88 | 2005 | 20.01 |
| 1985 | 18.62 | 2006 | 19.45 |
| 1986 | 18.53 | 2007 | 19.43 |
| 1987 | 19.16 | 2008 | 19.41 |
| 1988 | 19.24 | | |
| 1989 | 19.09 | | |

# Appendix 4: OVER THE LAKE EVAPOTRANSPIRATION

| Year | Evatra |
|---|---|
| 1969 | 131.66 |
| 1970 | 129.61 |
| 1971 | 128.75 |
| 1972 | 129.41 |
| 1973 | 130.55 |
| 1974 | 127.21 |
| 1975 | 128.27 |
| 1976 | 127.56 |
| 1977 | 131.51 |
| 1978 | 129.68 |
| 1979 | 130.19 |
| 1980 | 131.64 |
| 1981 | 129.45 |
| 1982 | 129.21 |
| 1983 | 133.04 |
| 1984 | 129.56 |
| 1985 | 128.39 |
| 1986 | 128.00 |
| 1987 | 130.86 |
| 1988 | 131.22 |
| 1989 | 130.56 |
| 1990 | 131.91 |
| 1991 | 130.19 |
| 1992 | 134.34 |
| 1993 | 131.09 |
| 1994 | 132.25 |
| 1995 | 132.68 |
| 1996 | 130.01 |
| 1997 | 130.67 |
| 1998 | 133.20 |
| 1999 | 130.00 |
| 2000 | 131.92 |
| 2001 | 132.31 |
| 2002 | 132.10 |
| 2003 | 132.48 |
| 2004 | 132.22 |
| 2005 | 134.74 |
| 2006 | 132.20 |
| 2007 | 132.08 |
| 2008 | 132.01 |

## Appendix 5: LAKE CHIUTA OUTFLOWS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Nov-92 | 69.63 | Feb-96 | 119.52 | May-99 | 44.07 | Aug-02 | -17.47 |
| Dec-92 | 150.92 | Mar-96 | 227.28 | Jun-99 | -15.48 | Sep-02 | -19.11 |
| Jan-93 | 258.65 | Apr-96 | 36.73 | Jul-99 | -15.25 | Oct-02 | -15.77 |
| Feb-93 | 239.09 | May-96 | -4.54 | Aug-99 | -16.45 | | |
| Mar-93 | 66.08 | Jun-96 | -14.98 | Sep-99 | -18.34 | | |
| Apr-93 | 57.95 | Jul-96 | -14.17 | Oct-99 | -6.33 | | |
| May-93 | -16.65 | Aug-96 | -14.83 | Nov-99 | 104.93 | | |
| Jun-93 | -15.43 | Sep-96 | -19.25 | Dec-99 | 82.38 | | |
| Jul-93 | -13.69 | Oct-96 | -19.78 | Jan-00 | 316.54 | | |
| Aug-93 | -15.31 | Nov-96 | 44.90 | Feb-00 | 216.72 | | |
| Sep-93 | -18.54 | Dec-96 | 164.34 | Mar-00 | 132.98 | | |
| Oct-93 | -20.23 | Jan-97 | 636.40 | Apr-00 | 59.63 | | |
| Nov-93 | 89.44 | Feb-97 | 633.99 | May-00 | -15.92 | | |
| Dec-93 | 85.54 | Mar-97 | 25.31 | Jun-00 | -17.17 | | |
| Jan-94 | 208.04 | Apr-97 | 171.47 | Jul-00 | -18.05 | | |
| Feb-94 | 121.24 | May-97 | -17.08 | Aug-00 | -16.71 | | |
| Mar-94 | 6.94 | Jun-97 | -14.18 | Sep-00 | -18.44 | | |
| Apr-94 | 109.85 | Jul-97 | -14.94 | Oct-00 | 38.73 | | |
| May-94 | -17.03 | Aug-97 | -19.02 | Nov-00 | 222.69 | | |
| Jun-94 | -15.57 | Sep-97 | -16.71 | Dec-00 | 33.26 | | |
| Jul-94 | -15.14 | Oct-97 | 36.05 | Jan-01 | 84.22 | | |
| Aug-94 | -16.28 | Nov-97 | 43.11 | Feb-01 | 402.83 | | |
| Sep-94 | -17.08 | Dec-97 | 148.95 | Mar-01 | 234.62 | | |
| Oct-94 | 119.28 | Jan-98 | 332.17 | Apr-01 | 1.61 | | |
| Nov-94 | 13.10 | Feb-98 | 56.92 | May-01 | -11.88 | | |
| Dec-94 | 119.52 | Mar-98 | 70.13 | Jun-01 | -16.00 | | |
| Jan-95 | 496.43 | Apr-98 | 1.34 | Jul-01 | -15.71 | | |
| Feb-95 | 258.88 | May-98 | -17.71 | Aug-01 | -16.55 | | |
| Mar-95 | -9.14 | Jun-98 | -15.88 | Sep-01 | -18.96 | | |
| Apr-95 | 20.02 | Jul-98 | -15.52 | Oct-01 | -20.76 | | |
| May-95 | -18.23 | Aug-98 | -16.58 | Nov-01 | 70.36 | | |
| Jun-95 | -14.79 | Sep-98 | -18.46 | Dec-01 | 208.80 | | |
| Jul-95 | -15.09 | Oct-98 | 7.42 | Jan-02 | 378.67 | | |
| Aug-95 | -18.07 | Nov-98 | 28.39 | Feb-02 | 220.67 | | |
| Sep-95 | -18.61 | Dec-98 | 176.74 | Mar-02 | 48.97 | | |
| Oct-95 | -21.55 | Jan-99 | 320.69 | Apr-02 | 16.83 | | |
| Nov-95 | 27.86 | Feb-99 | 215.52 | May-02 | -16.56 | | |
| Dec-95 | 149.82 | Mar-99 | 367.95 | Jun-02 | -15.27 | | |
| Jan-96 | 238.64 | Apr-99 | 119.98 | Jul-02 | -16.60 | | |

