REGIONAL FLOOD FREQUENCY ANALYSIS IN THE LAKE CHILWA BASIN

MASTER OF SCIENCE IN ENVIRONMENTAL SCIENCES THESIS

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DECLARATION

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

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CERTIFICATE OF APPROVAL

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DEDICATION

To my mum, siblings and progeny, who continue to astonish me with their resilience, patience and love.

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ABSTRACT

Floods are natural hazards that cause loss of life and property in many parts of the world. People need protection against flood disasters through accurate and reliable quantification of the frequency linked to a particular flood magnitude. Data for understanding flood behavior and frequency is however scarce in many parts of the world. Regional flood frequency analysis (RFFA) in the Lake Chilwa basin was undertaken to predict floods by evaluating river discharge characteristics as a key factor for flood estimation to support flood risk management using already verified procedures in data scarce regions. Annual maximum river discharge series atseven observation sites on Domasi, Mulunguzi, Likangala, Thondwe, Naisi, Namadzi and Phalombe in Lake Chilwa basin for the period 1970 – 2000 were analyzed using L-moments and flood index approach due to unavailability of consistent data for the other years. Discordancy measure (D_i)was used to screen the data for site discordancy at each of the seven sites. Homogeneity of the region was tested using the heterogeneity measure (*H*). Extreme value distributions such as, the Generalized Logistic (GLO), Generalized Extreme Value (GEV), Generalized Normal (GNO), Pearson type III (PE_3) and Generalized Pareto (GPA), were tested to find the most suitable distribution for the region under study. Based on the L-moment ratio diagram and Z^{Dist}statistic, four out of the five distributions can be used in estimating floods in the basin. The study recommends that Generalized Normal (GNO) and Generalized Extreme Value (GEV) are the appropriate distribution models for the Lake Chilwa basin region.

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LIST OF ACRONYMS AND ABBREVIATIONS

AMS	Annual maximum series
amsl	above mean sea level
^{o}C	Degree Celcius
D_i	Discordancy measure
e.g.	Example given
GEV	Generalized Extreme Value
GLO	Generalized Logistic
GNO	Generalized Normal
GPA	Generalized Pareto
H	Heterogeneity measure
ITCZ	Inter - Tropical Convergence Zone
Km	Kilometre
Km^2	Square Kilometre
L-Ck	Linear moment – Coefficient of kurtosis
L-Cs	Linear moment – Coefficient of skewness
L-Cv	Linear moment – Coefficient of variation
L-moment	Linear moment
LmomRFA	Linear moment for regional frequency analysis
LN_3	LogNormal
µ	Mean
m	metre

mm	millimetre
m^3s^{-1}	Cubic metre per second
NSO	National Statistical Office
PE_3	Pearson Type III
POT	Peak over Threshold
PWM	Probability Weighted Moments
$\bar{Q}(F)$	Regional Quantile Estimate
RFA	Regional Frequency Analysis
RFFA	Regional Flood Frequency Analysis
T	Return period
TTC	Teachers' Training College
Z	Goodness offit measure
Z^{Dist}	Goodness of fit distribution

CHAPTER ONE

GENERAL INTRODUCTION

1.0 Background Information

A flood is defined as unusual high stage in a river, normally the level at which the river overflows the banks and submerge the adjoining areas (Seckin *et al*., 2011). Floods can be natural or man-made hazards that cause deaths and damage infrastructure in many parts of the world annually as they occur in rivers and other types of drainage systems. People need protection against flood disasters by preparing protective measures through accurate and reliable quantification of the frequency related to a particular river discharge. Quantification and estimation of flood frequency is also needed for designing and construction of a variety of engineering works in water resources and other water related projects such as hydropower, irrigation and aquaculture (Calder *et al*., 1994). Accurate quantification is also needed for planning disaster risk management, avoiding future conflicts on water or fishery resources and in designing payment for ecosystem services and ecotourism. According to Sarkar *et al*. (2009), in many areas of environmental engineering, estimation of return period of an extreme hydrological event such as floods is a major concern. This is because floods cause so many disruptions which adversely affect disaster response thereby frustrating any intended recovery efforts.

Flood frequency analysis is the estimation of a return period of floods of a specified magnitude (Hosking and Wallis, 1997). In flood frequency analysis, characteristics of the observed flood peak discharge magnitude from a river gauging station are analyzed and a probability distribution is selected to fit the observed data.

Regional analysis consists of analyzing the hydrometric records of all gauged sites in a region by summarizing each record by statistic values calculated from it (Nash and Shaw, 1966). A relationship is then established between calculated values and numerically expressed catchment characteristics for a particular region with reference to a specific return period.

Atiem and Harmancioglu (2006) argue that the basic problem in flood studies is lack of consistent information which can be used for flood frequency analysis. If sufficiently long-term records of river discharge data are available at a site, their frequency distribution can be determined with adequate precision. However, this is not often the case in many parts of Southern Africa including Malawi (Ngongondo *et al*., 2011). At-site flood frequency analysis is thus hampered by insufficient gauging networks and insufficient stream flow data, especially when the interest is in estimating events of greater than 500 years return periods. According to Atiem and Harmancioglu (2006), hydrologists have tried more efficient and robust statistical methods for flood estimation to solve this problem since the true probability distributions of the flood phenomena are hardly known.

Estimation of frequencies of extreme hydrological events such as floods is critical in the design of hydraulic structures, flood plain zoning and economic estimation of flood protection projects (Sarkar *et al*., 2009). However, to make a reliable estimation of such extreme events requires long-term station records if single station data are to be used. Availability and quality of such data are often problematic in many parts of the world, especially in Africa and as a result it becomes a challenge to estimate flood frequency (Ngongondo *et al*., 2011). The Southern Africa region is one such region that is considered vulnerable to and poorly prepared for extreme events such as rainfall, flooding and droughts. Lack of hydro-climatic data at the desired spatial and temporal scales is one of the factors contributing to information gap in this region as far as flood estimation is concerned. According to Ngongondo *et al.* (2011), other factors include lack of research capacity, extensive poverty and political instability.

Regional flood frequency analysis (RFFA) is commonly used to provide information at sites with little or no stream flow data available (Zhang and Hall, 2004). The aim of RFFA is to improve flood estimation at some ungauged sites through the use of information at other gauged sites with long-term record data in a region that is considered homogenous. Hosking and Wallis (1997) regard this method as a way of "trading space for time". Flood estimation is dependent on site characteristics where historical flood data or *a priori* parameter estimates are used to determine future events using the similarity between the change under observation and predictions in changes not observed within a region. The assumption is that spatial relationship between catchment area and stream flow behavior is similar to the one between catchment characteristics and river discharge at a single location when observed over a long period. As a result, a coordinated accurate estimate of stream flow at both gauged and ungauged location in a homogenous region is obtained. Likewise, more accurate information has been obtained through RFFA by using several records from a region with identical behavior of flooding rather than using information from a single site. Through RFFA, probability distribution growth curves which are also known as common growth characteristics for accepted distribution models among sites have been identified (Hosking and Wallis, 1997). These growth curves can be used to determine accurate quantile estimates for individual rivers. Quantile estimates basically form an important class of performance measure such that estimates are typically concerned with providing values that correspond to the conditional mean of observed data or closely related quantities.

In analyzing impacts of extreme hydrological events among basin communities, predicting the future requires a different set of methods compared with analyzing the past (Wall and Marzall, 2006). The goal should be to provide accurate estimates of future occurrences and also facilitate building of resilience to the impacts of these extreme events among vulnerable communities. In this respect, this study focuses at generating information for disaster preparedness and decision making for planning recovery measures in the Lake Chilwa basin.

1.1 Justification for the Study

Tropical cyclones often bring with them extreme rainfall events during the rainy season, which sometimes reach two or three times greater magnitude than in a normal event (von Poschinger *et al*., 1998). The Lake Chilwa basin is therefore a flood prone area due to frequent cyclonic rainfall as well as the special morpholological and geological conditions from the Zomba Mountain Syenite complex (Mylius and von Poschinger, 2000).

Apart from studies by Drayton (1980) and Ngongondo *et al*. (2011), which looked at rainfall distribution, no study on regional flood frequency analysis has been documented in literature for Malawi and specifically in the Lake Chilwa basin, an economically and ecologically important region. In a regional frequency analysis of rainfall extremes in Southern Malawi, Ngongondo, *et al*. (2011) worked out a 20-year return period of the 1991 Phalombe flood. This was vindicated in March, 2011 when extremely high precipitation resulted in a landslide which destroyed property and claimed some lives on the south-western outer slopes of Mulanje Mountain. In the absence of a good river gauging network and long term stream flow data for the Lake Chilwa basin, at-site flood prediction has not been possible whose consequences have been damage to infrastructure, loss of life and property. Thus, using the available river flow data, RFFA can be used to estimate floods for both gauged and ungauged rivers. Uncertainty and lack of knowledge about the future in flood prone areas has been the motivating factor for regional flood frequency analysis in the Lake Chilwa basin. This study will be vital in among others, hydraulic engineering designing, vulnerability assessments, elements-at-risk mapping, planning for recovery measures and rebuilding process in the aftermath of flooding events because it will estimate flood magnitude with reference to specific return periods for decision making.

1.2 Problem Statement

Communities living along river banks and in flood plain areas are most vulnerable to thehydrological extremes such as floods. These communities are not prepared for future flood damages and disruptions which are predictable and inevitable in nature due to lack of information and prediction tools. This lack of foresightedness retards sustainable development of societies once disasters occur due to lack of disaster recovery plan. Floods bring with them so many disruptions such as loss and damage of communication networks, recording instruments and infrastructure among others which adversely affect disaster response thereby frustrating any intended recovery efforts. Thus, floods are one of the worst disasters because when they come they render an area unreachable. Despite the inaccessibility to flood disaster areas, the areas are left with no data on which to base future disaster preparedness since most facilities, data recording and storage equipment are disrupted, damaged or washed away. This phenomenon results is a general lack of information and tools to predict the frequency of the extreme flooding events in flood-prone areasof Malawi (Ngongondo *et al*., 2011). Flood frequency analysisis very critical as the effects of climate change and variability because floods will also occur alongside other environmental change processes. This study will, therefore, improve flood estimation at some poorly gauged and ungauged sites in the Lake Chilwa basinthrough the use of information at other gauged sites with long-term record data to support flood risk management using robust procedures.

1.3 Study Objective

The overall objective of the study is to evaluate river discharge characteristics using robust procedures as a key factor for flood estimation to support flood risk management in the Lake Chilwa basin.

1.3.1 Specific Objectives

Specifically, the study applied RFFA in analysing 1-,3- and 5-day annual maximum river discharge series within the Lake Chilwa basinto:

- Determine the flood homogeneity of the entire Lake Chilwa basin region;
- Develop regional flood index for each identified homogenous region(s) that can be applied in ungauged rivers of the basin;
- Apply the regional flood index in estimating the floods at gauged and ungauged parts of the basin.

1.3.2 Study Hypothesis

Lake Chilwa basin is one homogenous region in terms of river discharge characteristics.

1.4Study Site

This section introduces the Lake Chilwa basin where the study was conducted.

1.4.1 Geology and Physiography of the Lake Chilwa Basin

The geology of Lake Chilwa basin is varied and generally complex. Generally, the base complex is composed of metamorphic rocks derived from sedimentary and igneous rocks of Precambrian origin. The Shire Highlands dominate the topography of the southern region of Malawi while the Lake Chilwa basin dominates the topography of the eastern part of the southern region with major relief features like Zomba and Mulanje mountain massifs which rise to over 2,000 m above mean sea level in the Lake Chilwa catchment area of the Chilwa-Phalombe plain (Ngongondo *et al*., 2011). Zomba town lies at about 900 m on the steep mountain slopes which rise within a short distance to more than 2000 m (Mylius and von Poschinger, 2000).To the south of the region is a low lying flood plain known as the lower Shire valley. The Lake Chilwa basin faces the risk of floods because of its special morphololological and geological conditions from the Zomba Mountain Syenite complex (Mylius and von Poschinger, 2000). The relatively small catchment area of rivers in Zomba is said to be another contributing factor to flood risk. Small catchment areas have a short time of concentration which is the time taken for water to flow from any point in the catchment to the outlet. Other factors that affect time of concentration include topography, shape of catchment and land cover and slope. On the contrary, Michesi Mountain in Phalombe geologically belongs to group of rocks called the Chilwa Alkaline Province which consists of syeno-granitic and nepheline-syenite plutons. These plutonic rocks are partly classified as oversaturated alkaline rocks and pose a serious risk of floods as they are a large mass of intrusive igneous rock believed to have solidified deep within the earth.

1.4.2Climate and Rainfall in the Lake Chilwa Basin

According to the British Geological Survey (2004), the climate of Lake Chilwa basin is tropical wet and dry, commonly known as Savanna. The main rain bearing system is the Inter-Tropical Convergence Zone (ITCZ), where the north easterly monsoon and south easterly trade winds converge. A distinct rainy season is experienced between November and April when over 80% of the annual rainfall occurs. Tropical cyclones originating from the Indian Ocean frequently occur during the rainy season bringing very intense rainfall over few days. Annual rainfall varies from 700 mm in the low lying areas to 2,500 mm in highlands of Phalombe - Mulanje and Zomba(British Geological Survey, 2004). There is considerable sporadic winter rainfall locally called *chiperone* in the highlands during the period from May to August. The winter rains originate from an influx of cool moist south-eastern winds. Monthly average temperatures are around 10 – 16^{O}C in the highlands and 21–30^{O}C along the lower Shire valley (British Geological Survey, 2004).

