# UNIVERSITY OF ZIMBABWE

## FACULTY OF ENGINEERING

## DEPARTMENT OF CIVIL ENGINEERING

# AN UNDERSTANDING OF VARIATIONS IN THE AREA EXTENT OF LAKE LYAMBEZI: PERSPECTIVE FOR WATER RESOURCES MANAGEMENT

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**MSc. THESIS IN IWRM**

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**in collaboration with**

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**A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Integrated Water Resources Management of the University of Zimbabwe**

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DECLARATION

I, **MUKENDOYI A. MUTELO**, declare that this research report is my own work. It is being submitted for the degree of Master of Science in Integrated Water Resources Management (IWRM) of the University of Zimbabwe. It has not been submitted before for examination for any degree in any other University.

Date: ____________________

Signature: _____________________

*The findings, interpretations and conclusions expressed in this study do neither reflect the views of the University of Zimbabwe, Department of Civil Engineering nor of the individual members of the MSc Examination Committee, nor of their respective employers.*

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| DEM | Digital Elevation Model |
| DNO | Drainage Network Ordering |
| DWAF | Department of Water Affairs |
| ETM | Enhanced Thematic Mapper |
| FEWS | Famine Early Warning System |
| GDEM | Global Digital Elevation Model |
| GIS | Geographic Information System |
| GRN | Government of Republic of Namibia |
| GWP-TAC | Global Water Partnership-Technical Advisory Committee |
| ILWIS | Integrated Land and  Water Information System |
| IWRM | Integrated Water Resources Management |
| MAWF | Ministry of Agriculture Water and Forestry |
| MDG | Millennium Development Goal |
| MNDWI | Modified Normalised Difference Water Index |
| NDVI | Normalised Difference Vegetation Index |
| NDWI | Normalised Difference Water Index |
| NNF | Namibia Nature Foundation |
| NSA | Namibia Statistics Agency |
| OLI | Operational Land Imager |
| SADC | Southern Africa Development Community |
| SRTM | Shuttle Radar Topographic Mission |
| TI | Topographic Index |
| TM | Thematic Mapper |
| UNFCCC | United Nations Framework Convention on Climate Change |
| USGS | United Sates Geological Survey |
| WSSD | World Summit on Sustainable Development |

# DEDICATION

This thesis is dedicated to Esther Chaze Mufwanzala, Esther, Tofilwa and Kahundu.

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# ABSTRACT

Lyambezi is natural lake found in the Caprivi region, of Namibia. It provides the link between the Kwando-Linyanti and Chobe Rivers. The lake dried out for nearly two decades since the mid-1980s. However, Lyambezi re-emerged and went through 7 phases of drying out and reforming but has remained robust for the past half-decade. The study focused on enhancing the understanding of the variations in the lake's areal extent from a time series analysis of Landsat imagery. The area was quantified at intra and inter-annual temporal scales based on the analysis of satellite imagery i.e. Landsat TM, ETM+ and Landsat 8 OLI sensors. Water features were delineated using the modified normalized difference water index (MNDWI). The lake spectral classes were segmented based on five dynamic thresholds based on which the area covered by water was calculated. Results show that the lake exhibits a wide range of area variations at both inter-annual and intra-annual temporal scales. However, due to the presence of the thick vegetation in the open water body, the segmentation of spectral classes yielded poor to moderate accuracy levels (kappa=28-53). The application and success of DEM was tested and the results illustrated that the use of SRTM 3 DEM led to the successful extraction of topography-based hydrological parameters that served as inputs into various GIS-based hydrological models. These results imply that lake volume can successfully be estimated, leading to a better understanding of floods on water resources availability. On the other hand, hydrological analysis results show that flood events of a magnitude above the long-term average maximum have a 2 to 3 year return period and probability of occurrence in any given year ranges between 0.29 and 0.58. This implies that floods have the potential to inundate the lake every second year, which represents a flooding occurrence at a regular enough interval to prevent the lake from going into a drying-up phase. Therefore, rainfall variability is more linked to the inundation and hence, appearance of the lake. It as well represents the most important challenge for the water resources management of the lake. Overall, the results of this study provide a better understanding of Lake Lyambezi dynamics and therefore, enhance the understanding of the behaviour and response of previously-desiccated environments to prevailing hydrological conditions.

# 1. INTRODUCTION

## 1.1 Background

### 1.1.1 General overview

Lakes and reservoirs are important but sensitive ecosystems which are vulnerable to various natural and anthropogenic influences, at the same time remain invaluable to humans (Kayira, 2012; Tawfeeq, 2011). Lakes respond to climatological and water use impacts by exhibiting variations in area extent and water level, at time scales ranging from an hour to decades (Ghanbari and Bravo, 2008). Lakes also constitute an essential part of the hydrological cycle (Bai *et al*., 2010), that contributes significantly to the movement of water between land, sea and atmosphere. Therefore, lakes represent an important part of surface and subsurface hydrology of the region in which they are located (van der Kamp *et al*., 1999). Thus, variations in lake water levels and areal extent at different temporal scales i.e. inter-annual and inter-dekadal, will consequently affect the hydrological role of lakes. Some of the water cycle components affected by lake dynamics in time and space include soil moisture, ground water recharge, evapotranspiration and stream flows and flood routing.

Apart from their hydrological importance, lakes also have intrinsic ecological, environmental and economic importance. For instance, they provide habitat to aquatic and semi-aquatic fauna and flora, which in turn provide food for terrestrial animals, and serve as viable temporary habitats for migratory birds. More importantly, lakes serve as critical water resource systems for human development by providing water for *inter alia* irrigation agriculture, water supply, fisheries, tourism, and receiving wastewater effluents. The extent to which lakes provide water-related goods and services, and support ecological processes is affected by the nature and extent of lake changes in areal extent, water level and water quality (Murdoch *et al*., 2000).

### 1.1.2 Overview on Lake Lyambezi

Lake Lyambezi is a periodic water body that has always exhibited episodic changes in lake area and water levels in response to changes in climatic regimes. Hydrologically, it serves as the link between the Linyanti and the Chobe rivers in the west and east respectively (van der Waal, 1976; van der Waal and Skelton, 1984). The lake was reported to be increasing in area and water levels during the 1970s but shrunk to 10% of the maximum area by the early 1980s (van der Waal, 1990) and even desiccated in the latter part of 1985 (Schlettwein *et al*., 1991).

Before Lake Lyambezi desiccated in 1985, it was characterised by infestations of *Salvinia molesta* and other aquatic weeds. It also formed an important part of the fishery in the Eastern Caprivi, contributing fish catches amounting to an output of 600 000 tonnes per year (van der Waal, 1980). Lake Lyambezi started filling up in 2001 (Turpie and Egoh, 2002) and went through periodic phases of drying and filling up, until 2007 and has remained full since then as shown in Figure 1-1 (Hay in Peel, 2012).

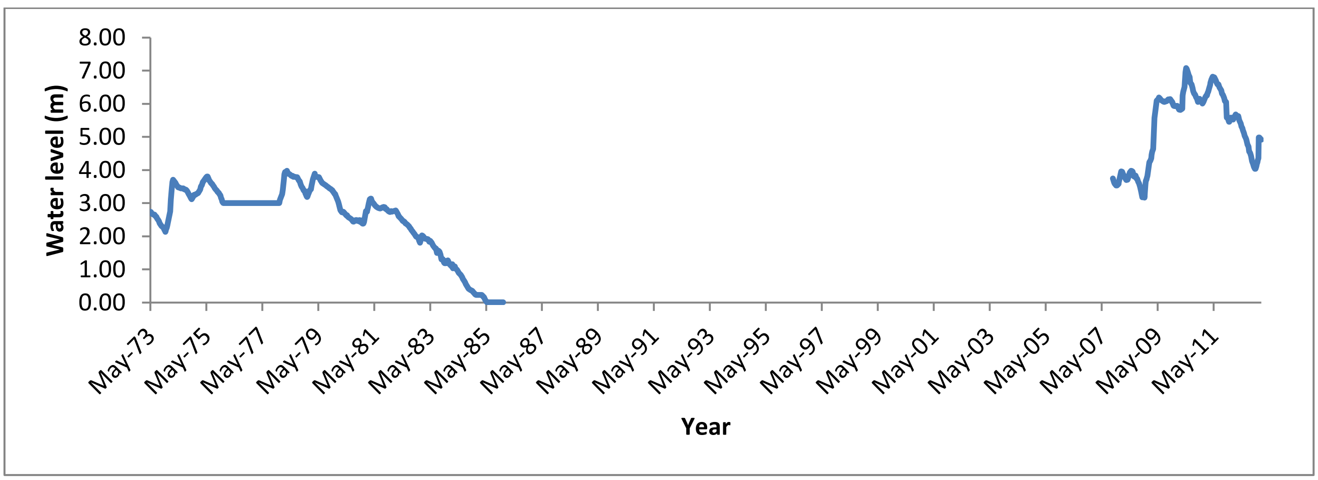


**Figure 1-1 Lake Lyambezi water level variations**

Since filling up, Lake Lyambezi has regained its former physical and limnological characteristics, and has also become an important part of the subsistence economy, supporting a robust subsistence fishery with an output of 1500 tonnes per annum since 2009 (Peel, 2012). Moreover, the lake serves as an important habitat for aquatic biodiversity and is a temporary site for migratory birds.

### 1.1.3 Overview of water resources management in Namibia

"The overall long-term goal of integrated water resources management (IWRM) in Namibia is to achieve a sustainable water resources management regime contributing to social equity, economic efficiency and environmental sustainability" (MAWF, 2010). To this end, the Water Resources Management Act of 2004 (GRN, 2004) promotes the protection of aquatic and wetland ecosystems including their biodiversity and ecological functions. Therefore, a legal and policy framework does exist that can be used as a basis to establish adequate water resources management regimes for sensitive water resources systems such as Lake Lyambezi. The Government of the Republic of Namibia has also adopted a national IWRM plan and strategies that provide an enabling environment for effective water resources management of climatically sensitive lake water resources in the predominantly arid Namibia.