# Appendix 6: LAKE CHIUTA MEAN HISTORIC LEVELS

| | | | | | |
|---|---|---|---|---|---|
| Oct-92 | 2.37 | Jan-96 | 3.37 | Apr-99 | 4.21 |
| Nov-92 | 2.59 | Feb-96 | 3.87 | May-99 | 3.96 |
| Dec-92 | 2.44 | Mar-96 | 3.71 | Jun-99 | 4.32 |
| Jan-93 | 2.42 | Apr-96 | 3.63 | Jul-99 | 4.45 |
| Feb-93 | 3.50 | May-96 | 3.68 | Aug-99 | 4.30 |
| Mar-93 | 4.60 | Jun-96 | 3.70 | Sep-99 | 4.25 |
| Apr-93 | 4.78 | Jul-96 | 4.00 | Oct-99 | 4.46 |
| May-93 | 4.24 | Aug-96 | 2.90 | Nov-99 | 4.21 |
| Jun-93 | 4.80 | Sep-96 | 3.21 | Dec-99 | 4.05 |
| Jul-93 | 4.38 | Oct-96 | 2.74 | Jan-00 | 3.87 |
| Aug-93 | 4.39 | Nov-96 | 2.59 | Feb-00 | 3.94 |
| Sep-93 | 4.30 | Dec-96 | 2.74 | Mar-00 | 3.88 |
| Oct-93 | 3.77 | Jan-97 | 3.70 | Apr-00 | 4.13 |
| Nov-93 | 4.40 | Feb-97 | 3.20 | May-00 | 4.02 |
| Dec-93 | 3.37 | Mar-97 | 3.25 | Jun-00 | 5.24 |
| Jan-94 | 3.70 | Apr-97 | 2.97 | Jul-00 | 5.56 |
| Feb-94 | 3.79 | May-97 | 4.60 | Aug-00 | 5.56 |
| Mar-94 | 3.73 | Jun-97 | 3.60 | Sep-00 | 5.14 |
| Apr-94 | 3.64 | Jul-97 | 3.40 | Oct-00 | 4.88 |
| May-94 | 4.10 | Aug-97 | 5.23 | Nov-00 | 4.33 |
| Jun-94 | 3.55 | Sep-97 | 2.88 | Dec-00 | 4.67 |
| Jul-94 | 3.40 | Oct-97 | 4.60 | Jan-01 | 4.46 |
| Aug-94 | 2.94 | Nov-97 | 5.08 | Feb-01 | 3.87 |
| Sep-94 | 2.67 | Dec-97 | 4.72 | Mar-01 | 4.20 |
| Oct-94 | 2.62 | Jan-98 | 4.33 | Apr-01 | 4.12 |
| Nov-94 | 2.80 | Feb-98 | 4.50 | May-01 | 4.02 |
| Dec-94 | 2.97 | Mar-98 | 4.28 | Jun-01 | 4.76 |
| Jan-95 | 2.70 | Apr-98 | 3.77 | Jul-01 | 4.97 |
| Feb-95 | 2.21 | May-98 | 4.45 | Aug-01 | 4.73 |
| Mar-95 | 2.59 | Jun-98 | 5.09 | Sep-01 | 4.91 |
| Apr-95 | 2.79 | Jul-98 | 5.22 | Oct-01 | 4.80 |
| May-95 | 4.53 | Aug-98 | 4.87 | Nov-01 | 4.60 |
| Jun-95 | 4.80 | Sep-98 | 4.58 | Dec-01 | 4.61 |
| Jul-95 | 4.46 | Oct-98 | 4.02 | Jan-02 | 4.91 |
| Aug-95 | 4.70 | Nov-98 | 5.23 | Feb-02 | 4.64 |
| Sep-95 | 4.28 | Dec-98 | 4.10 | Mar-02 | 4.74 |
| Oct-95 | 4.52 | Jan-99 | 4.26 | Apr-02 | 4.71 |
| Nov-95 | 4.31 | Feb-99 | 4.18 | May-02 | 4.72 |
| Dec-95 | 4.19 | Mar-99 | 4.00 | Jun-02 | 4.56 |