The onset of climate change and its predicted impacts on river flow and flooding is expected to further increase flood risk to Lake Chilwa basin communities. There is little doubt that modifications to temperature and precipitation regimes due to climate change will affect the hydrological cycle and various water usages at the watershed scale in the basin. This is because basins where rainfall constitutes the major proportion of the stream flow, studies have shown that regional temperature increases would affect river discharge in a particular season (Roy, 2001). A change in flood magnitude, either through intensification or reduction, is thus expected, depending on the combined effects of changes in precipitation quantities and increased off-season rains. Different climate models predict different outcomes and these predicted changes are likely to have different impacts on the hydrological cycle (Ingold *et al.*, 2010). The predicted changes in turn will affect level of precipitation and soil moisture content and subsequently increase occurrence of weather-related events like floods and cyclones. The Lake Chilwa basin is an ideal place to study regional flood frequency analysis considering the extreme hydrological events that have been already been experienced and expected in future.

1.4.3Hydrology and Water resources in the Lake Chilwa Basin

Lake Chilwa (Figure 1) lies 50 km east of the southern end of the western rift valley at an altitude of approximately 622 m above sea level. When at its highest level, it is 40km long (North – South) and 30 km wide (East – West). It is estimated that 70% of the inflow comes from the Shire Highlands including Zomba Mountain through Likangala, Namadzi, Thondwe, Domasi, Phalombe, Sombani and Naisi Rivers (Figure 1). From Mozambican side, Mnembo River flows into Lake Chilwa. The Lake Chilwa wetland is about 1850 km^2 in size with one third occupied by open water, one third by marshes and swamps and one third by flood plain.

There are different hypotheses from early studies concerning Lake Chilwa. For example, according to Lancaster (1979), the lake is endorheic and this state occurred in the last 15,000 years. Lake Chilwa which does not lie in the Rift Valley is separated from Lake Malawi and the Shire river drainages by a narrow watershed. Geologic evidence shows that during the late Pleistocene, Lake Chilwa was connected to Lake Chiuta and the

Lugenda River which drains into the Indian Ocean (Lancaster, 1979). The Lake Chilwa basin dates back to the cretaceous period and its formation are similar to that of Lake Victoria.

Another hypothesis is that the Lake Chilwa area forms part of a depression due to late warping, along a north-north-easterly line through Lake Chilwa and the Lugenda River, in the well-planed mid-tertiary surface forming the widespread plain surrounding Mulanje Mountain (Garson and Walshaw, 1969).

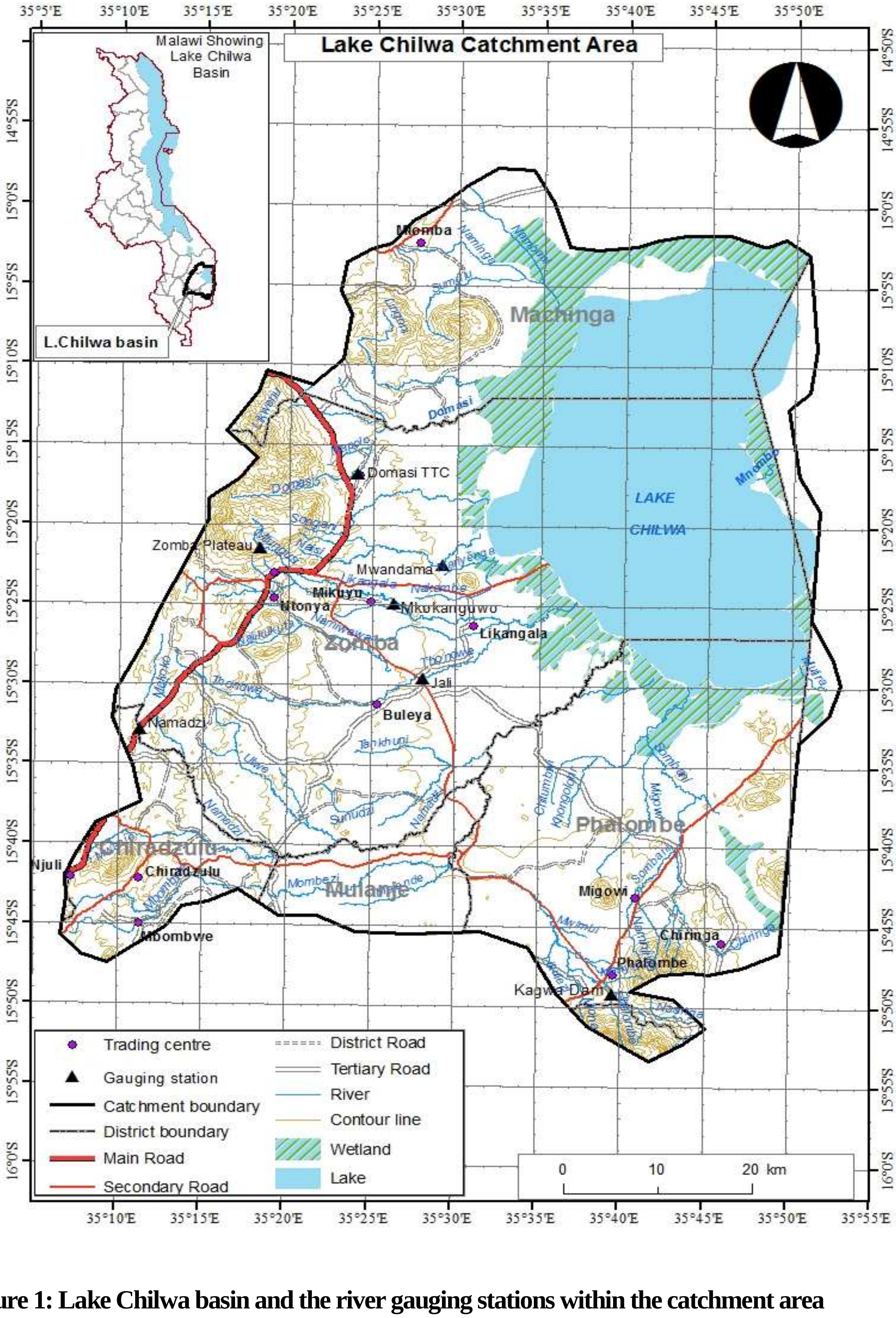

Figure 1: Lake Chilwa basin and the river gauging stations within the catchment area

The plateaux on Chisi Island and Chikala Mountain, and the summit level of Mpyupyu Hill presumably are remnants of a surface ascribed to the late-Cretaceous at about 105 – 1, 220 metres above sea level. According to Garson and Walshaw (1969), if it is accepted that the Chilwa Alkaline Province was initiated by warping, there is therefore the possibility that, in early Cretaceous times an elongatecymatogenic arch occupied the area between the present Lower Shire Valley and the southern part of Lake Malawi and the Chilwa depression. At that time, the Lake Malawi and Chilwa depressions would have been continuous, and separated from the Lower Shire/Zambezi basin by highlands that occupied the sites of the present Shire Highlands and Middle Shire Valley. Drainage to the north of the arch may have flowed into the Malawi/Chilwa basin and then direct to the coast in the surrounding area of Quelimane (in Mozambique) while southern drainage would have flowed into the Lower Shire Valley then into the Zambezi (Garson and Walshaw, 1969). Thus, there would have been two north-east trending depressions some separated by a highland divide. It is thus suggested, although the evidence is scanty and largely circumstantial, that the Plio-Pleistocene rifting, although broadly coincident with the areas of post-Gondwana warping, was not confined to the original depressions(Garson and Walshaw, 1969). The Lake Chilwa depression was thus separated by a fault scarp, trending almost at right angles to the Thyolo fault, from the down dropped Lake Malawi and Upper Shire. This may have brought a drastic change in the Lake Malawi outlet which cut a new channel, the rocky Middle Shire section, into the old-established Lower Shire Valley (Garson and Walshaw, 1969).

The other thesis being put forward is that in Lower Cretaceous times the Middle Shire Valley did not exist but was an area of high ground, continuous to the north-west and south-east and separating the present day Lower Shire from the upper which was an inlet channel into the Lake Malawi - Chilwa basin, reaching its mature stage of development in Miocene times. It is being suggested that before rifting, Lake Malawi drained through Chilwa into the Ruo system and then into the Lower Shire but the youthful nature of the Ruo valley makes this unlikely (Garson and Walshaw, 1969).

1.4.4 Land use and Vegetation in the Lake Chilwa Basin

The distribution of human settlements in the Chilwa basin is greatly influenced by the extent of water during the wet season (Mwafongo, 1996). Most settlements are located on dry sites provided by relief features such as sandpits or beach bars, levees of river channels and deltaic streams, and along road sides. Settlements and smallholder farms present an inefficient form of land use in the basin while numerous unutilized pockets of customary land exist in between cultivated patches.

Agricultural production in the Lake Chilwa basin can be divided into cultivation of crops and livestock grazing. The wetland area around the Lake Chilwa is ecologically suitable for specialized crops such as maize, sorghum, rice, vegetables and livestock grazing among others (Mwafongo, 1996). Most of the land under cultivation in the study area falls under customary land.

The Lake Chilwa basin offers a diversity of vegetation in the dry land such as *miombo* and *mopane* woodlands which are of special interest to humans, birds and various types of vertebrate and invertebrate animals. Vegetation is a source of livelihood to many people in the basin but also makes up an essential element of the habitat in providing food and shelter alongside soil enrichment. *Typhadomingensis* dominate in the swampy areas around Lake Chilwa (Schuijt, 2002).

1.4.5 Population of the Chilwa Catchment

The Lake Chilwa basin has a total population of about 1.7 million people (NSO, 2008). The corresponding intercensal annual growth rates for Machinga, Zomba, Chiradzulu and Phalombe for the 1997 – 2008 period were 2.9%, 2.45%, 2.1% and 3.1% respectively. The demographic statistics show that population density for Machinga district changed from 98 to 130 persons per km^2 between 1998 and 2008, while the corresponding figures for Zomba, Chiradzulu and Phalombe are 392 to 260; 308 to 379; and 166 to 225 respectively. The population in the four districts is predominantly rural.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Majority of poor people in the world live in less developed countries and their livelihoods are much dependent on climate-sensitive natural resources such as local water supplies and agricultural land, fuel wood, wild herbs and other ecosystem services (Ingold *et al.*, 2010). Floods can drastically reduce the availability of services that these local natural ecosystems provide and limit the options for rural households that depend on these resources for consumption or trade.

River basins offer the preferred land surface units for hydrological studies because their drainage areas represent natural spatial integrators of water (Palamuleni, 2009). Indirectly, forest clearance has influenced flooding and river drying. According to Mylius and von Poschinger (2000), dense vegetation used to cover most parts of the stream source in Zomba – Malosa Mountain forest but this is no longer the case due to increased exploitation of forest resource for domestic and industrial use. For example, indigenous fire resistant trees used to grow along most of the rivers in the Lake Chilwa basin in Malawi which gave stability and ability to absorb rain water (Mylius and von Poschinger, 2000). Replacement of the natural forests by Mexican pines in the Zomba Mountain forest catchment area since 1907 has considerably affected slope stability during the rainy season when tropical cyclones produce very high rainfall intensities. During such times the liquid limit of the soil is beyond infiltration of rainwater which drains into the rivers as surface run-off and consequently results in floods (Mylius and von Poschinger, 2000).

2.2 Floods and their Impacts

The increasing global temperature is likely to influence the global hydrologic cycle and as a result, agriculture and allied activities such as fisheries are likely to be hit most by hydrologic extreme incidences such as floods. Floods affect social, economic and ecological aspects of the landscape and subsequently affect the livelihood options of people especially the rural poor (Ingold *et al.*, 2010).

Developing and implementing adaptation strategies for impacts of extreme hydrological events such as floods is obligatory through specific formal international agreements (for example, the United Nations Framework Convention for Climate Change of 2007). However, adaptation research, policy and programmes necessary for encouraging adaptation have been disregarded, despite the growing awareness that many regions are becoming increasingly vulnerable to floods (Wall and Marzall, 2006). This disregard in term of flood disaster preparedness is evident in the flood plain of Lake Chilwa basin among vulnerable communities where this study has been carried out.

In Malawi, about 80 percent of the annual precipitation is restricted to the rainy season which lasts from November to March/April (Ngongondo, 2006). During this period, the Inter Tropical Convergence Zone (ITCZ) passes twice over Malawi. In the southern part of Malawi, the short time interval between the two passages of the ITCZ results in only one rainy season while in the northern part of Malawi the rainy season is split into two. Gondwe and Govati (1992) and von Poschinger *et al.* (1998), pointed out that the main triggering factor for flooding events in Malawi is high rainfall intensity. Although most models for the Southern Africa region predict a drier climate, Ingold *et al.* (2010), suggest that some parts of the world will generally experience a local increase in heavy rainfall with accompanying floods. There is a probability that some areas of Malawi will experience prolonged wet conditions while others will experience long dry spells during rainy seasons as observed by Ngongondo *et al*. (2014), through simulated changes in the water balance over Malawi during 1971 – 2000 period. This means that Malawi is getting drier although intense rainfall events associated with floods are getting more frequent and intense. Such a situation would certainly influence flooding while other rivers will experience little or no flow. Both scenarios will occur with attendant environmental changes. Nonetheless, recent studies on floods in Southern Africa (e.g. Ngongondo *et al*. 2013; Ngongondo *et al*. 2011; Kjeldsen *et al*. 2002) suggest an increase in future flooding.