## 1.2 Research problem

Many climatically sensitive African shallow lakes and their wetland systems are located on poorly gauged or ungauged sub-basins, resulting in their hydrology remaining poorly understood. Data on key physical and hydrological variables such as rainfall, discharge, evapotranspiration, stream cross section, lake area and volume are consequently unavailable (Sivapalan, 2003). Recent studies have focused on understanding flooding extent, its hazards, and its variable sources (Gumindoga, 2008; Pricope, 2013; Skakun 2012), but little work has been done on the use of alternative methods to assess lake water resources in arid and semi-arid environments of African countries such as Namibia. The major limitations in hydrological assessments of lake water resources in ungauged basins are that a time series of *in situ* input (hydrological) data to drive models are largely unavailable (Mostert and Junier, 2009; Seibert and Beven, 2009; Velpuri and Senay, 2012). It is important, therefore, to develop robust methods that enhance the understanding of lake hydrology of ungauged basins.

The development of remote sensing has provided useful tools and has made it increasingly possible to provide knowledge on the hydrology of climatically sensitive shallow lakes in ungauged basins. However, the robustness and efficiency of these remote sensing-based methods needs to be tested, particularly using water resources areal extent as an indicator.

## 1.3 Objectives

The overall objective is to investigate the variations in area extent of the Lake Lyambezi in order to enhance the understanding of its dynamics.

### 1.3.1 Specific objectives

1. To extract catchment characteristics of the sub-basin and the topography-based hydrological parameters useful for modelling
2. To perform a time series analysis of variations in Lake Lyambezi areal extent using satellite imagery
3. To investigate how the hydrological conditions at sub-basin level are related to the lake area variations
4. To test whether there is a relationship between variations in water levels of the Zambezi River and Lake Lyambezi
5. To determine the reliability of source floods using the probability of occurrence of floods and the associated implications to water resources management

## 1.4 Scope of the Study

The study focused on quantifying intra-annual lake areal variations of Lyambezi using remotely sensed data. The area was calculated based on the efficiency of dynamic thresholding of the MNDWI and by digitising. Emphasis was also placed on investigating the usefulness of DEM data in extracting catchment characteristics of the sub-basin and on analysing of hydrological conditions and the corresponding status of the lake.

## 1.5 Justification

Given that water resources are important strategic resources required for human survival and social development, it is necessary to monitor the changing dynamics of these resources (Li *et al*., 2009; Williamson *et al*., 2009). They constitute aquatic ecosystems that form an integral part of human existence and provide a wide range of essential ecological services, ranging from drinking water and food, to transportation and recreation (Williamson *et al*., 2009). However, they remain vulnerable to global climate variability, with tangible effects including varying lake levels, lake area shrinkage and drying up of lakes.

Lake Lyambezi which was previously desiccated represents a peculiar and interesting case study, as it provides an opportunity to enhance the understanding of the hydrology of climatically sensitive shallow lakes. Hence, this study seeks to provide scientific information about the lake, which will be useful for water resources development and management. The Caprivi region, where Lake Lyambezi is located is ranked fourth poorest in Namibia based on the poverty index scale and has a dependency ratio of one to six i.e. six dependent family members per employed family member (Dirkx *et al*., 2008). Therefore, the presence of a large water body should provide possibilities for alternative livelihoods, and opportunities for water resources development with the aim of alleviating regional poverty through adequate water resources management regimes. The ability for water resources managers to implement adequate management regimes and ensure sustainability of water resources development projects is dependent on the availability and quality of scientific information about the lake's water resources status. At present, the hydrologic dynamics of Lyambezi are poorly researched and documented. This justifies why undertaking a study that documents and improve the understanding of the dynamics of the lake is important.

## 1.6 Structure of the thesis

This thesis is organised into six chapters, including this introductory chapter. Chapter 2 comprises a literature review on the use of remote sensing for the delineation of water bodies, and the causes and consequences of lake area variations. Chapter 3 consists of a description of the study area. Chapter 4 is a description of the methods used in the study, while the results and discussions are presented in Chapter 5. Finally, the conclusions and recommendations are presented in Chapter 6.

# 2. LITERATURE REVIEW

## 2.1 Brief overview of natural and man-made lakes and their wetlands

Natural and man-made lakes are known to store large amounts of water and constitute the most important water resources systems for human development (Doğan, 2007; Kayira, 2012). They provide water for agriculture, domestic and industrial use, navigation and transportation, aquaculture and fisheries, and recreational use (Moss, 1998; Mitsch & Gosselink, 2000). Natural and man-made lakes can be categorised as shallow or deep water bodies. Taking area as a measure, most of the world's freshwater area is shallow, consisting of wetlands and individual lakes supporting littoral biodiversity that is more productive per unit area of water than deeper lakes (Moss, 1998; Doğan, 2007). Hence, shallow lakes and wetlands are particularly important in supporting water related livelihoods of local communities, especially in developing countries (Moss, 1998; Turpie and Egoh, 2002).

The socio-economic benefits of shallow lakes and wetlands at global and local scales are of enormous value. The total value of the global natural systems is estimated to be more than thirty trillion US dollars per annum, and the contribution of wetlands together with lakes and rivers accounts for a quarter of this value (Constanza *et al*., 1997; Neiland & Béné, 2006). Locally, the gross value of the Chobe-Lyambezi fishery excluding other benefits such as wildlife, tourism and agriculture is estimated to be US $1.5 million (Neiland and Béné, 2006). Shallow lakes and their wetlands are also important for the conservation of biodiversity in that they provide habitat for many species of fish, plants, waterfowls, mammals, invertebrates, zooplankton, and phytoplankton ( Bethune *et al*., 2012; Jeppesen *et al*., 1997).

## 2.2 Water resources management perspectives

Lake resources are important to local communities particularly with respect to supporting water related livelihoods such as fishing, and have the potential to enhance food security through irrigation agriculture (Allison *et al*., 2009; Cai *et al*., 2003). Thus, it is critical that such water resources systems are subjected to adequate water resources management regimes. The term "water resources management" in this thesis, is used generically and refers to issues of water use, allocation, distribution, governance, regulation, policy and planning (Mollinga, 2008).

### 2.2.1 Global and SADC perspectives of IWRM

The recognition of the impact of humans on natural resources has triggered a shift towards sustainable development in global natural and water resources management efforts (UNFCCC, 1992). Since the 1990s, water resources management has shifted from infrastructural-based to IWRM. Natural and man-made lakes represent the most important water resources systems for livelihood sustenance, poverty reduction and economic development in general. However, the complex nature of interactions between human and earth systems requires an integrated approach in resources management (Hanjra and Gichuki, 2008; Mulengera, 2011). IWRM has been globally accepted as an essential component of sustainable development, where water is recognised as a key national asset. The World Summit on Sustainable Development (WSSD) held in Johannesburg in 2002, served as a platform for promoting IWRM to the worldwide community. One of the key mandates of the WSSD was for countries to develop IWRM plans and strategies and offering of support to developing countries.

Originally the concept IWRM stems from the Dublin principles (GWP-TAC, 2000), which are as follows:

1. Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment
2. Water development and management should be based on a participatory approach, involving users, planners and policy makers at all levels
3. Women play a central part in the provision, management and safeguarding of water
4. Water has an economic value in all its competing uses and should be recognised as an economic good.

The Southern African Development Community (SADC), a political and regional economic grouping to which all the southern African countries belong has incorporated various aspects of IWRM in its regional policies, strategies and legal frameworks (SADC, 2000; SADC, 2005a; SADC, 2005b; SADC, 2006).

### 2.2.2 IWRM in Namibia

In independent Namibia (since 1990), water resources management started with reforms of legislation governing the water sector. The reforms resulted in the adoption of the Water Policy of 1993, whose key goals were to control water use and promote the conservation of water resources for agriculture, domestic, mining and industry use *inter alia* (GRN, 1993). Other key developments were the adoption of the Water Supply and Sanitation Policy of 1993 and the promulgation of the Water Utility Act of 1997.

Namibia launched a water resources management framework review in March 1998, which resulted in the perpetuation of the Water Policy of 2000 and the Water Act of 2004. The Water Act of 2004 includes the water conservation strategy and water resources management institutions that promote the establishment of basin management agencies, particularly on shared river basins (Macdonald, 2007).

In 2004, the Government of the Republic of Namibia launched its Vision 2030, which serves as the overarching framework for development of Namibia with the main goals of improving the quality of life of its people and achieving the status of a developed country by the year 2030 (MAWF, 2010). Water resources development is important to the achievement of the goals stipulated in the Vision 2030 programme, which embraces the millennium development goals (MDGs). The National Vision Programme guides the country's framework for water resources management, which is based on IWRM. The long-term objective of the IWRM plan for Namibia is to enable the country to achieve sustainable water resources management regimes, thereby contributing to social equity, economic efficiency and environmental sustainability (MAWF, 2010). The benefits of this will be improved health and sanitary conditions for communities, improved water related livelihoods, benefits to agriculture, and reduced risk of floods and droughts.

## 2.3 Areal variations of natural and man-made lakes

Natural lakes are known to respond to changes in environmental phenomena , and this response manifest as variation in morphometry, water levels and area extent at different temporal scale (López-Caloca *et al*., 2008). Variations in areal extent of lakes have been observed to occur in different parts of the world, ranging from minimum area changes to completely drying-up. One example is that of the Aral Sea, once the fourth largest in the world in terms of areal extent, continually shrunk in spatial size and volume. It is reported that by the year 2006, the Aral Sea had shrunk to 10% of the size it was in 1960 (Micklin 2007). Several lakes of China have also been reported to exhibit large spatial variations at inter-annual and inter-decadal temporal scales (Chen *et al*., 2001; Hui *et al*., 2008; Zhang *et al*., 2010). The Poyang Lake was reported to have gone through an inter-annual area change ranging from 1500 to 3400 $km^2$ between December 1999 and December 2000 (Hui *et al*., 2008), while the lakes on the Tibetau Plateau shrunk by over 40 000 $km^2$ since the 1970s (Qiao *et al*., 2010).

In Africa, Lake Chad is reported to have shrunk in size from 25 000 $km^2$ to 1 350 $km^2$ between 1960 and 2000, approximately 5% of the total area (Coe and Foley, 2001; Gao *et al*., 2011). Bryant (1998) also reported that the playa Chott El Djerid of Southern Tunisia expanded to approximately 1352 $km^2$ after the floods of January 1990 and shrunk by nearly 50% to 727 $km^2$ by March of the same year. In the Caprivi region of Namibia, the water levels and area of Lake Lyambezi was reported to be rising in the early to mid-1970s, and by 1984 the lake had shrunk to approximately 10 % of the lake area and eventually dried up in 1985 (van der Waal, 1984). A case of continual increase in area of an African lake has been documented, as Lake Basaka of Ethiopia is reported to have increased in area from 3 $km^2$ in 1960 to approximately 48.5 $km^2$ in 2010 (Dinka, 2012).