## Appendix 7: TOTAL ANNUAL INFLOWS INTO LAKE CHIUTA DURING 1960/61 TO 2008/09

| Year | Total Inflow (mm) | Year | Total Inflow (mm) |
|---|---|---|---|
| 1960 | 1212.9 | 1985 | 1296.9 |
| 1961 | 1120.9 | 1986 | 1185.8 |
| 1962 | 1276.0 | 1987 | 1057.5 |
| 1963 | 1024.1 | 1988 | 1144.5 |
| 1964 | 822.8 | 1989 | 1093.8 |
| 1965 | 1025.4 | 1990 | 1164.3 |
| 1966 | 1146.2 | 1991 | 554.0 |
| 1967 | 798.7 | 1992 | 1021.6 |
| 1968 | 929.9 | 1993 | 910.0 |
| 1969 | 1134.7 | 1994 | 1044.0 |
| 1970 | 1169.7 | 1995 | 958.3 |
| 1971 | 1114.6 | 1996 | 2025.2 |
| 1972 | 1006.1 | 1997 | 849.0 |
| 1973 | 1558.9 | 1998 | 1466.3 |
| 1974 | 806.0 | 1999 | 1075.1 |
| 1975 | 1743.7 | 2000 | 1123.9 |
| 1976 | 1146.9 | 2001 | 1114.3 |
| 1977 | 1986.3 | 2002 | 963.0 |
| 1978 | 966.2 | 2003 | 1403.3 |
| 1979 | 1038.3 | 2004 | 728.3 |
| 1980 | 1055.5 | 2005 | 1297.1 |
| 1981 | 934.6 | 2006 | 1261.3 |
| 1982 | 1050.2 | 2007 | 888.5 |
| 1983 | 828.0 | 2008 | 826.8 |
| 1984 | 1058.1 | | |