The Lake Chilwa basin has been a centre of several studies in the run up to declaring Lake Chilwa a Ramsar site (Schuijt, 2002). General circulation models for the Lake Chilwa basin suggest that the continued emission of greenhouse gases into the atmosphere will lead to an increase in temperature by 2.6 - 4.7^{o}C by the year 2075, whereas rainfall will continue to show variability with both floods and droughts being experienced in the basin (Chavula and Chirwa, 1998). While some of the previous research activities have been carried out with a view to determining the impact of lake level changes on the biological productivity of Lake Chilwa, and describing the geological history of the lake, those studies did not determine the nature of river discharge within the basin for flood estimation. Previous studies on water resources assessment (e.g. Delamore, 1987), either used crude data in form of average rainfall to determine the availability of water resources in the catchment area to evaluate the water balance equation (Chavula and Chirwa, 1998). However, RFFA has the advantage of using recorded data from various river gauging stations to estimate floods for both gauged and ungauged rivers with better accuracy.

2.3Basis and Justification for Regional Flood Frequency Analysis

In hydrological and hydraulic engineering applications, maximum discharge and its frequency are indispensable for flood risk assessment, water resources management, design of hydraulic structures such as dams, spillways, highway and railway bridges and culverts, design of urban drainage systems and flood plain zoning (Seckin *et al*., 2011). All these aspects are necessary for economic evaluation of flood protection projects. Such being the case, stream flow records at or near the site of interest are critical for hydrologists to derive reliable flood estimates directly. Accurate estimation is of utmost importance in these engineering works to avoid problems associated with crude estimates (Seckin *et al*., 2011). This is because overestimation of flood magnitudes may cause excessive costing of the hydraulic structures while their underestimation may result in high flood damage costs and even loss of human lives. Regional flood frequency analysis (RFFA) involves identification of homogeneous regions, selection of suitable regional frequency distributions and estimation of flood quantiles at sites of interest (Dalrymple, 1960; Hosking and Wallis, 1997). This is achieved by using data from several sites which are judged to follow the same probability distribution as a way of trading space for time. Regional frequency analysis has also been used to understand rainfall distribution. An important stage in regional frequency analysis is the demarcation of homogeneous region.

2.4 Regional Frequency Analysis Methods

Regional frequency analysis is generally a process of providing information at sites with little or no data and this data can be temperature data, rainfall data or stream flow data. Consequently, regional flood frequency analysis (RFFA) is commonly used in flood estimation to provide information at sites with little or no stream flow data available (Zhang and Hall, 2004). The aim of RFFA is to improve flood estimation at some ungauged sites through the use of information at other gauged sites with long term record data in a region that is considered homogenous.

Regionalization methods can be broadly classified as those used for prediction in data scarce areas and those used for forecasting (Chen *et al.*, 2006;Sivapalan*et al.*,2003; Hosking and Wallis, 1997). Regional frequency analysis (RFA)studies on rainfall in Southern Africa (Jackson,1972) used the spatial correlation by applying simple linkage analysis on rainfall data collected between 1930 and 1960 from 30 stations in Tanzania. In another study, Parida and Moalafhi (2008) used L-moments to analyse annual rainfall series for 11 stations in Botswana for the period 1960–2003 and established that the whole of Botswana behaved homogeneously and the Generalized Extreme Value (GEV) distribution was accepted as the best model for the data. Similarly, Kjeldsen *et al*. (2002), conducted a regional frequency analysis of annual maximum series (AMS) of flood flows from relatively unregulated rivers in the KwaZulu-Natal province of South Africa including identification of two homogeneous regions and suitable regional frequency distributions based on an index of monthly rainfall concentration. In Malawi, Drayton (1980) analysed 1-day annual maximum rainfall from 38 stations across Malawi using the Gumbel (Extreme Value I) distribution to derive estimates of point daily rainfall with reference to 20 and 50 years return period. This study is usually referred to as a basis to regional frequency analysis in Malawi which focused on rainfall. Ngongondo *et al*. (2011), analyzed 1-,3-, 5- and 7-day annual maximum rainfall series for the period between 1978 and 2008 at 23 selected rainfall stations in Southern Malawi using rainfall index and L-moments and came up with three rainfall regions or groups for Southern Malawi. This study focuses on flood estimation on gauged and ungauged rivers using regional flood frequency analysis.

Cunnane (1988) focused on several methods for the identification of homogenous regions, including the choice of acceptable distribution, appropriate parameter estimation by probability weighted moments (PWM) which was suggested by Greenwood *et al*. (1979), and quantile estimation which is robust and less biased for small samples. An index flood procedure by Hosking and Wallis (1993), assumed that the flood distributions at all sites within a homogenous region are identical except for index flood parameter and hence used L-moments to undertake regional flood frequency analysis.

L-moments have been used progressively more by hydrologists and many studies have been undertaken on the extreme flow or flood frequency using L-moments. For example, Parida *et al*. (1998), studied regional flood frequency analysis for Mahi-Sabarmati basin in India using L-moments and flood index and found that the three parameter logNormal distribution (LN_3) is an appropriate distribution for modeling floods in this basin. Similarly, Kumar *et al*. (2003), carried out a regional flood frequency analysis for the Middle Ganga Plains sub-zone in India using the L-moment ratio diagram and the goodness-of-fit test and concluded that the Generalized Extreme Value (GEV) distribution is a robust distribution for the study area. Lim and Lye (2003), used an index flood estimation procedure based on L-moments and found that the GEV and Generalized Logistic (GLO) distributions were appropriate for the distribution of extreme flood events in the Sarawak region of Malaysia. Likewise, using the flood index and L-moments, Atiem and Harmancioglu (2006), studied 14 gauging stations on the Nile River tributaries (Blue Nile, White Nile, and Atbara River) and grouped them into three regions to identify and establish the regional statistical distribution. This signifies that different appropriate distributions are determined by locality and available data set.

L-moments are analogous to the theory of conventional moments. L-moments have theoretical advantages over conventional moments because of being able to characterize a wider range of distributions (Hosking, 1990). When estimated from a sample, L-moments are more robust to the presence of outliers in the data. Compared with conventional moments, L-moments are less bias in estimation and approximate their asymptotic normal distribution more accurately in small samples. Parameter estimates obtained from

L-moments are sometimes more accurate in small samples than even the maximum likelihood estimates.

L-moments can be defined for any random variable whose mean exists and forms the basis of a general theory which covers the summarization and description of theoretical probability distributions, summary and description of observed data samples, estimate of parameters and quantiles of probability distributions, and hypothesis tests for probability distributions (Hosking, 1990). Thus, L-moments summarize the basic properties such as location, scale, skewness, kurtosis of a data set. The main advantage of L-moments over conventional moments is that L-moments, being linear functions of data, defy the effects of sampling variability. L-moments, therefore, enable more secure and accurate inferences to be made from small samples about an underlying probability distribution.

Hosking and Wallis (1993) suggested an index flood procedure by assuming that the flood distributions at all sites within a homogeneous region are identical except for a scale or index-flood parameter and using L-moments to undertake regional flood frequency analysis. One of the commonly used regional flood frequency procedures is the United States Geological Survey index flood method proposed by Dalrymple (1960). Traditional at-site estimation of design flood considers only the data available from the specific site under consideration and the reliability of the estimate is directly related to the length of series available for analysis. On the other hand, regional frequency analysis methods, such as the index flood method, include information from nearby stations exhibiting similar statistical behaviour as at the site under consideration in order to obtain more reliable estimates (Kjeldsen *et al*., 2002). Index flood procedures yield suitably robust and accurate quantile estimates. These regional methods can also be used to obtain estimates at ungauged sites, which are important in countries such as Malawi, where the flow gauging network density is poor.

2.5 Conclusion

The literature review has explored regional frequency analysis methods especially those that have been applied to rainfall distribution and flooding events worldwide and specifically in the Southern African region. The search has discovered that L-moments have been used in many RFA studies due to their ability to summarize the basic properties such as location, scale, skewness, kurtosis of data set. L-moments as linear functions of data defy effects of sampling variability and are more robust to outliers in the data while enabling accurate inferences to be made from small samples about an underlying probability distribution. The review has also managed to identify already tested probability distribution models applicable to various homogenous regions identified through RFA.

An index flood procedure assumes that the flood distribution at all sites within a homogenous region are identical and are used with L-moments to undertake regional flood frequency analysis. While RFA has been used in rainfall studies in Malawi, they have never been used in flood estimation and this study will apply regional flood frequency analysis in the Lake Chilwa basin to estimate future floods with reference to specific return periods using river flow data.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

Regional frequency analysis procedure used in this study followed same procedure that was used by Ngongondo *et al*. (2011) among many other studies. This includes procedure used to determine the possible number of regions and the four steps in RFA using the L-moments approach which include discordancy measure; heterogeneity test; distribution selection; and derivation of regional flood index. Regionalization methods and procedures were selected as they can ably deal with data scarce situations and have demonstrated considerable robustness in flood prediction in many parts of the world. Flood prediction or understanding of hydrological extremes in regions recommends the use of data from many stations instead of single stations analyses.

3.2Data Availability

For regionalization, secondary river discharge data measured in cubic metres per second (m^3s^{-1}) from year 1970 up to 2000 recorded from various river gauging stations has been used in this study. The study is spanning over this period to capture river discharge tendencies due to availability of consistent data over this period. The study analyzed annual maximum series (AMS) for 1, 3 and 5 days of river discharge derived from daily readingsat seven (7) river gauging stations in the Lake Chilwa basin. The stations are

Domasiat Teachers' Training College, Mulunguzi at Zomba plateau, Likangala at Mkokanguwo, Thondwe at Jali, Namadzi at Namadzi, Phalombe at Kagwa dam and Naisi at Mwandama. AMS 1, 3 and 5 days were chosen simply because floods have generally short duration with varying magnitude.AMS model replaces the hydrograph for each year by its largest flood. Due to the reason that AMS replaces the hydrograph in any year with a discrete value, a distortion of the return period scale is introduced (Langbein, 1949). As a result, one feature of theAMS model is that time scale is measured in years as a discrete unit and therefore part-years are not recommended. The river discharge data were sourced from the Department of Water Resources in Malawi. Although data from Naisi and Phalombe River gauging stations had gaps, none had a record less than 9 years. It is the insufficient data coverage over the years and scarcity of data due to limited river gauging stations in a catchment area of 8,350 km^2 which calls for RFFA in the Lake Chilwa basin.

Apart from AMS model, peak over threshold (POT) can also be applied in this study. AMS of river discharge were chosen mainly to preserve the number of stations and station years available since some sites had missing values for considerable time periods. Previous studies have shown that threshold selection is a key problem for peak over threshold (POT) analysis and is said to be subjective in many cases. Such being the case, POT analysis could not be applied in this study as it requires a common period of analysis which would imply a reduction in the available number of stations and station years (Ngongondo *et al*., 2011; Ngongondo *et al*., 2013). Filling of missing values was considered impractical in this study because of the perceived low spatial correlations among stations in this sparsely gauged region. The AMS procedure used in this study was deemed feasible as it was not supposed to satisfy any of the POT analysis conditions.

3.3 Regional Flood Frequency Analysis

Ward's hierarchical unsupervised technique was applied to identify homogeneous regions. This technique was chosen owing to its successful application in other regionalization studies done in areas with few gauged stations like Lake Chilwa basin (e.g. Hosking and Wallis, 1997; Ward, 1963). The L-moments algorithm (Hosking and Wallis, 1997) was used for the RFA. This is because L-moments have shown to be more robust for both large and small samples.

3.4 Discordancy Measure (D*i*)

The discordancy measure (D_i) is used to screen data within the identified homogenous region(s) (Hosking and Wallis 1997). The L-moment ratios of a group of sites in a potentially homogenous region are expected to form a cluster of close points. Discordancy measure (D_i) is defined as:

$$D_i = \frac{1}{3}\left(u_i - \bar{u}\right)^T s^{-1}\left(u_i - \bar{u}\right) \qquad (1)$$

Where, $\mathbf{u_i}$is the vector of L-Cv, L-Cs, L-Ck for the site *i*, S is the covariance matrix of$\mathbf{u_i}$and $\bar{\mathbf{u}}$ is the mean of the vector $\mathbf{u_i}$.

If D_i is greater than the critical value of the discordancy statistic given in a table formed by Hosking and Wallis (1997), the site *i* is declared to be discordant and it is excluded from further analyses of regionalization. Stations in a homogenous region having either gross error in their data or not belonging to the region, will have $D_i \geq 3$. The case of gross errors in the data requires careful scrutiny of the data. If gross errors are not detected in the data, but $D_i \geq 3$, it is recommended to relocate such stations to other regions/groups or exclude from further analyses (Hosking and Wallis, 1997; Seckin *et al*., 2011). Details of the discordancy measure are described in details by Hosking and Wallis (1997).