## 2.4 Causes of variations in lake area

Variations in spatial extent and water levels of natural water bodies that are free from anthropogenic influences have been reported by different authors (Bryant, 1999; Coe and Foley, 2001; Qiao *et al*., 2010). The primary drivers of areal extent changes of natural waterbodies are therefore climate based. Natural and man-made lakes characteristically exhibit spatial variations of varying degrees in response to climate variability. However, anthropogenic factors are known to accelerate and pronounce the lake area changes (Liu *et al*., 2006; Su and Jassby, 2000; Wang *et al*., 2012). The causes of variations in areal extent of lakes can be grouped in three categories, i.e. natural factors, anthropogenic factors and, interactions between natural and anthropogenic factors and their cumulative effects (Micklin 2007; Schindler 2001).

### 2.4.1 Natural drivers of lake areal changes

Climate variability represents the principal driver of variations in natural and man-made lake area. Climatological and physical meteorological factors exert direct and indirect pressures on water bodies and broadly affect water resources, and subsequently their goods and services (Bryant, 1999; Gao *et al*., 2011; Middelkoop *et al*., 2001; Wang *et al*., 2012). Thus, variations in areal extent are a way of responding to and exhibiting the effect of changes in magnitude and timing of climatological and meteorological components such as solar radiation, temperature, precipitation, evapotranspiration, floods, droughts and winds *inter alia* (Williamson *et al.*, 2011).

Other physical factors influencing lake dynamics are bathymetry, regional lithology and tectonic activities. The bathymetry of the lake determines the nature of interactions between the water body and meteorological factors, thereby shaping the physical response of the lake. Shallow lakes respond rapidly to climate variability, particularly changes in rainfall and run-off resulting in rapid areal and water level changes (Coe and Foley, 2001). The inclusion of lake bathymetry as a parameter while modelling the causes of the shrinkage of Lake Chad is reported to achieve more accurate results (Gao *et al*., 2011).

### 2.4.2 Human-based drivers of area variations of lakes

The human-based factors affecting the spatio-temporal variations of natural and man-made lakes are those pertaining to water abstractions and changes in river discharge. The abstraction of irrigation water represents the most important way through which human activities bring about lake area shrinkage (Becht and Harper, 2002; Chen *et al*., 2001; Coe and Foley, 2001; Gao *et al*., 2011; Micklin, 2007). Other water abstractions that exert pressure on stream flows and lake water volumes are those related to domestic water use, mining and industrial water uses, and redirecting water flows to augment discharge in neighbouring water systems (interbasin transfers) (Bai *et al*., 2011). Other key activities include land conversion and land use change. The conversion from natural grassland to forest plantation is one of the land use changes associated with a reduction of stream flows. In Canada, the conversion of prairie wetland area from cultivation to brome grass plantation in an effort to enhance bird habitats, is reported to have resulted in the drying out of the wetland area (Liu *et al*., 2006; Van Der Kamp *et al*., 1999).

### 2.4.3 Interactions between natural and human-based factors, and their cumulative effects

The interactions between natural and human based drivers of spatio-temporal variations of natural and man-made lakes create a complex environment for water resources. Events of climate variability such as low rainfall, dry spells and droughts, result in lower lake volumes, poor soil moisture (Nicholson, 2000) and triggers an increase in irrigation water requirements (Bai *et al*., 2011; Chen *et al*., 2001; FEWS, 1997; Zhang *et al*., 2010). Moreover, the occurrence of adverse conditions related to low rainfall events and droughts in successive years has a cumulative effect on water resources, causing massive shrinkage and desiccation of natural lakes (Chen *et al*., 2001; Gao *et al*., 2011; Nicholson, 2001; Schindler, 2001).

Several authors have reported on the cumulative impact of droughts on the water resources and lake size changes in major lakes of China and other parts of Asia (Agrawala *et al*., 2001; Aladin *et al*., 2005; Su and Jassby 2000, Wang *et al*., 2012). In Africa, it has been reported that the combined effects of climate variability and increased human water use has caused considerable changes to the water balance of the Chad basin (Coe and Foley, 2001; Gao *et al*., 2011; Liu *et* *al*., 2006). Another cause of pressure on the water resources of Lake Chad is stemming from population growth, which results in a higher demand for irrigation agriculture water (FEWS, 1997). Lake Chad has been reduced from 25 000 $km^2$ in area of open water to a small area of 1350 $km^2$, owing to the combined effects of climate variability and human water abstractions (Gao *et al*., 2011). The same fate befell the Aral Sea, which shrunk markedly due to irrigation water use and low rainfall between 1965 and 2000. However, an increase in average precipitation and a reduction in irrigation water withdrawals are reported to have improved the Aral Sea basin water balance in recent years. This shows that different sets of interactions between natural and human-based drivers of spatio-temporal variations can have a negative or positive effect on lake area (Micklin, 2007; Wang *et al*., 2012).

## 2.5 Climate change and climate variability

Global warming owing to the enhanced greenhouse effect is likely to have a significant impact on water resources management by increasing the variability and unpredictability of climate regimes and uncertainties in hydrological assessments. Climate change is characteristically associated with intermittent floods and droughts, low rainfall and increasing temperatures *inter alia* (Downing *et al*., 1997; Lioubimtseva and Henebry, 2009; Mortsch *et al*., 2000). The change in climatic phenomena at a greater magnitude has the potential to create a different water balance. Climate variability can also create a new set of natural conditions and perpetuate new local disturbance regimes on water resource systems, thereby affecting the environment, ecosystem and water availability due to the shrinkage of lakes (Middelkoop *et al*. 2001). Human water use for agricultural and other purposes is known to impact on water resources. However, it is reported that the major factor that controls inter-annual water fluxes and spatio-temporal variations is climate variability or change (Coe and Foley 2001; Gao *et al*., 2011; Liu *et al*., 2006; Qiao *et al*. 2010). Therefore, the major way in which humans affect water resources and the spatio-temporal variations of lakes is through economic activities that drive climate change.

## 2.6 Impacts of areal changes and shrinkage of lakes

The dynamic change in spatial extent of lakes impacts on the environment, water resources, local hydrology and climate, ecology, fisheries, and the socio-economic state. The shrinkage and drying up of lakes affects the contribution of lakes to the surface and sub-surface hydrology of the region. It also affects the ability of lakes to contribute to the flux of water between land and atmosphere (Bai *et al*., 2010; van der Kamp *et al*., 1999).

The shrinkage and drying up of lakes also triggers environmental and ecological problems by perpetuating conditions that exceed natural thresholds of ecosystem tolerance, giving rise to a different hydro-biological state (Aladin *et al*., 2005; Williamson, *et al*., 2009). The consequences of shifts in the hydro-biological equilibrium of lakes are diminished water quality, and changes in the trophic state, habitat types, and in the timing and range of processes. As such, the resident biodiversity is affected and lake productivity decreases (Lake 2003; López-Caloca, Tapia-Silvaa, and Escalante-Ramírez 2008).

Lake area changes are coupled with changes in lake water volumes and water resources availability for irrigation agriculture, economic development and other non-economic activities that support socio-economic well-being (Güneralp and Barlas, 2003). This situation results in reduced food security, given that climate variability also impacts on rain-fed agriculture, fisheries and other goods and services of lakes. Other impacts of lake area changes on humans are related to the spread of disease. The spread of bilharzia agents and mosquitos were reported in two areas (Minakawa *et al*., 2008).

## 2.7 The Use of remote sensing for environmental applications

The basic principle behind using remotely sensed data is that any subtle change in land cover results in a change in the radiance of that object and can be detected by satellite sensors (El-Asmar and Hereher, 2010). The advantages of using remote sensing for studying earth resources include the large ground coverage by satellite images, multiple spectral information of the satellite images, high temporal resolution of satellite data and the long-term time series of the satellite data archives (El-Asmar and Hereher, 2010; Sass *et al*., 2007).

Remote sensing techniques provide quick and useful tools to map surface water features and monitor the dynamics of surface water (Ji *et al*., 2009; Zhang *et al*., 2010). Owing to peculiar properties in reflection, absorption and transmission, water manifests obvious differences on remotely sensed images, and the boundary of water and land is relatively clear (Ho *et al*., 2010; Qiao *et al*., 2010). This development is of significant importance to hydrology research, particularly estimating water area and delineating the shoreline of water bodies (Li, 2011).

## 2.8 Remote sensing techniques for water resources delineation

One of the remote sensing techniques used for identification and delineation of water bodies is the band ratio technique. One of the commonly used band ratio techniques is the normalised difference water index (NDWI). This index borrows the principle (A-B/A+B) of the normalised difference vegetation index (NDVI) by using the reflectance difference of water and non-water features in certain pairs of bands.

The application of the NDWI to delineate water features is varied in that different scientists apply a different band combination (Tewari *et al*., 2003; Alesheikh *et al*., 2007). The initial application of the NDWI included the computation of a band ratio where the green and the near infrared bands are used in the band ratio function (McFeeters, 1996). Other band combination that make up the NDWI as applied in other studies include band ration computation based on the near infrared and short wave infrared (Gao, 1996), and red band and mid-infrared (Xu, 2002).

The problem associated with the existence of different band combination for the application of the NDWI technique for isolating water features is determining which band combination is most suitable and best achieves the objectives of the study in question. This situation presents a challenge in that the application of various band combinations is known to generate different results (Ji *et al*., 2009). Another problem associated with NDWI is that the threshold used as a basis for separating water, non-water and mixed pixels is a dynamic value.

In order to overcome the problems indicated above, the modified normalised difference water index (MNDWI) was developed (Bai *et al*., 2010; Ji *et al*., 2009; Li *et al*., 2011). The MNDWI separates the water features from vegetation, built-up area and soil more easily than the NDWI by computing a band ratio from the green and the mid-infrared bands (Li *et al*., 2009). In this band ratio technique, vegetation, built-up area and soil assume negative values, while water and city assumes positive values. Therefore, by applying a manual threshold, water and non-water features can be clearly separated (Ji *et al*., 2009).