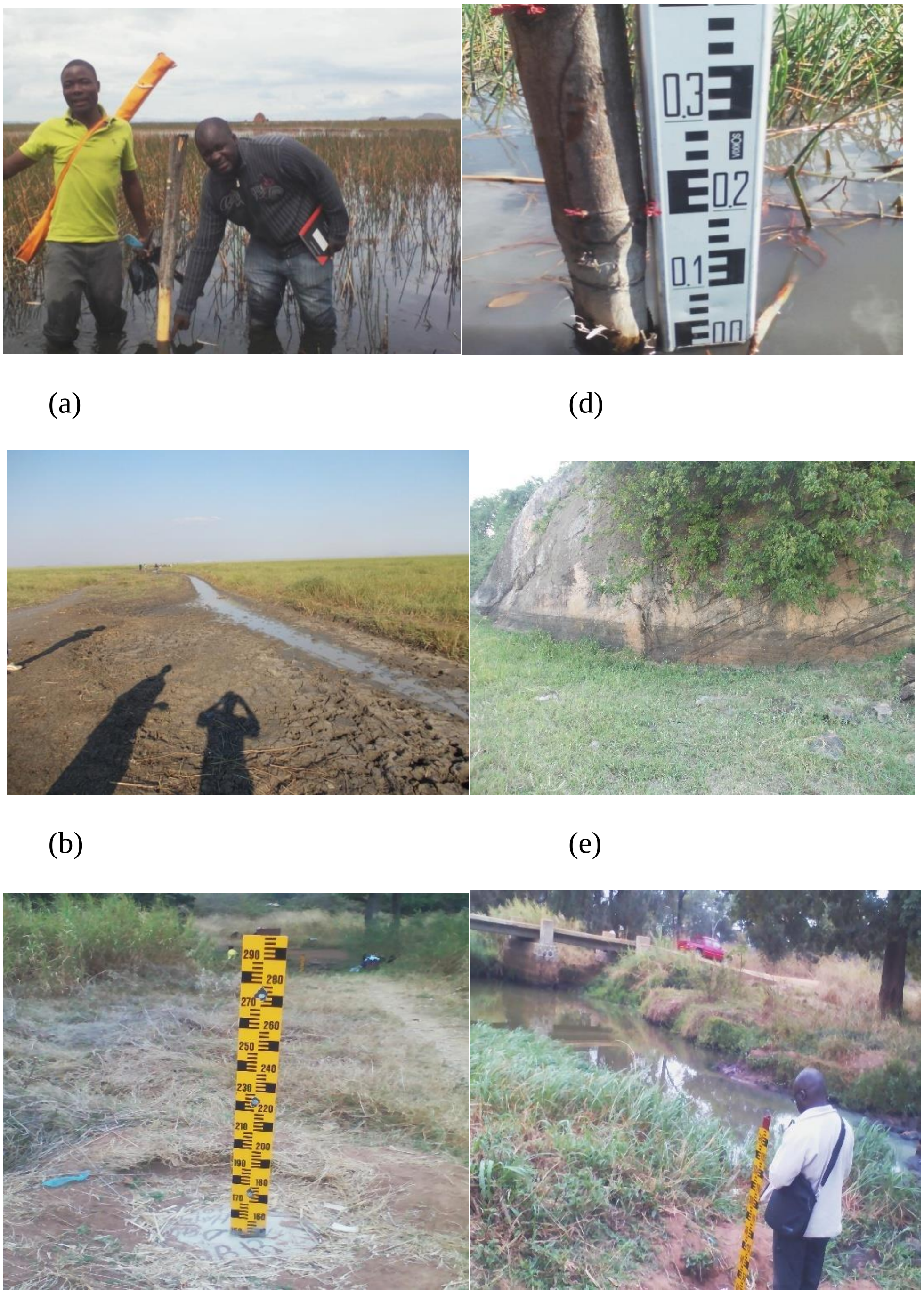
***Total Inflow= Catchment Rainfall + Over the lake rainfall**

****Figures are for the Hydrological year from November to October**

# Appendix 8: FORECASTED TOTAL ANNUAL INFLOWS INTO LAKE CHIUTA DURING 2009/10 TO 2029/30

| Year | Predicted Inflow (mm) | ± Standard Error (mm) |
|---|---|---|
| 2010/11 | 1198.43 | 235.58 |
| 2011/12 | 1058.96 | 249.48 |
| 2012/13 | 1154.56 | 253.22 |
| 2013/14 | 1150.72 | 257.86 |
| 2014/15 | 1205.59 | 257.99 |
| 2015/16 | 1170.21 | 266.21 |
| 2016/17 | 1188.05 | 267.41 |
| 2017/18 | 1160.44 | 271.26 |
| 2018/19 | 1154.87 | 271.94 |
| 2019/20 | 1130.04 | 272.80 |
| 2020/21 | 1121.80 | 272.81 |
| 2021/22 | 1106.03 | 272.81 |
| 2022/23 | 1101.76 | 273.01 |
| 2023/24 | 1096.13 | 273.22 |
| 2024/25 | 1097.91 | 273.61 |
| 2025/26 | 1099.48 | 273.87 |
| 2026/27 | 1104.84 | 274.09 |
| 2027/28 | 1109.44 | 274.19 |
| 2028/29 | 1115.01 | 274.22 |
| 2029/30 | 1119.07 | 274.22 |

## Appendix 9: RESEARCH PICTURES


(a) (d)

(b) (e)

(c) (f)

a) Level gauge installation (b) Lake Chiuta Recession (c) Mpiri River Gauge (d) Lake level drop staff reading (e) Lake Recession Marks (f) Low flows in Mpiri River