3.5 Heterogeneity Measure

Heterogeneity measure (*H)*, is used for identification of a potentially homogenous region based on observed and simulated dispersion of L-moments for a group of sites in the region (Hosking and Wallis, 1997) and is defined as:

$$H = \frac{V - \mu_V}{\sigma_V} \qquad (2)$$

Where, **V** is the weighted standard deviation of L-coefficient of variation values, and μ_V, σ_V are the mean and standard deviation of a number of simulations of V respectively.

The heterogeneity measures H_n (n=1, 2, 3) are used to verify whether the proposed sites make up a spatially homogeneous region with the same underlying distribution apart from a site-specific scale factor (Hosking and Wallis, 1997). The check is based on observed and simulated dispersion of L-moments for a group of sites under consideration.

A region is considered 'acceptably homogenous' if $H_n<1$; 'possibly heterogeneous' if $1<H_n< 2$; and 'definitely heterogeneous' if $H_n \geq 2$.

A large positive value of H_1 indicates that the observed L-moments are more dispersed than what is consistent with the hypothesis of homogeneity. H_2 indicates whether the at-site and regional estimates are close to each other. A large value of H_2 indicates a large deviation between regional and at-site estimates. H_3 indicates whether the at-site and the regional estimates agree. Large values of H_3 suggest a large deviation between at-site estimates and observed data. Computation details for the calculation of H_n are given in Hosking and Wallis (1997).

3.6 Distribution Selection for Homogenous Region

The best fitting distributions for each homogeneous region can be identified in different ways: visually on the L-moment ratio diagram, a plot of sample L-skewness (t_3) versus L-kurtosis (t_4) where the best distribution fits evenly through points; the goodness of fit measure $|Z^{Dist}| \leq 1.64$; and the difference between sample kurtosis and distribution kurtosis ($|t_{4(sample} - t_{4(DIST}|$), which should be the minimum. Acceptable distribution is the one satisfying the criteria $Z \leq |1.64|$ whereas the best distribution is the one which satisfies the criteria min $Z_{Crit}^{Dist} \leq |1.64|$ among the acceptable distributions. Hosking and Wallis (1997) presented details for the calculation of the $|Z^{Dist}|$ statistics.

Five commonly applied probability distributions which are the Generalized Logistic (GLO), Generalized Extreme Value (GEV), Generalized Normal (GNO), Generalized

Pareto (GPA) and Pearson type III (PE_3) were tested in this study. The parameters of each distribution were estimated using the method of L- moments and were fitted to the annual maximum stream flow series. The theory of statistical probability distribution, often provides a basis for flood frequency analysis and developing the engineering prediction.

3.7 Derivation of Regional Flood Index for the Identified Regions

River discharge quantiles of the best frequency distribution were derived for the region using the index flood method which was first introduced for floods by Dalrymple (1960). The procedure assumes that the frequency distributions of all sites in a homogenous region are identical, except for a site-specific scale factor. The quantile estimates Q̧̄(F) with non-exceedance probability F, at a site in a region with N sites is then computed by: $Q_i(F) = l_1 q(F)$; where q is a common dimensionless quantile function (growth curve) and l_1 is a site specific scaling factor, also called the index river discharge value, representing the T-year quantile of the normalized regional distribution. In this study, the median was used as the site specific scale factor at a given location for all stations except Kagwa Dam (Phalombe) and Mwandama (Naisi) because the two stations had a lot of gaps in their data and calculated median yielded zeros. In the two cases, mean (μ) was used as the at-site scale factor. At-site AMS1, AMS3, and AMS5 values with return periods T years were estimated from the regional quantiles.

The quantile estimates for the Lake Chilwa basin region were used to estimate at-site flood magnitudes for various return periodsat the gauged rivers within this region. This was achieved by multiplying the quantile estimate with the median river discharge or mean river discharge in the case of Phalombe and Naisi.

At-site mean river discharge of the ungauged rivers was estimated using the ratio of the individual river's catchment area to the catchment area of the nearest gauged stations multiplied by the median discharge of the gauged river.

For all the procedures presented above, various packages and macros of the free statistical software R were used (R Development Core Team, 2008). The L-moments approach used the package lmomRFA (http://cran.r-project.org/web/ packages/lmomRFA/index.html) by Hosking (2009) in R Software (R Development Core Team, 2008).

3.8Research Design

Quasi-experiment was used in this study. A quasi-experimental design is more or less an experimental design but lacks the key ingredient which is random assignment. There is something compelling about these designs because taken as a group, they are easily more frequently implemented than true experiments. The results from this type of study are still compelling because their ecological validity is very strong (Trochim, 2004).

3.9Study Limitation

Since quasi-experimental research design was used, the results may often appear not to have a strong internal validity and be considered inferior to randomized experiments. This is so because the study has certain elements of experimental design but do not fulfill all the internal validity requirements. As a natural experiment it was invariably not possible to randomly assign subjects to experimental and control groups. The absence of random assignment in the research weakens the study's internal validity.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Determination of Flood Homogeneity for the Region

The first specific objective of this study was to determine the flood homogeneity of the entire Lake Chilwa basin region.

4.1.1 Identification of Homogenous Regions

Lake Chilwa basin was firstly treated as one large homogeneous group. The supposedly large homogenous region was then tested using the discordancy measure (D_i) and the heterogeneity measures (H_1, H_2 and H_3). The basin passed the discordancy test since all stations had $D_i < 3$ which was the critical value. This means that the data did not have gross errors and all stations could be used in further analyses. The heterogeneity values for the Lake Chilwa basin were:

$H_1 = 0.75$, $H_2 = 1.72$, $H_3 = 2.43$. The region should therefore be considered as acceptably homogeneous since $H_1 \leq 1$ and did not warrant further clustering. In this case the hypothesis that the Lake Chilwa basin is one large homogenous area is accepted. H_1 is the primary measure for the heterogeneity test as both H_2 and H_3 rarely yield values larger than 2 even for grossly heterogeneous regions (Hosking and Wallis 1997). The results, therefore, show that the observed L-moments are not dispersed than what is consistent with the hypothesis of homogeneity. The selected Lake Chilwa basin region extending over an area of about 7,745 km^2 is gauged at 7 bridge sites with catchment areas ranging from 4 to 446 km^2. LCv, LCs and LCk values computed using data from gauged stations have been presented in Table 1. Discordancy (*Di*) computed using Equation (1) has been found to be 1.70 (which is less than 3.0), suggesting that no site is discordant. Based on simulations obtained from observed and 500 sets of simulated data, the heterogeneity (H) measure was computed and yieldedobserved standard deviation (s.d.) of group LCv = 0.1450; Simulated mean of s.d. of group LCv = 0.0745; Simulated standard deviation of s.d. of group LCv = 0.0231 came out to be H_1 = 0.75. Since the heterogeneity measure is less than 1.0, the region under study is therefore acceptably homogeneous.

Table 1: Summary statistics for annual maximum flow for the seven stations

River	**Station name**	**Catchment Area (Km^2)**	***N***	**Median flood (m^3s^{-1})**	**Average flood (m^3s^{-1})**	**LC_V (*t*)**	**LC_S (t_3)**	**LC_K (t_4)**	**D_i**
Mulunguzi	Zomba Plateau	18.1	31	15.16	20.05	0.5649	0.3059	0.2480	0.64
Domasi	Domasi TTC	72.8	31	20	50.73	0.6625	0.4064	0.2491	0.44
Likangala	Mkokanguwo	144	31	22.52	40.76	0.5365	0.4317	0.3538	1.10
Thondwe	Jali	302	31	15.20	34.55	0.5417	0.1538	0.0703	0.21
Namadzi	Namadzi	26.6	31	0.51	0.62	0.3014	0.1409	0.0554	1.44
Phalombe	Kagwa Dam	55.8	13	-	0.13	0.6634	-0.0693	-0.0871	1.70
Naisi	Mwandama	75	9	-	8.06	0.9198	0.6445	0.4373	1.46
					Weighted means	0.5521	0.2797	0.1869	

n is the record length

4.1.2 Assessment of Hydrological Extremes

The overall average for AMS1, AMS3 and AMS5 were 22.1, 16.4 and 20.3 m^3s^{-1}, respectively for the seven (7) gauged rivers. The highest mean AMS1-AMS5 river discharge during the period was 50.7, 40.8, 34.6 and 20.0 m^3s^{-1} recorded in Domasi, Likangala, Thondwe and Mulunguzi rivers respectively. These rivers have their catchment areas located in the Zomba – Malosa Mountains which has the highest average annual rainfall ranging between 1500 mm and 2,500 mm (British Geological Survey, 2004). The results show that Domasi, Likangala, Thondwe and Mulunguzi have a high propensity to flooding compared to the other observed gauged rivers. Though these rivers stretch from a high rainfall forest catchment area, they pass through different land covers and land uses such as agricultural land which may influence their behavior through the river developmental stages.

4.1.3 Goodness-of-fit Measure (Z)

Goodness-of-fit values (Z) were computed for five (5) candidate distributions such as Generalized Logistic (GLO), Generalized Extreme Value (GEV), Generalized Normal (GNO), Pearson Type III (PE_3) and Generalized Pareto (GPA). Results showed that 4 distributions namely; GLO, GEV, GNO and PE_3 distributions satisfied the criteria of being a possible candidate for having Z values less than |1.64|. Goodness-of-fit (Z) test results for candidate distribution in the region have been worked out (Table 2).Amongst the 4 candidate distributions, GNO (-0.15) and GEV (0.34) distributionsare acceptable as the best fitting distributions because the two distributions have the least Z value. As such, GNO being the best fit distribution has values of location, scale and shape parameters respectively as ε = 0.7301, α = 0.8489 and k = -0.5833; while GEV is presented as ε = 0.4865, α = 0.6679 and k = -0.1639.

Table 2: Values of Goodness of fit measure for different distributions

No.	Distribution	Z value	$\lvert Z^{Dist} \rvert$
1	Generalized Logistic (GLO)	1.1	1.1
2	Generalized Extreme Value (GEV)	0.34	0.34
3	Generalized Normal (GNO)	-0.15	0.15
4	Pearson Type III (PE3)	-1.03	1.03
5	Generalized Pareto	-1.67	1.67[a]

[a] Value of |Z DIST| that exceeds 1.64

L-moment ratio diagram showing the location of regional average L-Cs and L-Ck and their theoretical relationships with the different candidate distributions, is displayed (Figure 2) for the Lake Chilwa basin region. The L-moment ratio plot showing the location of regional average L-Cs and L-Ck have therefore been used to verify appropriate distribution which is closer to the regional average value. The L-moment ratio diagram confirms that Generalized Normal (GNO) and GEV are the appropriate regional distributions for all rivers in the Lake Chilwa basin region. The GNO and GEV distributions have been observed to be close to the regional weighted L- moment mean. Thus, it can be concluded that GNO and GEV are the distributions that best explain river discharge characteristics in the Lake Chilwa basin.

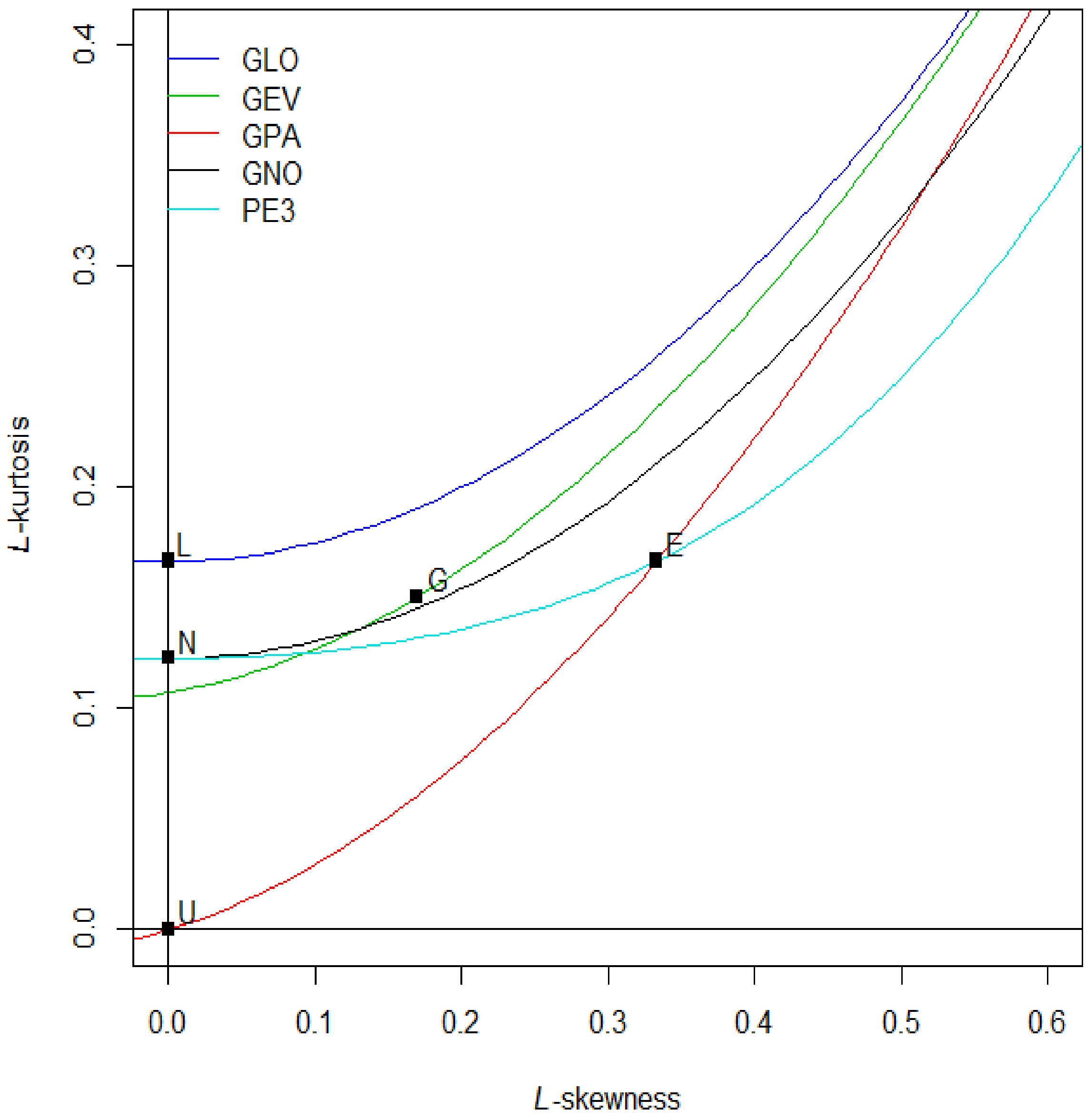

Figure 2: L-moment ratio diagram for the candidate distributions in the Lake Chilwa basin region

4.2 Development of Regional Flood Index for Identified Homogenous Region

The second specific objective of the study was to develop regional flood index for the identified homogenous region that can be applied in ungauged rivers of the basin.