## 2.9 Dynamic thresholding and segmentation for the delineation of the lake

Segmentation refers to the process of partitioning an image into regions that are homogeneous based on a given criteria (Gonzalez and Woods, 2002; Lira, 2006). One satellite scene usually contains objects that belong to various spectral classes such as water, bare land and vegetation *inter alia*. This represents a problem in remote sensing research which requires segmentation of different classes. In order to delineate water bodies i.e. mapping the shoreline of lakes and other water resources, the MNDWI is applied to enhance the water features of the lake and consequently suppress the non-water features. However, since this index is based on a band ratio rule as NDVI, an arbitrary threshold is required to generate a segmentation of the water bodies (Lira, 2006). The subsequent application of dynamic thresholding is important because different spectral classes take up different characteristics in the same satellite while similar classes may take up different characteristics in scenes from different periods. Therefore, an application of manual dynamic thresholding achieves accurate results in the segmentation and subsequent delineation of water bodies (Xu, 2006; Ji *et al*., 2009). Once segmentation of the water bodies is achieved, basic morphologic measure such as area calculation can be applied by means of mathematical morphology (Sagar *et al*., 1995; Lira, 2006).

**Table 2-1 dynamic thresholds for delineating of open water bodies**

| | | NDWI and NDVI threshold | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $f_w = 25\%$ | | | $f_w = 50\%$ | | | $f_w = 75\%$ | | | $f_w = 100\%$ |
| | Spectral water index | $f_s = 75\%$ | $f_s = 37.5\%$ | $f_s = 0\%$ | $f_s = 50\%$ | $f_s = 25\%$ | $f_s = 0\%$ | $f_s = 25\%$ | $f_s = 12.5\%$ | $f_s = 0\%$ | $f_s = 0\%$ |
| Sensor | | $f_v = 0\%$ | $f_v = 37.5\%$ | $f_v = 75\%$ | $f_v = 0\%$ | $f_v = 25\%$ | $f_v = 50\%$ | $f_v = 0\%$ | $f_v = 12.5\%$ | $f_v = 25\%$ | $f_v = 0\%$ |
| Landsat ETM+ | $NDWI_{L2,4}$ | −0.351 | −0.553 | −0.657 | −0.313 | −0.512 | −0.619 | −0.236 | −0.416 | −0.528 | 0.015 |
| | $NDWI_{L2,5}$ | −0.611 | −0.563 | −0.504 | −0.568 | −0.519 | −0.459 | −0.464 | −0.414 | −0.356 | 0.123 |
| | $NDWI_{L2,7}$ | −0.587 | −0.458 | −0.223 | −0.542 | −0.410 | −0.181 | −0.433 | −0.300 | −0.096 | 0.179 |

Table 2-1 shows the stable dynamic thresholds for the segmentation of open water bodies with various degrees of mixed pixels achieved from the application of the MNDWI (Ji *et al*., 2009). The dynamic thresholds for open water bodies have been examined and determined in various parts of the world (Hui *et al*., 2008 and Ji *et al*., 2009). This technique uses the pixel count information to calculate the area, the method is widely applied and even though it is reported to be downward biased (Gallego, 2004; Skakun, 2012). However, it is quick to apply and its accuracy is within an acceptable threshold, making it a commonly applied technique. The stable dynamic thresholds for delineating open water bodies have been reported in Ji *et al*., (2009).

## 2.10 The application of DEM for the extraction of catchment characteristics and topography-based hydrological parameters

The square grid DEM has been widely used in water resources and environmental application over the last decade. Principally, topography defines the pathways of surface water movement across a watershed. Therefore, the hydrological and land-surface response to rainfall and runoff in a catchment is driven by topography (Beven and Kirkby, 1979; Lane *et al*., 2004). DEM application has also been useful in the reconstruction of palaeodrainages owing to the ability of radar to penetrate sand and sediments, thereby revealing the characteristics of the subsurface features. The use of DEM for the reconstruction of palaeodrainages has been successfully applied in the Tushka basin located in Ethiopia (Yang *et al*., 2011).

In respect to hydrological research, the most important topographic attributes obtained from DEM application include flow accumulation, slope, and upslope contributing area, sub-catchment and the catchment area. Flow accumulation is critical in the extraction of stream networks. On the other hand, upslope contributing area is important when determining the topographic index. The topographic index is vital in GIS-based water resources application and modelling of parameters such as soil moisture and rainfall-runoff response of catchments (Beven and Kirkby, 1979; Stieglitz *et al*., 1997).

DEM provides a consistent basis for successfully extracting catchment characteristics over spatially large areas. Catchments can be delineated manually from topographic maps, but this process is compromised by the introduction of human errors, where output results differ from researcher to researcher. The use of DEM in hydrologic modelling of mesoscale area is proved to produce results of sufficient quality, but its use still presents some challenges in terms of reliability and accuracy. The accuracy of DEM application is affected by the resolution of square grids in the data and this often serves as a source of systematic errors during hydro-processing. The use of DEM data with different spatial resolution has varied effects on the topographic attributes obtained during extraction of parameters. For instance, low resolution DEMs tend to lump up slope and flow pathways, resulting in reduced magnitude of flow length, which in turn affects the stream network ordering outputs (Wu *et al*., 2008). In areas of generally flat topography, the inaccuracies of some DEM data are pronounced (Wu *et al*., 2007; Zhao *et al*., 2011). The use of moderate to high resolution DEM in the flat topography of the Caprivi region of Namibia for hydrological research and modelling has been reported to yield erroneous results (Pricope 2013; Skakun 2012).

## 2.11 Reliability of source floods

Water resources management strategies should be based on a comprehensive assessment of components that affect the availability of water resources, particularly components such as floods and rainfall that are responsible for the recharge of lakes and reservoirs. Generally, the flood hazard is best understood by specifying the probability of exceedence and return period of floods (Apel *et al*., 2004; Skakun, 2012). However, floods also represent a major source of water resources at local scale, in the case of Lake Lyambezi the Zambezi floods represents the major driver of its water resources variations (van der Waal, 1980). Therefore, in order to determine the reliability of source floods in recharging the lake water resources, the probability of exceedence concept is borrowed. This is also useful to ascertain whether floods or rainfall variability affect the inundation of Lyambezi the most.

## 2.12 Conclusion

Intra and inter annual variations in the area of natural and man-made lakes have been reported globally and principally, it is a phenomenon of climate variability. Human water use for agricultural purposes and economic development is the other important factor driving the changes in area of water bodies. The various degrees of spatial variations have several consequences on environment, ecosystem, regional hydrology, food security and spread of disease. Therefore, scientific information on the dynamics regarding changes in lake area is important for water resources management, particularly in the implementation of appropriate management regimes.

The water features of the lake can be extracted from remotely sensed data using MNDWI and the application of dynamic thresholding to segment water from non-water features. The use of remote sensing based square grid DEMs is also useful in the extraction of catchment characteristics. However, there are still some challenges pertaining to reliability and accuracy of outputs of DEMs of different resolutions.

# 3. DESCRIPTION OF THE STUDY AREA

## 3.1 Description of the Caprivi and location of Lake Lyambezi

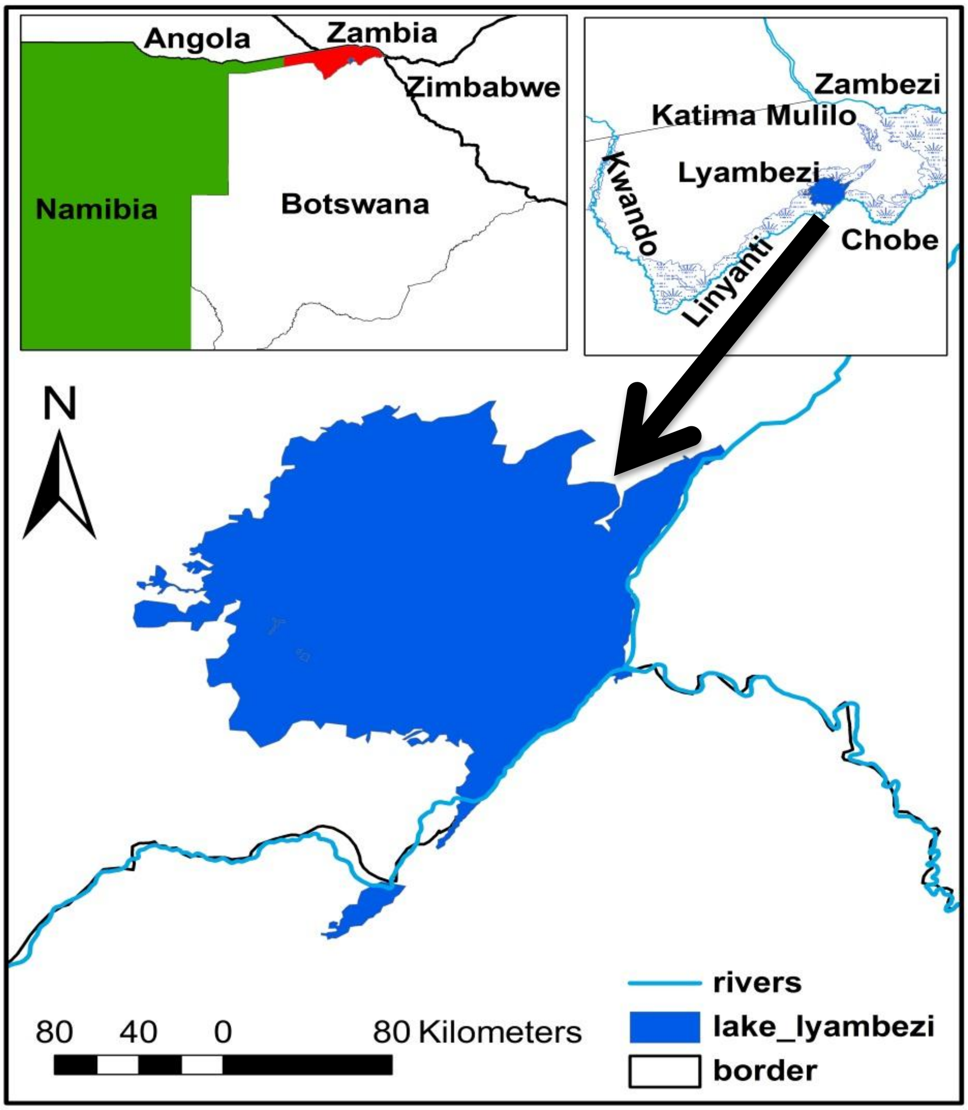


**Figure 3-1 Location of Lake Lyambezi**

The study was done on Lake Lyambezi which is located in northeastern Namibia's Caprivi region. As shown in Figure 3.1, the Caprivi region is an arm-like extension of Namibia that is bordered by four southern African countries of Zambia and Angola in the north and northeast, and Botswana and Zimbabwe in the south and southeast. Lake Lyambezi is located on the

Chobe-Linyanti wetland system (Pricope, 2013) southeast of Katima Mulilo, where it connects with the rivers forming a border between Namibia and Botswana (van der Waal, 1980). When it is beyond 200 $km^2$ threshold in area extent, Lyambezi extends into Botswana, thereby becoming a transboundary water body.