4.2.1 Estimation of Regional Quantiles

The regional quantile estimates $\bar{Q}(F)$ with non-exceedance probability *F* for acceptable distributions are given in Table 3. Values for regional floods index have been computed from these regional quantiles with return periods T = 2, 5, 10, 20, 50, 100, 500 and 1000 years. The quantile estimates for the four distributions are almost identical at*F* (0.5), *F* (0.8)and *F* (0.9) which has reference to 2, 5 and 10 years return period respectively. Generally, the quantile estimates are not far apart as non-exceedance probability (*F*) progresses from 0.05 to 0.99 with reference return period spanning between 2and 500 years.

The growth curves for GLO, GEV, GNO and PE_3 using regional quantile estimates are presented in Figure 3. It has been observed that the growth curves pattern for the GLO, GEV and GNO distributions follow the same pattern and are almost identical up until 500 years return period. PE_3 seem to show large uncertainty.

Table 3: Quantile estimates with non exceedance probability F

Distribution	*F*						
	0.5	0.8	0.9	0.95	0.98	0.99	0.999
GLO	0.756	1.575	2.224	2.967	4.162	5.279	10.962
GEV	0.739	1.622	2.304	3.042	4.136	5.073	9.053
GNO	0.730	1.653	2.348	3.074	4.097	4.928	8.101
PE_3	0.717	1.707	2.414	3.103	3.996	4.664	6.848

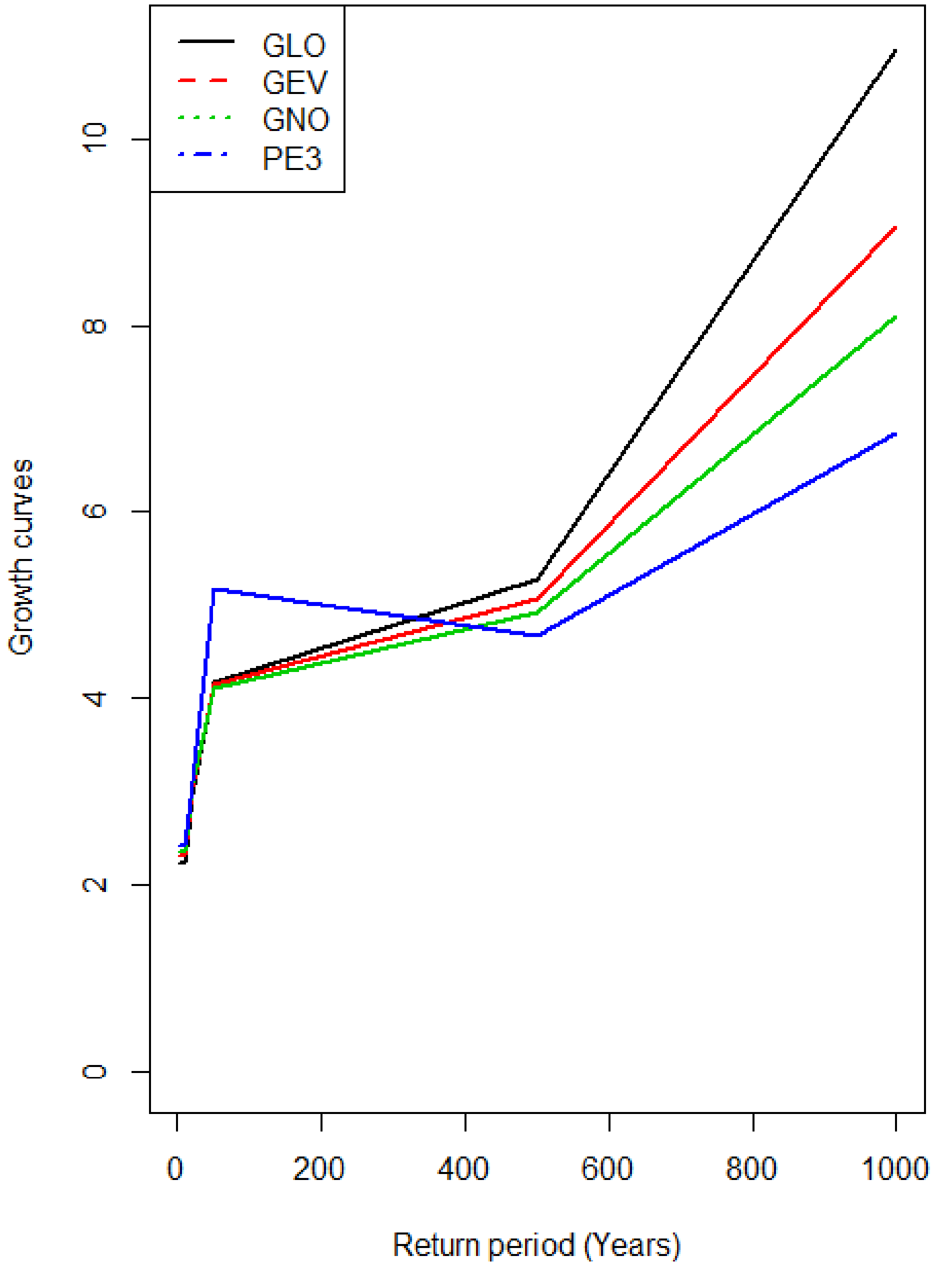

Figure 3: Growth curves for accepted distributions in the Lake Chilwa Basin

4.3 Application of Regional Flood Index in Estimating Floods at Gauged and Ungauged parts of the Lake Chilwa Basin

The third specific objective of the study was to apply the regional flood index in estimating floods at gauged and ungauged parts of the Lake Chilwa basin.

In this study, quantile estimates for the Lake Chilwa basin regionhave beenused to estimate at-site flood magnitudes for various return periodsat the gauged rivers within this region. The variation of floods for Mulunguzi, Domasi, Likangala, Thondwe, Namadzi, Phalombe and Naisi rivers using GNO distribution for AMS1, AMS3 and AMS5 are presented in Tables 4a, 4b and 4c. Generally, it can be observed that the floods for Mulunguzi and Thondwe rivers are almost identical in terms of flooding up to 1000 years return period; while those of Domasi and Likangala; Namadzi and Phalombe Rivers are not far from each other for AMS1, AMS3 and AMS5. Naisi River seems to be following its own flow pattern in terms of flooding in all the listed reference return period for the observed three (3) AMS. Specifically, AMS3 river floods for all the reference return period are identical to AMS5 river floods (Tables 4b and 4c). This could be attributed to gaps in the daily record of river discharge data collected from the gauging stations of the basin.

Table 4a: AMS1 at-site estimated floods with reference to specific return periods for the gauged rivers in Lake Chilwa basin

Return Period (Years)	Mulunguzi (m^3s^{-1})	Domasi (m^3s^{-1})	Likangala (m^3s^{-1})	Thondwe (m^3s^{-1})	Namadzi (m^3s^{-1})	Phalombe (m^3s^{-1})	Naisi (m^3s^{-1})
2	11.07	14.6	16.44	11.10	0.37	0.09	5.88
5	25.06	33.06	37.23	25.13	0.84	0.21	13.32
10	33.41	44.08	49.63	33.50	1.12	0.29	17.76
20	48.21	63.60	71.61	48.34	1.62	0.41	25.62
50	72.77	96.00	108.10	72.96	2.45	0.62	38.68
500	95.72	126.28	142.19	95.97	3.22	0.82	50.88
1000	122.81	162.02	182.43	123.14	4.13	1.05	65.28

Using the regional index flood and mean annual river discharge (since the median was giving zeros due to gaps in the data and short record length), the expected river discharge with return period of 50 years for Naisi and Phalombe rivers were estimated to be 38.68and 0.62m^3s^{-1} respectively for a 1, 3 and 5-day annual maximum series (Tables 4a, 4b and 4c).

Table 4b: AMS3 at-site estimated floods with reference to specific return periods for the gauged rivers in Lake Chilwa basin

Return Period (Years)	Mulunguzi (m^3s^{-1})	Domasi (m^3s^{-1})	Likangala (m^3s^{-1})	Thondwe (m^3s^{-1})	Namadzi (m^3s^{-1})	Phalombe (m^3s^{-1})	Naisi (m^3s^{-1})
2	9.05	11.94	13.44	9.07	0.30	0.08	4.81
5	20.89	27.56	31.03	20.95	0.70	0.18	11.10
10	32.73	43.18	48.62	32.82	1.10	0.28	17.40
20	47.56	62.74	70.65	47.68	1.60	0.41	25.28
50	72.62	95.80	107.87	72.81	2.44	0.62	38.60
500	96.37	127.14	143.16	96.63	3.24	0.83	51.22
1000	213.56	281.74	317.24	214.12	7.18	1.83	113.51

At 50 years return period, Likangala and Domasi rivers have the highest at-site AMS1, 3 and 5floodsestimated at 108 and 96 m^3s^{-1} respectively while Phalombe and Namadzi rivers have the least at-site river discharge estimated at 0.62 and 2.44m^3s^{-1} respectively for the same return period. The results, however, show that Mulunguzi and Thondwe are almost identical in their estimated at-site floods for 2, 5, 10, 20, 50, 500 and 1000 years return periods (Tables 4a, 4b and 4c).

Table 4c: AMS5 at-site estimated floods with reference to specific return periods for the gauged rivers in Lake Chilwa basin

Return Period (Years)	Mulunguzi (m^3s^{-1})	Domasi (m^3s^{-1})	Likangala (m^3s^{-1})	Thondwe (m^3s^{-1})	Namadzi (m^3s^{-1})	Phalombe (m^3s^{-1})	Naisi (m^3s^{-1})
2	9.08	11.98	13.49	9.10	0.31	0.08	4.83
5	21.41	28.24	31.80	21.46	0.72	0.18	11.38
10	33.41	44.08	49.63	33.50	1.12	0.29	17.76
20	48.34	63.6	71.61	48.34	1.62	0.41	25.62
50	72.77	96	108.10	72.96	2.45	0.62	38.68
500	95.72	126.28	142.19	95.97	3.22	0.82	50.88
1000	206.27	272.12	306.41	206.81	6.94	1.77	109.64

4.3.1 Estimation of Floods for Ungauged Sites

Sombani River, whose discharge data was not part of the analysis for the gauged stations, has seven (7) years river discharge data over the period of observation (1970 - 2000). The Sombani River can thus be regarded as poorly gauged. As such, regional flood index for Lake Chilwa basinhas been used to estimate at-site floods for specific return periods. At-site flows generated from the median annual discharge (median=10.34; mean=20.96; n=7) for Sombani River at 50 years return period is estimated to be 42.36m^3s^{-1} and 42.77m^3s^{-1} for AMS1 using GNO and GEV distributions respectively while AMS5 using GNO and GEV distributions at the same return period, estimates flood at 49.63 $m^3s^{-1}$and 48.26 m^3s^{-1}respectively (Table 5).The results derived from GNO and GEV show that they are almost identical. Generally the estimated floods agree from 2 years to 500 years of return period for both AMS1 and AMS5 of the poorly gauged Sombani River.

This shows that GNO and GEV distributions provide accurate results up to 500 years but may not give a true reflection on estimated floods at 1000 years. Thus, for return periods greater than 500 years, the values of predicted floods should be used with caution as preliminary estimates. These results are graphically presented in Figure 4.