Lake Lyambezi is regarded as a periodic water body. However, it has a history of being inundated for long periods. When the lake is robust, it forms an important part of the local fishery (Hay *et al.,* 2002; van der Waal, 1980). Therefore, for several generations the lake formed an integral part of society, supporting biodiversity, livelihoods and transport systems until when it completely desiccated late in 1985. After drying up the lake bed was utilised for crop and livestock farming by local communities. However, fire outbreaks were frequently reported owing to the presence of pockets of methane. The lake started filling up again in 2001 when the region went through a wet period (Turpie and Egoh, 2002).

The Caprivi region has a mosaic of land uses, with one urban settlement at Katima Mulilo, which serves as an exit out of Namibia through the Trans Caprivi highway, which forms part of the Capetown-Lumbubashi flow path. The other key land uses include conservancies and protected areas, and communal lands that are used for crop farming, grazing and veld land (Pricope, 2013). The roads connecting rural settlements to the town of Katima Mulilo are gravel except for the Ngoma road and the Trans Caprivi. Since independence, rural areas have also been provided with school and health infrastructure.

## 3.2 Elevation and physical characteristics

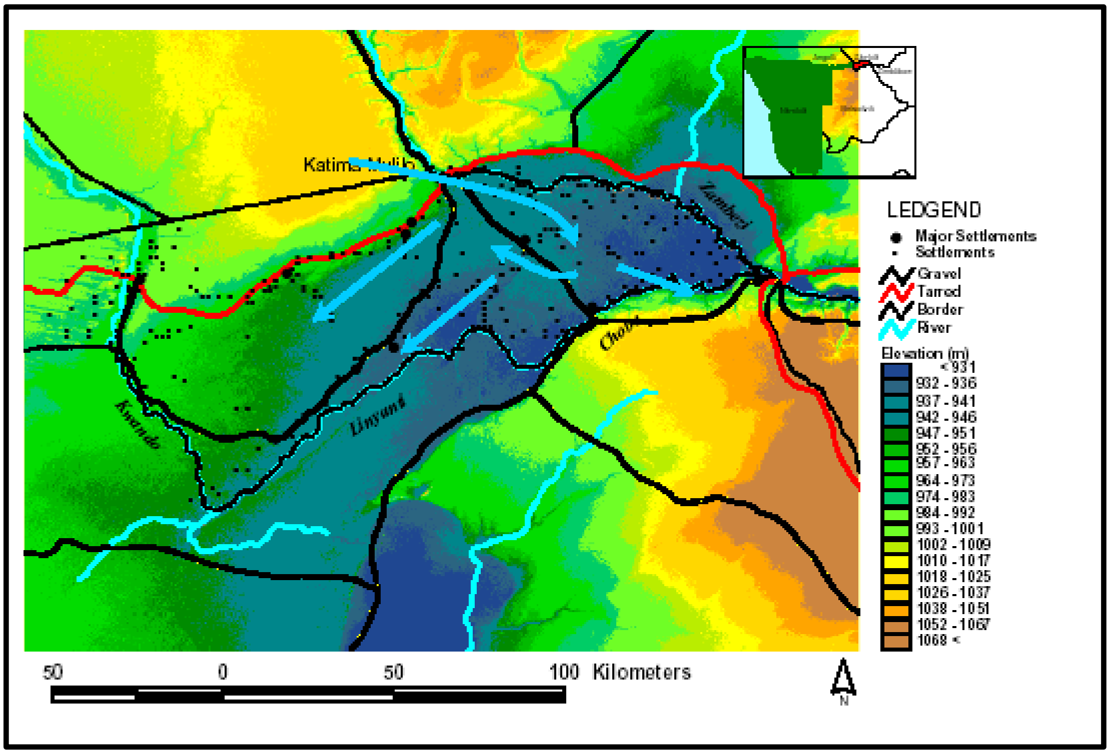


**Figure 3-2 Elevation and topographical features of the Caprivi (source: Murwira in Gumindoga, 2008)**

The regional terrain relief is generally flat to gently undulating. As shown in Figure 3.2 above, actual regional elevation varies between 900 and 1110 m.a.s.l. The eastern part of the region represents areas of lower elevation (less than 950 m.a.s.l), while areas towards the west represent areas of higher elevation (950 m.a.s.l)

## 3.3 Hydrology of the Caprivi

The hydrology of the Caprivi region is characterised by a presence of two of Namibia's five perennial rivers, as shown in Figure 3.3. The Zambezi and Kwando Rivers enter the region at Katima Mulilo and Singalamwe while their catchment areas lie in Zambia and Angola. The rivers flood up to a third of the region however, the actual extent of flooding is dependent on the magnitude of the local rainfall (Mendelsohn and Roberts, 1997).

The region also consists of the Chobe and the Linyanti rivers, which are essentially extensions of the Zambezi and the Kwando Rivers (Mendelsohn and Roberts, 1997). The Linyanti River disintegrates into a wetland system that connects to Lake Lyambezi. The Chobe seems to originate from the Lake and is characterised by bidirectional flow, depending on the level of floods. During the flood season, the Chobe serves as a flood release point and tributary of the Zambezi, with an east to west directional flow. If the Zambezi floods are high, the Chobe will end up flowing into Lake Lyambezi. Therefore, the Chobe is the main system with which the Zambezi interacts and through which it impacts on water resources of Lake Lyambezi. When floods recede, the Chobe assumes a west to east directional flow, connecting to the Zambezi at Kazungula.

The region also has an extensive wetland system along the main rivers. The wetland area is grouped into three wetland systems. The Mamili wetland system lies at the heart of the Kwando River, and connects to the Linyanti-Chobe wetland system which is linked to the Zambezi wetland system (Pricope, 2013). During the floods, major parts of the wetland sub-categories become inter-linked.

Lake Lyambezi forms part of the Linyanti-Chobe wetland system, and it is located at the centre of influence of all the rivers in the Caprivi region. During normal hydrological conditions Lyambezi will seasonally receive flood water from the Kwando via the Linyanti and from the Zambezi via the Chobe River. However, during very wet seasons characterised by more rainfall and high floods, a third source of inflow is created. The lake receives water from the Zambezi via the Kalengwe channel which receives overland flow coming from the Zambezi through the Bukalo-Isuma flood flow path.

### 3.3.1 Rainfall and flood regimes

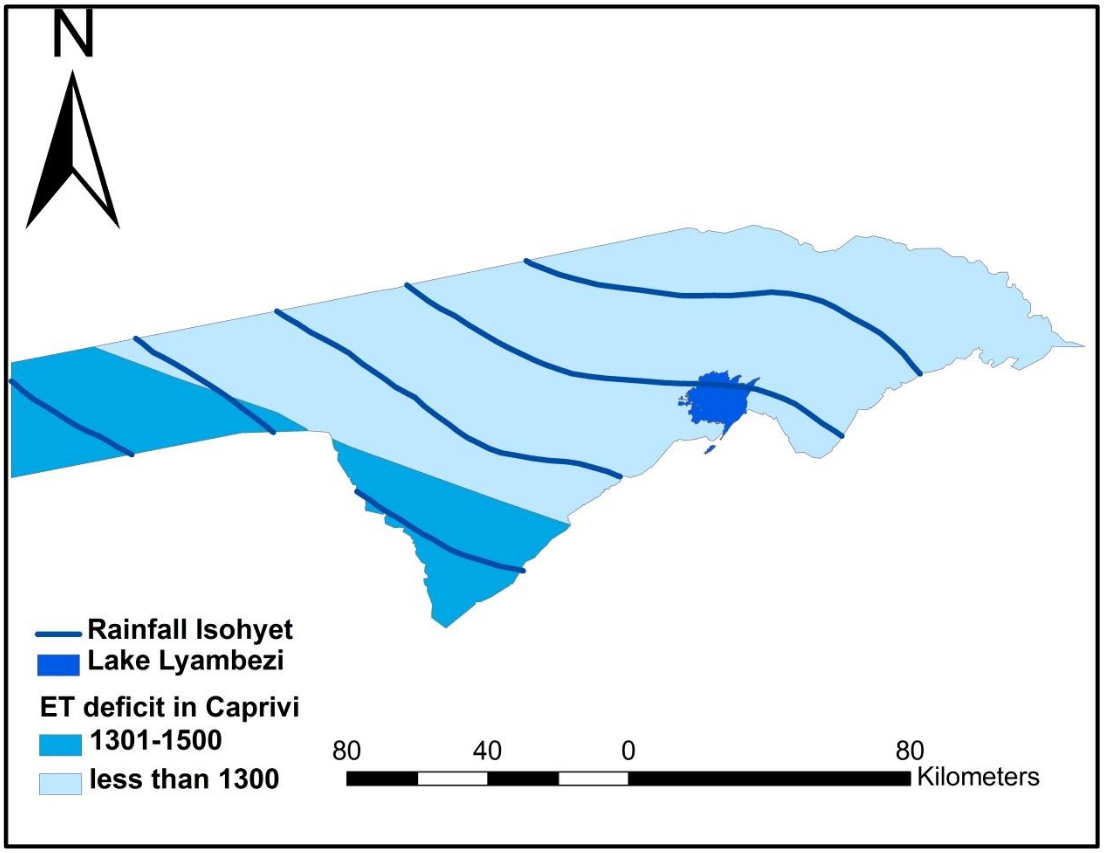


**Figure 3-3 Regional Isohyets and ET deficit variation**

Namibia is an arid to semi-arid country with highly variable rainfall. Figure 3-3 shows the isohyets which represent the variation of total annual regional rainfall. In the eastern Caprivi, total annual rainfall varies between 660 and 700 mm (Mendelsohn *et al*., 2002). Lake Lyambezi is located in the area that receives between 680 and 690 of total annual rainfall.

The Caprivi receives seasonal flood pulse driven by the Zambezi, where the flood water originates from the catchments in Zambia and Angola, where annual rainfall is more than 1000mm. The magnitude and impact of the floods at local scale is dependent on the amount of rainfall received locally. The region also receives floods in the areas that lie along the Kwando River. The Kwando receives a delayed flood pulse, as the flood water from the rain season is collected by the Silowana floodplains that act as a sponge and store large quantities of water and releasing it slowly, thereby flooding the Kwando during the months of August and September.

On the other hand, the consequence of aridity of the Namibian climate is that the country has higher evapotranspiration than annual rainfall resulting in very large ET deficit. Figure 3.4 shows that in the Caprivi regional, ET deficit ranges between 1301 to 1500 mm in the Southwest and Western part of the region, while the entire region has an ET deficit less than 1300 mm.

## 3.4 Geology, soils and vegetation

The geology of the Caprivi is characterised by thick deposits of Kalahari sands. Patchy rock deposits are found in the Zambezi River at Katima Mulilo and at Impalila Island (Hay *et al*., 2002; Mendelsohn & Roberts, 1997). Some rock deposits occur on the Chobe at Kabulabula and Kasika areas. The Kalahari sands in Western Caprivi are of the Omuramba dune association and hence they constitute the region of higher elevation. The sands along the Kwando are a terrace of the Okavango and Kwando Rivers, while those on the central part of the region form a stabilised sand drift with few pans, the rest of the sands form the floodplain of the Zambezi-Kwando-Linyanti-Chobe River systems.

Vegetation in the Caprivi varies according to soil type and incidence of flooding and fires. The Kalahari sands support trees commonly known as teak, kiaat, mangetti and false mopane. Camel thorns, leadwood and knob-thorns grow in light clay soils, while mopane trees are characteristic of the heavy soils. Vegetation in many areas was previously classified as dense woodlands but most parts have been converted to open grass, shrubland and false woodland as a result of frequent fires and floods. A frequent occurrence of fires harms the vegetation and increases the vulnerability of the region to bush encroachment. Wetland areas are characterised by tall grasses and thick reed beds (Mendelsohn and Roberts, 1997).

## 3.5 Demography and livelihoods

The population in the Caprivi region based on the national population census statistics of 2011 is 90 100 (NSA, 2012). The majority of the population lives in rural settlements along main and trunk road networks in the region. The local livelihood is based on a subsistence economy driven by small-scale rainfed agriculture, fisheries, wild foods and a reliance on natural resources such as wood for fuel, tree products for building, grass for thatching, reeds for building courtyards and sleeping mats while Lala palm products are used for weaving baskets (Mendelsohn and Roberts, 1997; Purvis, 2001). The main crops grown are maize, millet and maize, beans and pumpkins. Cattle and goat rearing is common, and rearing of cattle is regarded as the major way of accumulating wealth. Cattle are integral to the traditional way of living and are important means of transport particularly drawing of sledges and ploughs during the season to till the land.

### 3.5.1 The communities around Lyambezi

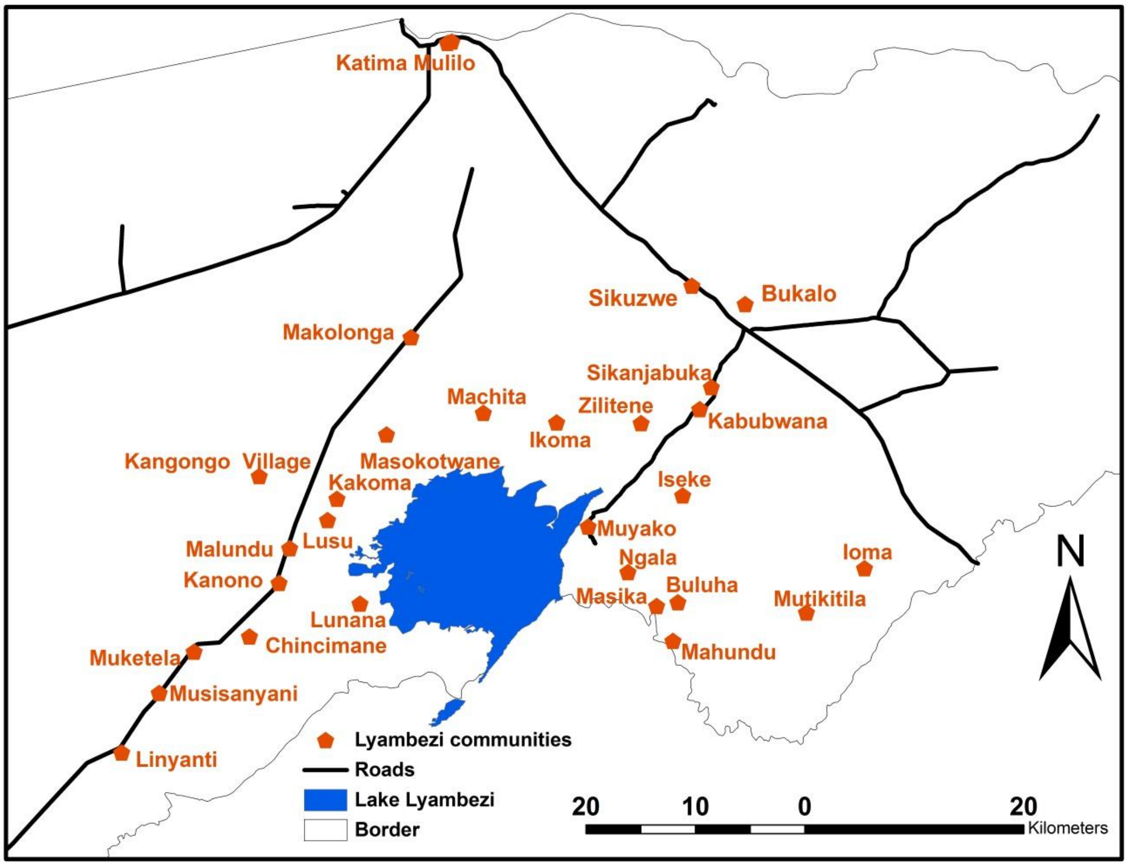


**Figure 3-4 Community settlements around Lymbezi Lake**

According to traditional land tenure system, traditional authorities serve as custodians of natural and water resources on behalf of their subjects. In other cases, exploitation rights are held by residents living next to the water body (Purvis, 2001). Figure 3.5 shows the set of villages and communities around Lake Lyambezi. The communities located on the eastern side of the lake fall under the Bukalo traditional authority while the rest of the communities belong to the Cincimani traditional authority.

# 4. METHODS

## 4.1. Data

The data used in this study are shown in Table 4.1.

**Table 4-1 Data used in the study**

| Data type | Source |
|---|---|
| Digital Elevation Model (DEM) | 90m DEM resolution SRTM and SRTM 3, and 30m resolution ASTER GDEM, Earth Explorer, USGS |
| Satellite imagery (Landsat TM, ETM+ and Landsat 8 OLI) | LP DAAC DATA POOL, NASA |
| Lake Lyambezi water levels (2007 – 2013) | NNF |
| Lake Lyambezi water levels (1973 – 1985) | DWAF, Statistics division |
| Zambezi, Kwando and Chobe River Levels | DWAF, Statistics division |

## 4.2. DNO hydroprocessing for the extraction of catchments characteristics

The Drainage Network Ordering (DNO) hydroprocessing of the DEMs was based on Maathuis and Wang (2006), with methods described in the next subsections. The application of DEM generally is important for the extraction of parameters used when performing distributed or lumped rainfall-runoff modelling.

### 4.2.1. Flow determination

***Filling sinks***

Three different DEMs with 30m and 90m pixel resolution were used in modelling catchment characteristics. The initial preparation of the DEM started with filling sinks. Sinks are depressions contained in single or multi pixels as a result of errors in interpolation, especially in areas of gentle relief. Sinks represent a problem because they disrupt the drainage topology and need to be removed to produce a continuous flow direction grid.

***Flow direction***

The flow direction was calculated using ILWIS DNO hydroprocessing tools (ITC, 2003). By definition the flow direction is the direction in which water in the neighbouring pixels would flow, following the topographic slope. This is the basis of all further catchment modelling processes. In ILWIS the DNO hydroprocessing algorithm was used to compute the flow direction. The output of the flow direction is a grid map showing directions of flow based on the eight main directions on a compass. The flow direction was used to determine the flow accumulation and stream networks and further, as a step-wise process of DNO hydroprocessing.

***Flow accumulation***

The flow accumulation performs a cumulative count of the upstream water flowing naturally into a single outlet. It was computed by using the flow direction grid as input layer while performing DNO hydroprocessing in ILWIS 3.1.

### 4.2.2 Stream networks

The flow accumulation grid was used to extract the drainage network (streams). A minimum flow accumulation value of 300 was used to reduce the fuzziness of stream networks in the catchment. Values beyond the specified flow accumulation threshold (300) were defined as stream. The output is a segment map showing the water channel network in the catchment.

### 4.2.3 Extraction of the catchments

For each drainage segment or channel created during the stream networking process, the corresponding catchment area was computed in the step-wise process of DNO hydroprocessing performed using ILWIS 3.1. Two output maps, in raster and shape format were produced and they consisted of numbered microcatchment areas. The catchments were extracted based on the stream network obtained from 4000 flow accumulation threshold in order to produce outputs with less fuzziness and appropriate for water resources planning.