Table 5: Comparison of accuracy for GNO and GEV in estimating floods for poorly gauged Sombani River

Return Period (Years)	Sombani AMS1 GNO (m^3s^{-1})	Sombani AMS1 GEV (m^3s^{-1})	Sombani AMS5 GNO (m^3s^{-1})	Sombani AMS5 GEV (m^3s^{-1})
2	7.55	7.64	6.19	6.47
5	17.09	16.77	14.60	14.02
10	24.28	23.82	22.79	21.36
20	31.79	31.45	32.88	30.89
50	42.36	42.77	49.63	48.26
500	50.96	52.45	65.29	66.42
1000	83.76	93.61	140.69	181.75

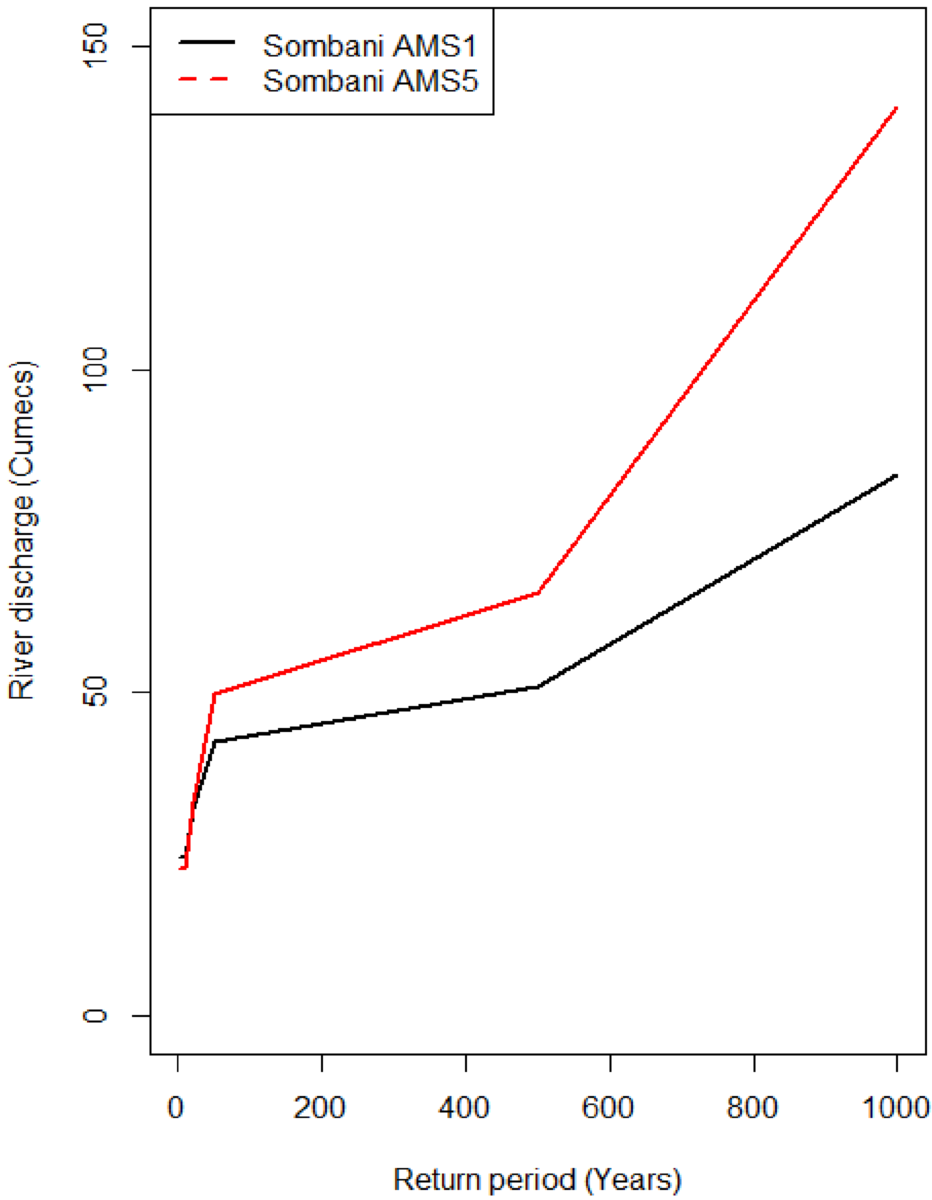

Figure 4: Estimated AMS1 and AMS5 using GNO distribution for Sombaniat-site river discharge

Likewise, using the regional growth curves, floods for ungauged Likwenu, Lingoni, Bwaila, Mponda, Songani, Namiwawa, Khongoloni and Migowi rivers have also been estimated. Using catchment area ratio multiplied by the median discharge of the gauged river, at-site mean river discharge of the ungauged rivers has been accurately estimated up to 500 years return period and beyond this point the results become less reliable (Table 6).

Table 6: Estimated at-site river discharge for the ungauged rivers in the Lake Chilwa basin

Return Period (Years)	Likwenu (m^3s^{-1})	Lingoni (m^3s^{-1})	Bwaila (m^3s^{-1})	Mponda (m^3s^{-1})	Songani (m^3s^{-1})	Namiwawa (m^3s^{-1})	Khongoloni (m^3s^{-1})	Migowi (m^3s^{-1})
2	53.88	16.05	2.27	2.67	16.81	46.98	0.29	0.11
5	122.00	36.35	5.15	6.05	38.07	106.39	0.65	0.26
10	173.30	51.64	7.32	8.59	54.07	151.11	0.92	0.36
20	226.88	67.60	9.58	11.25	70.79	197.84	1.18	0.48
50	302.39	90.10	12.77	15.00	94.35	263.68	1.57	0.63
500	363.72	108.38	15.35	18.04	113.49	317.16	1.88	0.76
1000	597.92	178.16	25.24	29.65	186.57	521.37	3.18	1.25

The results show that Likwenu River in Machinga and Namiwawa River in Zomba dominate in terms of high estimated flood records throughout the reference return periods. The two rivers have higher estimated flooding records of 302.39 m^3s^{-1} and 263.68 m^3s^{-1} respectively at 50 years return period than the rest of ungauged rivers. Figures 5a and 5b show graphically estimated river discharges for eight (8) ungauged rivers with specific return periods. Using these cases of RFFA application, the importance of the regional flood index using L-moments approach in estimating at-site floods for gauged, poorly gauged and ungauged rivers have been demonstrated and cannot be challenged.

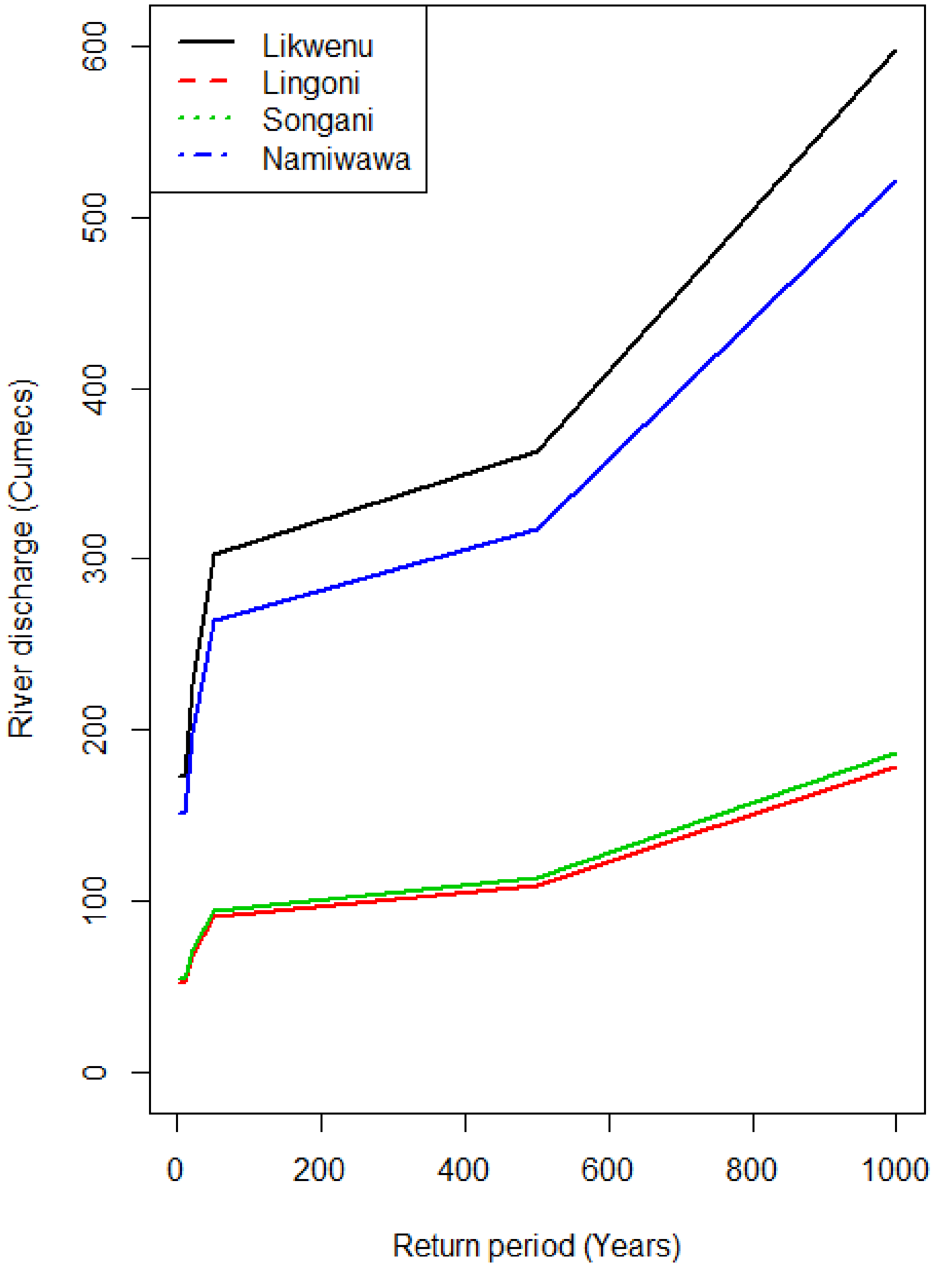

Figure 5a: Estimated at-site river discharge for ungauged rivers in the Lake Chilwa basin

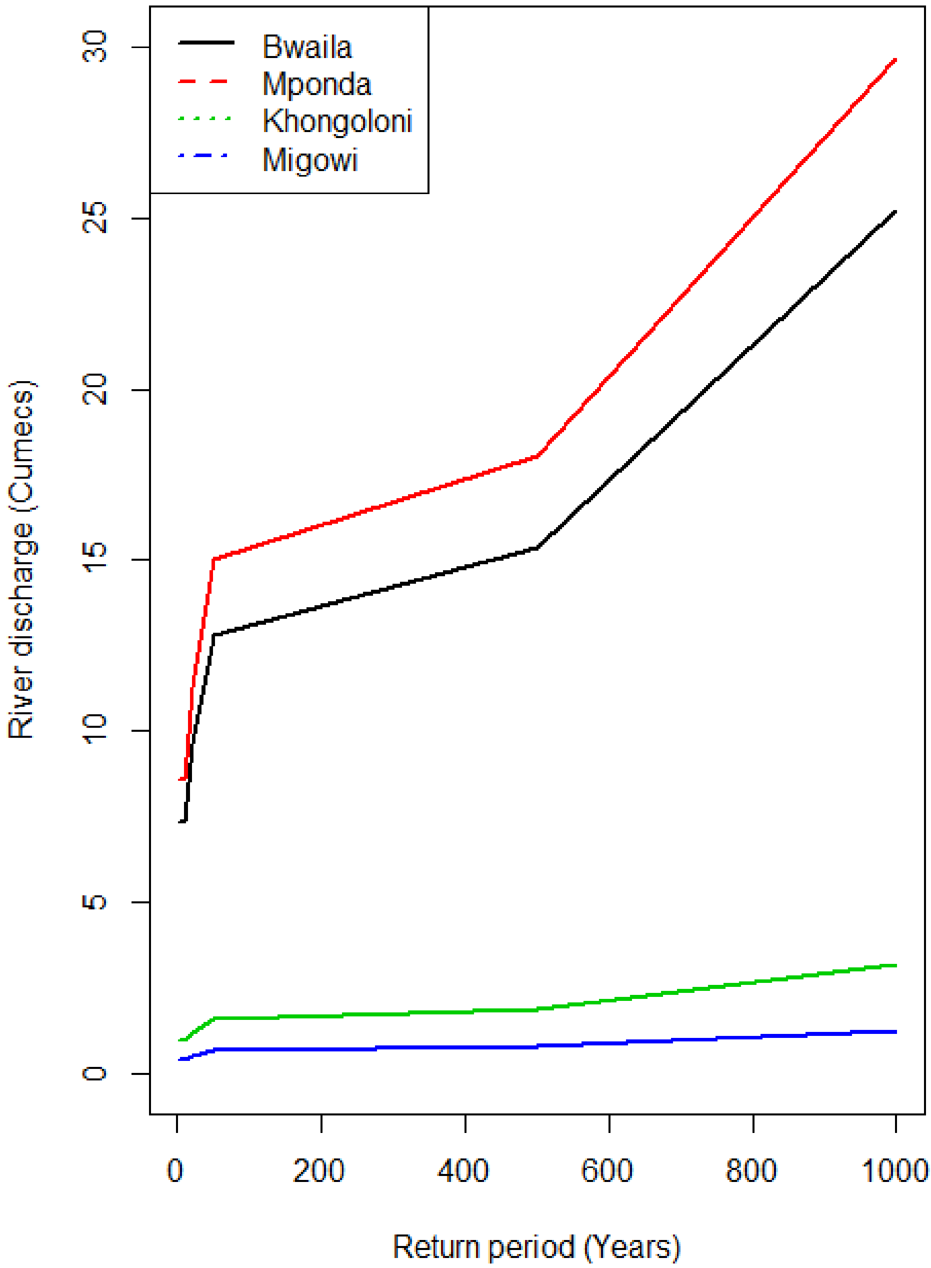

Figure 5b: Estimated at-site river discharge for ungauged rivers in the Lake Chilwa basin

4.4 Discussion

The National Disaster Management Plan for Malawi of 1997 lists Likangala and Thondwe rivers as being very vulnerable to flood hazards. This has been reflected in this study where Likangala and Thondwe recorded the second and third highest average river discharge at 40.76 and 34.55 m^3s^{-1} respectively after Domasi River (50.73 m^3s^{-1}). In addition, high record floods such as those estimated for ungauged Likwenu (302.39 m^3s^{-1}) and Namiwawa (263.68 m^3s^{-1}) at 50 years return period could be disastrous to human life and infrastructure if preparations are not done in advance to manage the risks associated with such floods.