### 4.2.4 Compound parameter extraction

In a GIS environment, the following maps were computed: the overland flow length, the flow length to outlet, the wetness index, the sediment transportation index and the slope contributing area. The overland flow length is the distance of water flow from the stream network. The wetness index is represented by the following function (Beven and Kirkby, 1993):

$$w = \ln(As/\tan(\beta)) \quad (2)$$

## 4.3. Creating colour composite images

The first step to determining the dynamic lake water areal extent was onscreen digitising of the shoreline as the represented by the outer extent of the lake body from remotely sensed data. In order to digitise the shoreline, colour composite visual image outputs were created using ILWIS 3.1 based on Landsat TM, ETM+ and Landsat 8 OLI data. For Landsat TM and ETM+; bands 5, 4 and 3 were used to represent the red, blue and green (RGB) band combination to form a vegetation analysis colour composite which enhances the difference between vegetation, water and other feature classes in the scene. Band 5 records radiance in the bandwidth between 1.55-1.75µm while band 4 records radiance between 0.77-0.99µm, and band 3 records radiance in the bandwidth between 0.63-0.69µm. For Landsat 8 OLI data, the vegetation analysis colour composite image of was formed using bands 6, 5 and 4 in the RGB band combination order. Band 6 of Landsat 8 records radiation in the bandwidth of 1.55-1.65µm, while band 5 records radiation in the bandwidth of 0.85-0.88µm and band 4 records radiation in the bandwidth 0.64-0.67µm (USGS, 2013). The enhanced difference between water and other spectral classes paved the way for digitisation of the lake boundary.

## 4.4. Calculating the maximum area of the lake from DEM

In order to calculate the potential maximum area of Lake Lyambezi, the DEM was loaded as unique values to so as to visualise the depression and shape of the lake. Subsequently, the maximum lake boundary was digitised by following the outermost boundary of the topographic depressions as seen on DEM, and its area was calculated from the histograms of the rasterised polygon resampled to 30m spatial resolution.

## 4.5. Determining the area by digitising

Using ILWIS GIS tools (ITC, 2003) the dynamic areal extent of the lake water resources was calculated based the histograms of the rasterised polygons that were resampled to 30m spatial resolution. In the case of Lake Lyambezi, the area obtained from this method will result in the overestimation of the lake volume when used in the mathematical models for lake water resources quantification. This is because it does not exclude the area covered by land features (a series of islands) in the lake.

## 4.6. The use of MNDWI for enhancing water features

The Modified Normalised Difference Water Index (MNDWI) was used to enhance the water features in the satellite scenes (Xu, 2006). The MNDWI represents an improvement on the NDWI described by McFeeters (1996) as a way of separating water features from non-water features in the same scene of satellite imagery. The MNDWI is better able to enhance open water features while efficiently suppressing, and in some cases completely removing non-water feature noise in the same satellite scene. The MNDWI was applied as a band ration involving the green and mid-infrared band and is expressed as follows (Xu, 2006; Xu, 2007; Ji *et al*., 2009):

$$MNDWI = \frac{Green - MIR}{Green + MIR} \quad (1)$$

For Landsat TM and ETM+ imagery, the above expression was satisfied by using band 2 and band 5 to represent green and mid-infrared respectively and was applied as shown by equation 1a. Some of the available Landsat ETM+ images were stripped as the result of the scan line corrector failure of the sensors onboard Landsat 7. Therefore, some of the scenes had missing pixels. The striped images were used without correcting the line strips, in spite of this, they still proved useful in representing the dynamic changes in the areal extent of Lake Lyambezi.

$$MNDWI = \frac{Band\ 2 - Band\ 5}{Band\ 2 + Band\ 5} \quad (1a)$$

For Landsat 8 OLI imagery, the MNDWI expression was satisfied by using band 3 and band 6 to represent the green and the mid-infrared respectively, and was applied as follows:

$$MNDWI = \frac{Band\ 3 - Band\ 6}{Band\ 3 + Band\ 6} \qquad (1b)$$

The MNDWI function was applied on Landsat imagery using ILWIS tools, by writing the equations 1(a) and 1(b) as a script in the ILWIS command line.

### 4.6.1 Dynamic thresholding and segmentation for the delineation of the lake

The segmentation of water and other spectral classes in the satellite images was performed based on the thresholds indicated below.

**Table 4-2 Dynamic thresholds used for delineating Lyambezi Lake**

| Spectral class | Threshold A | Threshold B | Threshold C | Threshold D | Threshold E |
|---|---|---|---|---|---|
| Water | 0-1 | 0-1 | 0-1 | 0-1 | 0-1 |
| Water and Vegetation | (-0.10)-0 | 0-(-0.20) | 0-(-0.30) | 0-(-0.25) | 0-(-0.46) |
| Land and Vegetation | (-0.10)-(-1) | (-0.20)-(-1) | (-0.30)-(-1) | (-0.25)-(-1) | (-0.46)-(-1) |

In this study, the dynamic thresholds were grouped into 5 categories as shown in Table 3-2 above. The segmentation of spectral classes on the satellite scene (including lake) was done based on the five categories of dynamic thresholds. After segmentation, the lake boundary obtained from digitising was used to clip the lake body from the satellite scene. The clipping of the lake area was performed by writing a GIS overlay function. After clipping the lake area, the threshold performing best in segmentation of spectral classes for each satellite scene, was chosen based on how it conformed to ground truthing data. To test the efficiency of the thresholds the error matrix was generated in Excel after the pixel information was obtained from a cross of the segmentation and the ground truthing data. Subsequently, the area covered by the spectral classes forming the lake was calculated from the histograms and a one-sample t-test was used to compare and test for significant differences with the means of lake areas obtained based on different thresholds for MNDWI.

## 4.7 Hydrological analysis

The hydrological analysis started with the construction and visual inspection of the regional hydrographs and the long-term isohyetal graph. The hydrographs and isohyetal graph were constructed using Microsoft Excel to show the long-term variations in the water levels of the Caprivi Rivers, Lake Lyambezi, and in rainfall.

### 4.7.1 The link and inter-relatedness between rivers and the lake

In order to investigate the link and relationship between rivers and Lake Lyambezi, a correlation analysis was performed using SPSS. This was done to determine which river system affects the lake water variations.

### 4.7.2 The probability of exceedence and return period of floods

In order to determine the reliability of source floods, the probability and frequency of occurrence of flood events equal or greater than the average long term maximum flood level. The concepts of probability of exceedence/occurrence and return period of floods were adopted from flood hazard management through development of flood routing infrastructure (Apel *et al*., 2004). Therefore, the probability of exceedence and the return period of maximum annual flood level were calculated using the Weibull equation (Skakun, 2012):

$$R = (n + 1)/m \qquad (3)$$

Where *m* denotes the rank order of the flood event and *n* denotes the total number of flood years being investigated. i.e. *m*=1 denotes the rank of the year with the maximum flood, *m*=2 denotes the second maximum discharge and so on. Based on the Zambezi water levels data, the maximum annual discharges were sorted in descending order and subsequently the probability of occurrence was calculated. The return period of flood events was calculated as the inverse of the of the Weibull equation (Skakun, 2012).

# 5 RESULTS AND DISCUSSION

## 5.1 Topographic based hydrological components in the Caprivi

### 5.1.1 Flow determination

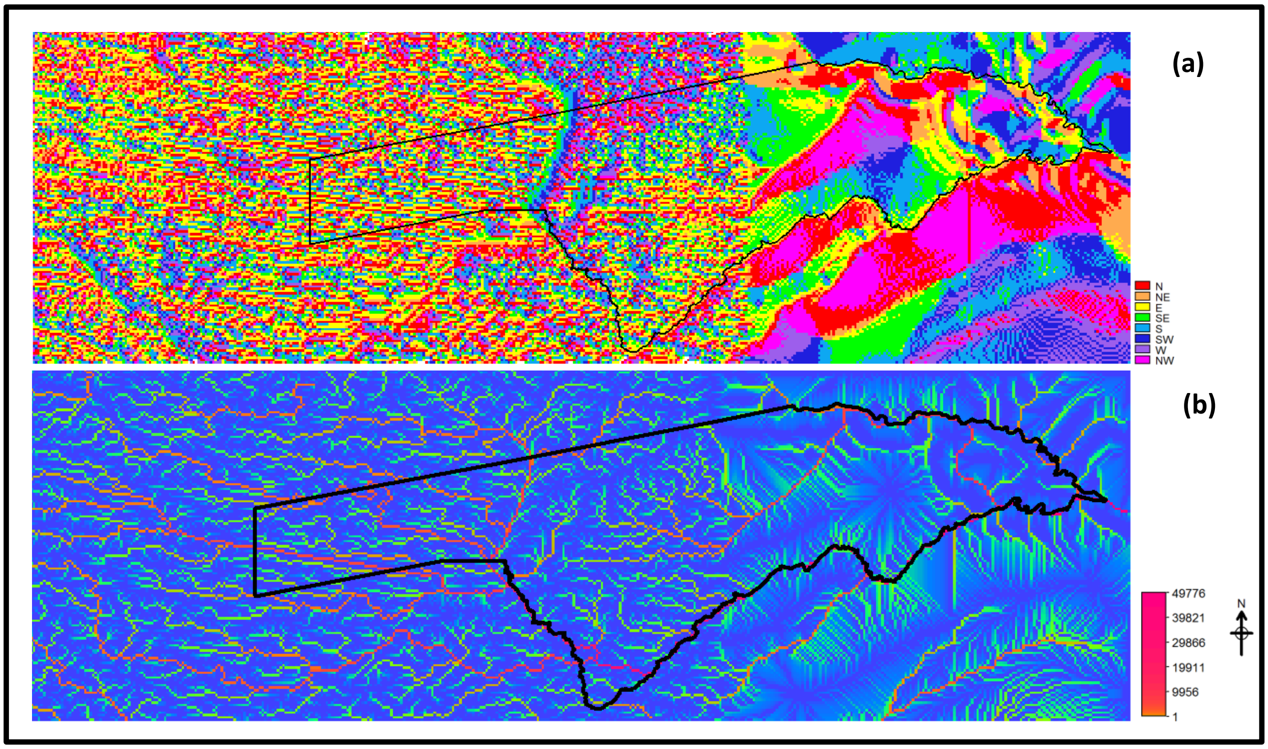


**Figure 5-1 Flow direction (a) and Flow accumulation (b) maps**

In the Caprivi region the application of DEM for watershed modelling has been reported to yield errors. The failure of DEM in watershed modelling has been linked to the flat topographic terrain and its characteristic sandy nature (Pricope, 2013; Skakun, 2012). The ability of radar to penetrate through sediment and sand results in the successful modelling of palaeo stream networks (Yang *et al*., 2011), but maybe attributed to the poor extraction catchment characteristics of the sandy terrain of Caprivi region. However, critical investigation of the usefulness of available DEM data has proved that SRTM 3 DEM yields useful results and was successful in extracting of topography-based hydrological modelling parameters. It can be observed in Figure 5-1(a) that modelling the flow direction of accumulated water in the Caprivi sub-basin showed an eastern flow direction for the Zambezi, Linyanti and Chobe Rivers which was consistent with actual flow direction. The Chobe has a seasonal western direction flow during floods, but assumes a predominantly eastern directional flow, while the greatly meandering Kwando showed a southeast and eastern directional flow, which is consistent with actual flow direction. At Kongola, the Kwando flows southeast before it meanders eastward towards Mamili wetland system. The flow accumulation (Figure 5-1 (b)) results showed that water accumulated in the stream network, this was also consistent with condition of the ground features, since at the sub-basin level water accumulates in the channels, thereby creating perennial and ephemeral rivers. On the other hand, the use of SRTM and ASTER DEM yielded erroneous results when applied in the process of flow determination. The error was related to failure to fill sinks, this step of DNO hydroprocessing on SRTM and ASTER DEM resulted in a blank map output.