Ngongondo *et al.*, (2011) in a regional frequency analysis of rainfall extremes in Southern Malawi identified the Lake Chilwa catchment to be within the rainfall group 3 which is a high rainfall area. However, the Lake Chilwa basin catchment area has undergone degradation in terms of forest cover overtime and in most cases land use has changed from forest to agricultural crops. Therefore, the different types of land use and land cover are likely to have an influence on the amount of river discharge despite the fact that rivers such as Mulunguzi, Phalombe and Migowi flow from catchment areas with high average annual rainfall within the Lake Chilwa basin.

According to Chavula and Chirwa (1998), the estimation of average rainfall in determining high rainfall areas could be one of the major sources of error in evaluating the water balance equation for the Lake Chilwa basin. Such being the case, areas that are perceived as high rainfall areas may not necessarily be high rainfall areas and vice versa.

The main shortfall with using average rainfall is that it assumes that the gauging stations are uniformly distributed and that the basin has uniform topography, which is not true of the basin under study. For example, Phalombe River which is among gauged rivers is considered to be flowing from a high rainfall area but has the least mean river discharge (0.13 m^3s^{-1}) recorded. In addition, Migowi River in Phalombe has the least estimated flood (0.63 m^3s^{-1}) among ungauged rivers at 50 years return period. Thus, an area experiencing large or low flows yet it does not experience high or low rainfall respectively may be attributed to other factors such as type of land use. This implies that rainfall alone may not influence flood magnitude of a particular river. To determine other flood influencing factors may require further investigations through a different study.

Scientific understanding from research on evaporation from forest catchment areas in dry and wet conditions based on process studies show reduced runoff from areas under forests as compared to areas under shorter crops (Calder, 1990). In dry conditions, studies have shown that transpiration from forests tend to be higher because of the increased rooting depth of trees as compared with shorter crops and their resultant greater access to soil water. It is thus not easy to assume that the rainfall amount alone in the Lake Chilwa catchment area has a bearing on the expected river flow due to various processes taking place within the basin catchment ecosystem.

Calder *et al.*(1994) argue that forests play a role in watershed conservation including storing excess rainfall through interception of run-off and increasing the infiltration of rain water, thereby recharging underground aquifers and serving as a source of stream flow. Land use and land use change which results in land degradation is a cause for concern because the net effect of the various feedback processes involved appears to be destabilization of ecosystems, making such lands prone to increasing flood risk and damage. In the Lake Chilwa basin the largest changes in terms of land area and arguably also in terms of hydrological impacts has arisen from on-going modest afforestation and significant deforestation activities which counter each other.

There is another argument by Robinson *et al*. (1997) which contend that for the upper catchment area, drainage activities associated with plantation forestry increase dry season river discharge through both dewatering and hydraulics alterations in the drainage system. This argument may hold true for Mulunguzi River and other rivers that have been dammed or whose water is diverted for irrigation or other uses.

Generally, rivers flowing within the Lake Chilwa basin reveal annual variability with maximum flows occurring in rainy season such as the month of February and declining rapidly thereafter. According to Chavula and Chirwa (1998), a notable characteristic about rivers flowing in the Lake Chilwa basin is that they are perennial in their upper reaches but gradually lose their flow in the Chilwa – Phalombe plains due to the porous nature of the area. This suggests that flows recorded by some gauging stations such as those on Mulunguzi or Domasi rivers which are located very far from the lake do not give a clear indication about the amount of river flow that is actually discharged into the lake. It follows then that the Lake Chilwa level reacts sensitively to the amount of rainfall received than the amount of river flow into the lake. The findings imply that the water levels of the Lake Chilwa can effectively be sustained with high rainfall amounts considering that land use and land use change appear to have a considerable effect on stream flow.

The chapter has presented and discussed the results of the study with reference to the set study objectives. The results derived from GNO and GEV distribution models for gauged, poorly gauged and ungauged rivers show that the models are almost identical and characterize river discharge in the homogenous Lake Chilwa basin. The estimated floods provide evidence that the two distribution models tend to agree in describing the expected flood at a specific return period. Generally, the estimated floods agree from 2 years to 500 years of return period. This is proof that GNO and GEV distributions provide accurate results up to 500 years for the Lake Chilwa basin but may not give a true reflection on estimated floods at return period greater than 500years.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Regional flood frequency analysis using daily river discharge data from seven (7) gauging stations in the Lake Chilwa basin has been implemented using flood index approach andL-moments. The basin has only 7 gauged rivers whose river discharge data span from 9 to 31 years and one gauged river whose river discharge data covers 7 years between 1970 and 2000. The river discharge records in the Lake Chilwa basin show a typically data scarce region whose data was consistently collected for some rivers and inconsistently for few rivers over the years (between 1970 and 2000) but with a lot of gaps for daily readings.

Through discordancy test, Lake Chilwa basin has been identified as one homogenous region. Such being the case, Mulunguzi, Domasi, Likangala, Phalombe, Naisi, Namadzi, Thondwe and many more ungauged rivers belong to this one group. Four distributions namely Generalized Logistic (GLO), Generalized Extreme Value (GEV), Generalized Normal (GNO) and Pearson Type III (PE_3) passed as candidate distributions. Using a Goodness-of-fit measure and L-moment ratio plots, theGNO and GEV distributions were identified as the appropriate regional flood distributions for the Lake Chilwa basin region.The L-moment ratio plot confirmed thetheoretical relationship of the identified candidate distributions since GNO and GEV were the best fitting regional distribution closer to the regional weighted L- moment means. Growth curves and at-site floods for the gauged and ungauged rivers in the Lake Chilwa basin with reference to return periods T = 2, 5, 10, 20, 50, 500 and 1000 years have been computed and estimated respectively from the regional flood index. The growth curves which are dimensionless can be used to estimate expected river discharge at a specified return period for any ungauged rivers as long as they are located within the study region.

The study has also shown that index flood method assumes that a region is a set of gauging sites whose flood frequency behavior is homogeneous in some quantifiable manner, and the more homogeneous a region is, the greater is the advantage in using regional instead of at-site estimation. The study also developed unique flood quantiles (dimensionless numbers) which can be used to estimate floods even at the ungauged rivers within the Lake Chilwa basin and this has been demonstrated in the study. The study further concludes that these numbers can be used not only for flood prediction but also in engineering design and vulnerability assessment or mapping among others.

5.2 Recommendations

The study recommends the Generalized Normal (GNO) and the Generalized Extreme Value (GEV)as the appropriate regional flood frequency distributions for the Lake Chilwa basin.GNO and GEV has shown to accurately estimate at-site floods in poorly gauged and ungauged rivers up to 500 years return period and for return periods greater than 500 years, the predicted flood values should be used with caution. Efforts should be intensified nationally in the collection of daily river flow data consistently covering all hydrological years in view of the challenge posed by short record length and data gaps to achieve reliable flood quantile estimation for return periods greater than 500 years. The density of stream gauging networks in river basins in the country should be increased to enhance national water resources planning and development but also to effectively assist in flood risk planning and disaster preparedness. It is further being recommended that similar studies should be carried out in all other river basins in Malawi such as the Shire river basin to identify appropriate flood frequency distribution(s). Outcome of such studies will assist in hydraulic engineering design either for proper planning and designing of culverts, irrigation channels and bridges; protection of various engineering projects such as highways or dams against floods; and flood risk planning to avoid loss of property and life. A study on factors influencing low discharges in rivers flowing from high rainfall catchment areas are also crucial for informed water resources management.

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APPENDICES

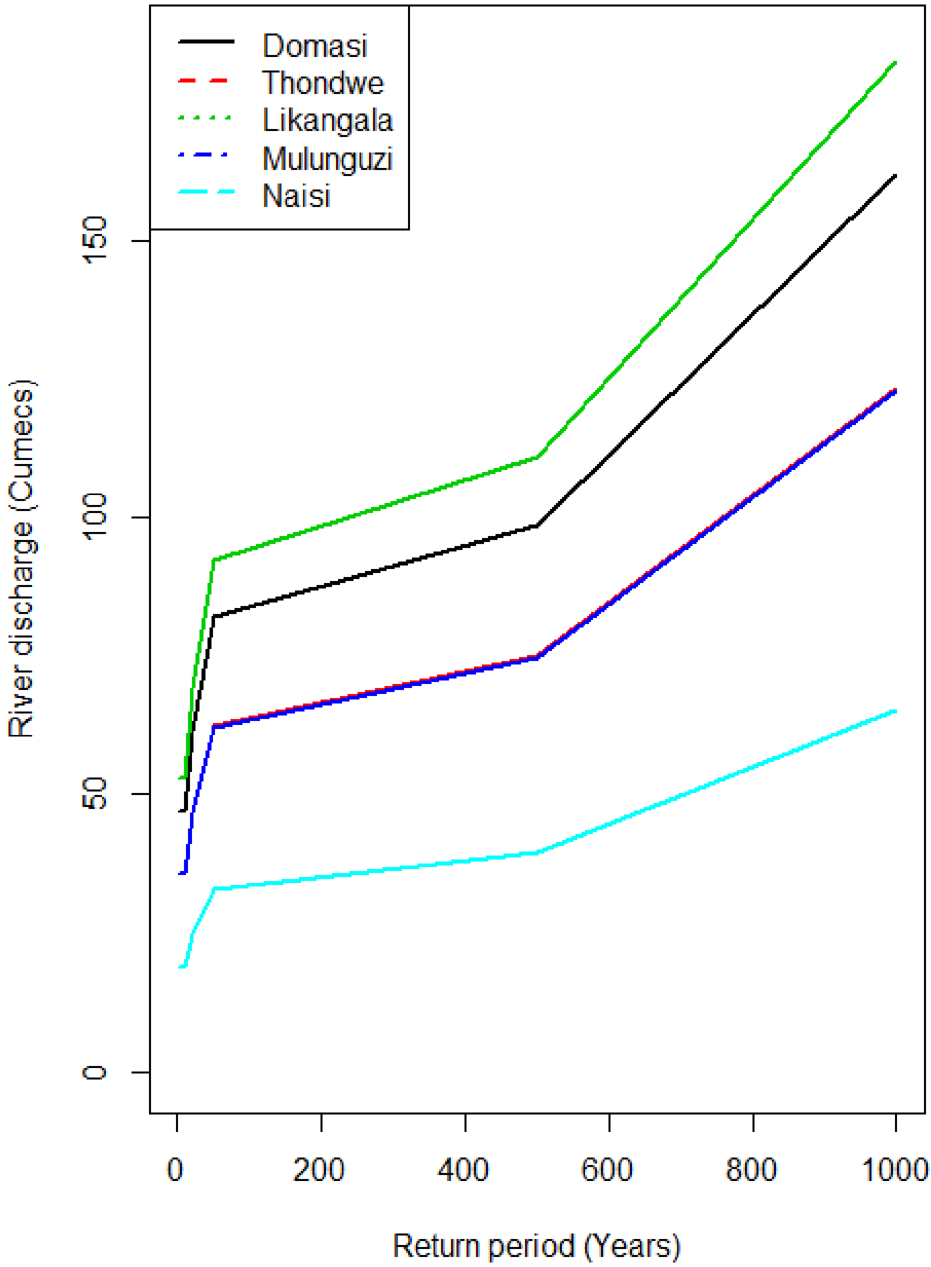
Appendix1: Geographical location of the river gauging stations in the Lake Chilwa basin

Serial	River	Station	Latitude(^{0})	Longitude(^{0})	Elevation (m.a.s.l)
1	Mulunguzi	Zomba Plateau	-15.35	35.31	1472
2	Domasi	Domasi TTC	-15.28	35.38	736
3	Likangala	Mkokanguwo	-15.4	35.3	924
4	Thondwe	Jali	-15.48	35.47	677
5	Namadzi	Namadzi	-15.55	35.18	949
6	Phalombe	Kagwa Dam	-15.81	35.35	809
7	Naisi	Mwandama	-15.38	35.49	646

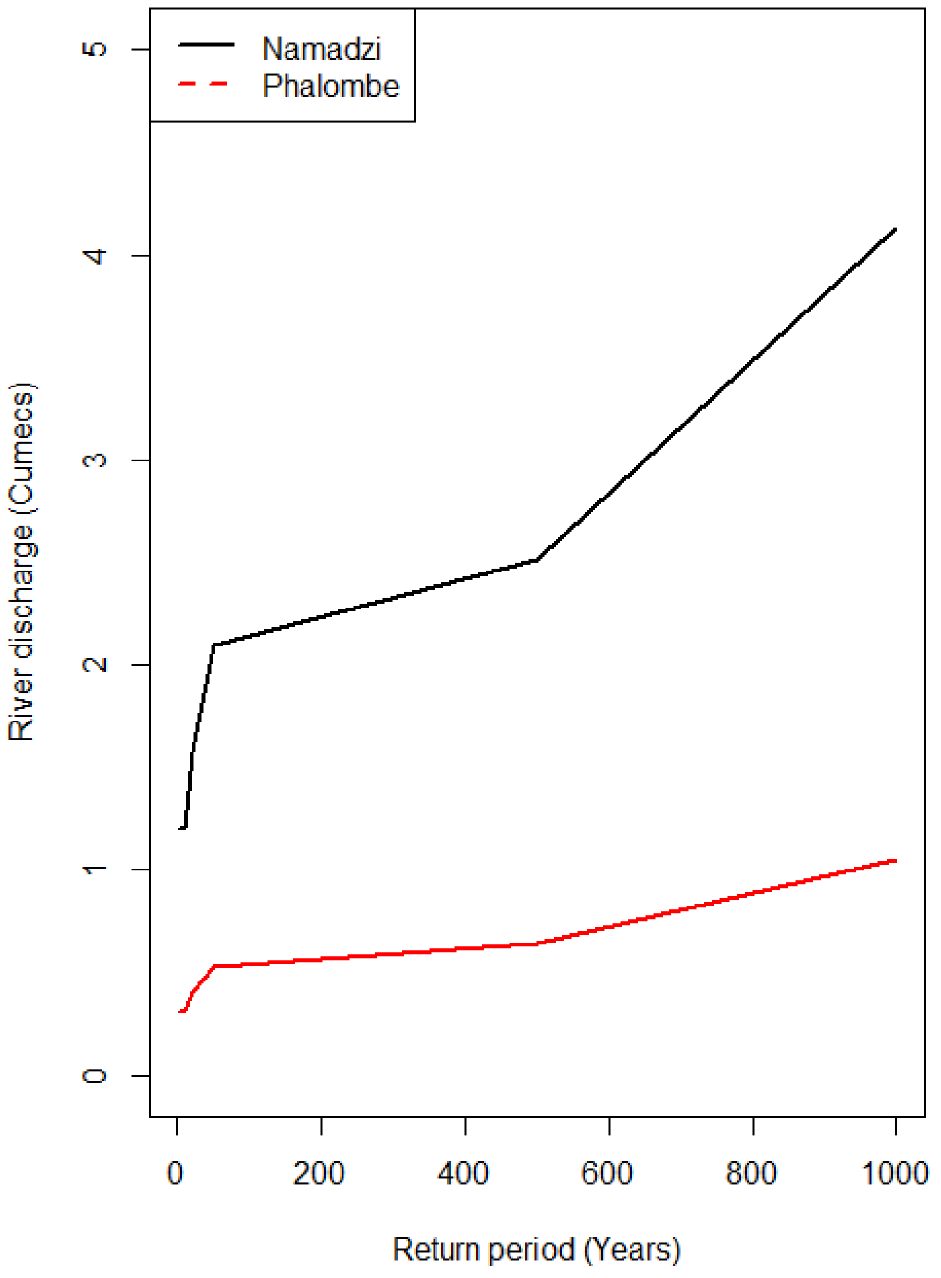
Appendix 2: Estimates of parameters for the four candidate distributions for the Lake Chilwa basin region

Distribution	Parameters of the distribution		
GLO	$\varepsilon_{\iota} = 0.7556$	$\alpha = 0.4837$	$k = -0.2797$
GEV	$\varepsilon_{\iota} = 0.4865$	$\alpha = 0.6679$	$k = -0.1639$
GNO	$\varepsilon_{\iota} = 0.7301$	$\alpha = 0.8489$	$k = -0.5833$
PE_3	$\varepsilon_{\iota} = 1.0000$	$\alpha = 1.0671$	$k = 1.6804$

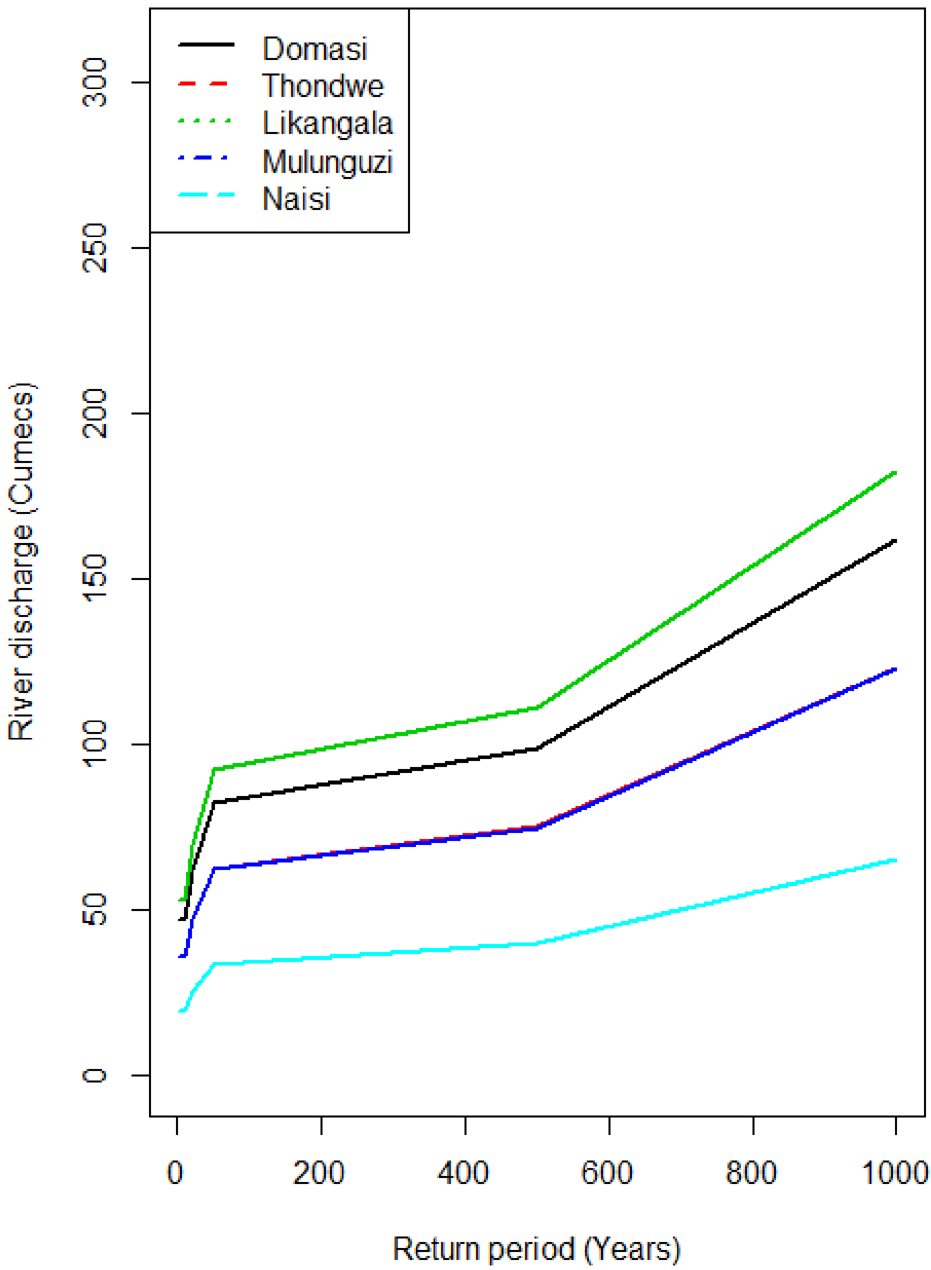
Appendix 3a: Estimated AMS1 at-site river discharge for the 5 gauged rivers in the Lake Chilwa basin



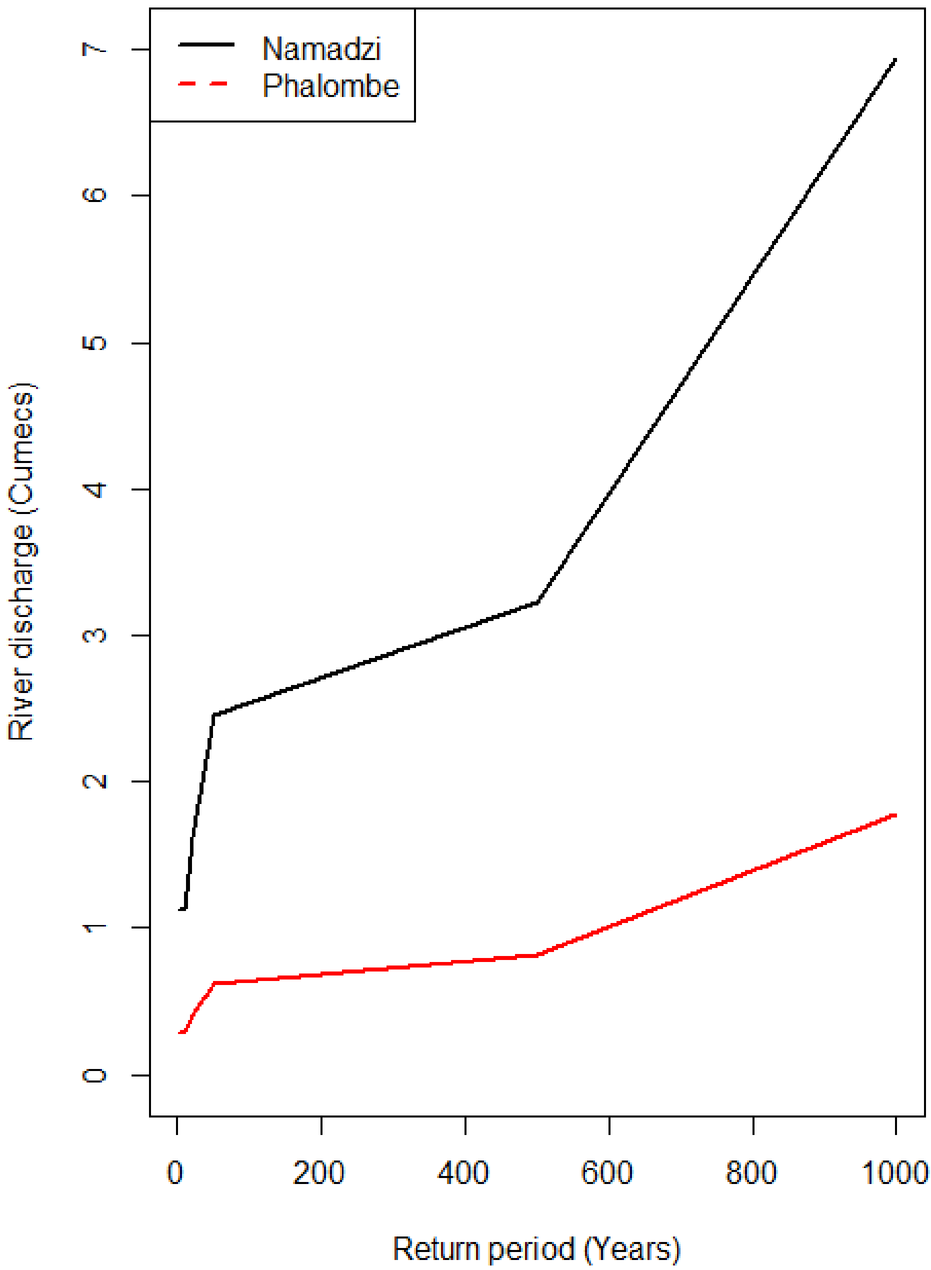
Appendix 3b: Estimated AMS1 at-site river discharge for the 2 gauged rivers in the Lake Chilwa basin



Appendix 3c: Estimated AMS5 at-site river discharge for the 5 gauged rivers in the Lake Chilwa basin



Appendix 3d: Estimated AMS5 at-site river discharge for the 2 gauged rivers in the Lake Chilwa basin



Appendix 4: Relationships between gauged and ungauged rivers which were used to calculate at-site flood estimates for ungauged rivers in the Lake Chilwa basin

Ungauged River	Catchment area (Km^2)	Nearest gauged station	Catchment area (Km^2)	Catchment area ratio	Median discharge (m^3s^{-1})	Mean discharge (m^3s^{-1})
Likwenu	268.66	Domasi TTC	72.8	3.7	20	50.73
Lingoni	80.05	Domasi TTC	72.8	1.1	20	50.73
Bwaila	3.72	Zomba plateau	18.1	0.2	15.16	20.05
Mponda	4.37	Zomba plateau	18.1	0.2	15.16	20.05
Songani	83.83	Domasi TTC (Domasi)	72.8	1.2	20	50.73
Namiwawa	76.84	Zomba plateau	18.1	4.2	15.16	20.05
Khongoloni	168.48	Kagwa dam*	55.8	3.0	-	0.13
Migowi	66.49	Kagwa dam*	55.8	1.2	-	0.13

***For Kagwa dam on Phalombe river a mean was used instead of a median**