### 5.1.2 Stream network and catchment extraction

The delineation and extraction of topography-based sub-catchments at basin and sub-basin scales is important for indicating micro-zones with similar hydrologic characteristics and responses to local factors.

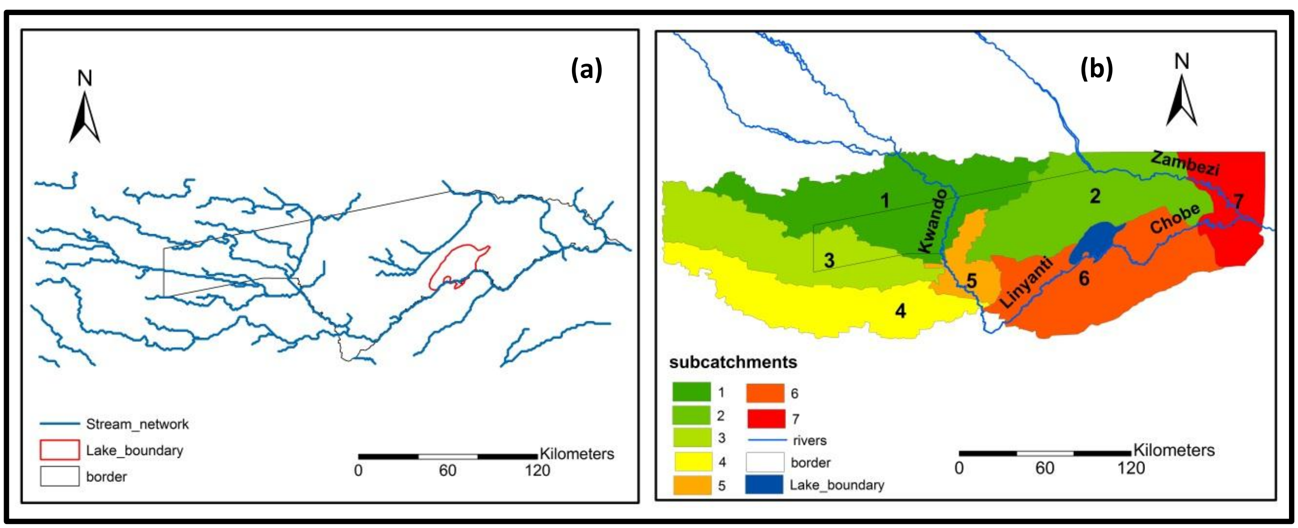


**Figure 5-2 (a) Stream networks of the Caprivi sub-basins (b) Sub-catchments**

The topography-based stream network of the Caprivi sub-basin is shown in Figure 5-2(a). The stream network extracted reveals the presence of perennial and ephemeral rivers. The rivers extracted from DEM are of a homogeneous nature. This is not consistent with actual characteristics of rivers in the sub-basin because the main rivers are larger than the side streams and the ephemeral streams, but these results remain highly useful in the modelling watersheds (Maathuis and Wang, 2006).

Figure 5-2(a) also shows Zambezi River disjointed in two sections and a representation of the location of Lake Lyambezi in relation to the stream network. The first part of the Zambezi branches sharply to the southeast and reaches the Chobe, while the second part also forms intersection with the Chobe at the end of the Caprivi sub-basin. This representation of the topography-based stream network deviates from the actual state of the rivers, as the Zambezi River is the largest in the Sub-basin and exists as a continuous river. The branching section of the first Zambezi clearly demarcates the boundary between the Zambezi and the Chobe-Linyanti wetland system which is consistent with the wetland grouping by Pricope (2013). Also, the branching channel may represent the palaeo Zambezi or maybe a result of DEM-borne inaccuracies. Therefore, this requires further investigation.

Figure 5-2(b) shows the topography-based sub-catchments of the Caprivi sub-basin. The Caprivi sub-basin is categorised in 8 sub-catchments based on the 4000 stream network threshold. Seven of these sub-catchments are presented while the small section that belongs to catchment 8 was excluded owing to the limitations based on the limited spatial size of the acquired DEM data. It is also observed from Figure 5-2(b) that Lake Lyambezi lies in sub-catchments 2 and 7.

### 5.1.3 Compound parameter extraction and indices

The compound parameters shown in Figure 5-3 are important for characterising the flow length of discharge overland and to an outlet point. They also serve to indicate areas of potential ground water recharge *inter alia*.

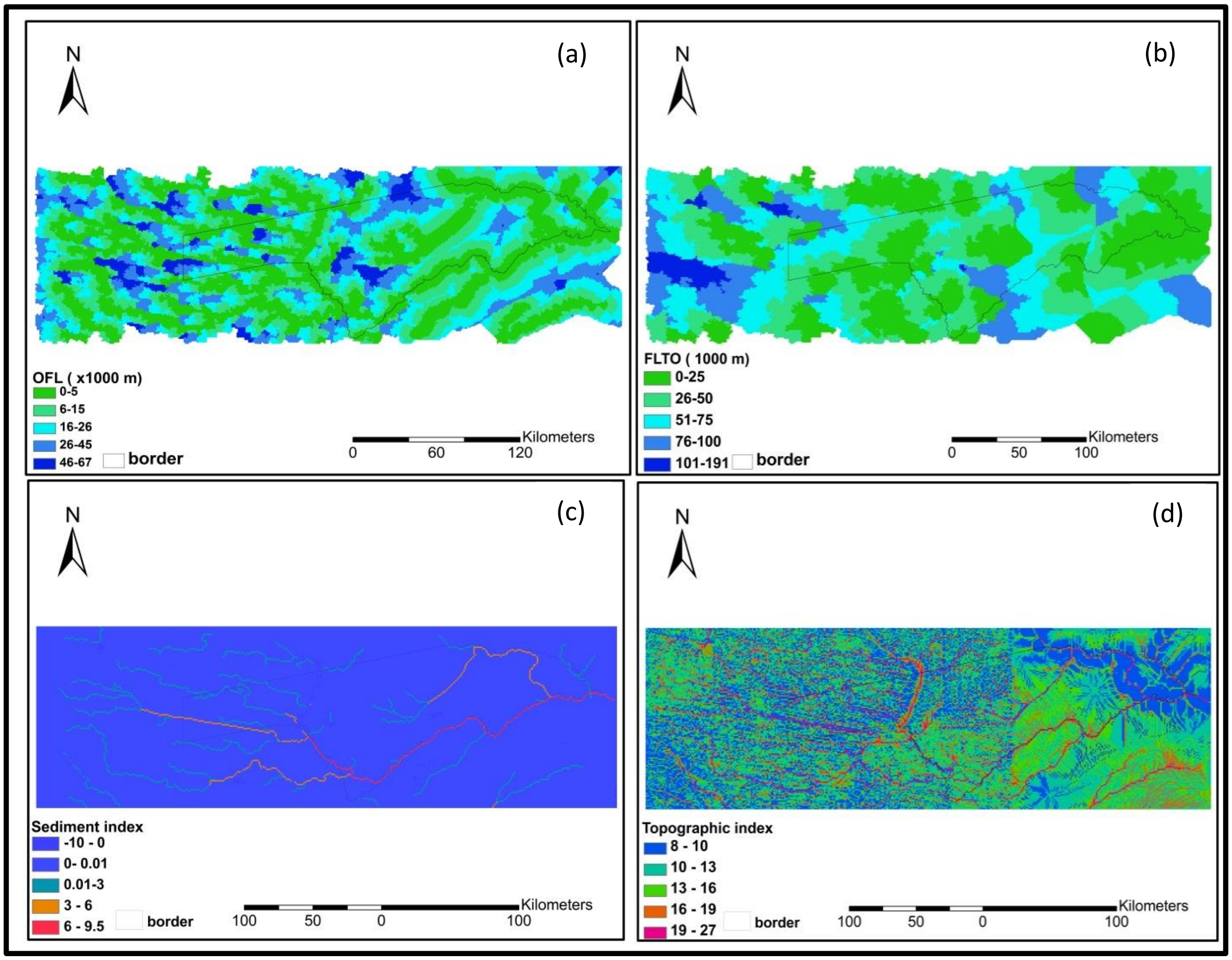


**Figure 5-3 The Compound parameter index**

Part (a) and (b) of the Figure 5-3 shows the overland flow length and the flow length to outlet. The location of Lake Lyambezi lies in the 0-25 km range of overland flow length from the Chobe, Linyanti and the Linyanti-Chobe outlet. Part of Lake Lyambezi lies on sub-catchment 2, which includes the Zambezi River. However, the actual location of the lake has an OFL between 46 and 67 km from the Zambezi. The distance between the lake and the Zambezi lies with the OFL range, therefore, runoff generated from the Zambezi can trickle to Lyambezi as overland discharge. This is however, dependent on the prevailing hydrological conditions particularly the Zambezi water level and rainfall in the Caprivi sub-basin.

Figure 5-3(d) also shows the topographic (*wetness*) index of the Caprivi sub-basin. The lower TI values represent drier areas that will shed water i.e. zones of runoff generation, while the higher values represent areas that will gather water i.e. zones of moisture saturation. It is observed that the rivers represent areas of moisture saturation while the eastern part of the Zambezi and the Chobe-Linyanti wetland systems (commonly called *Chana* by locals) are predominantly areas of runoff generation. Thus at a local scale, point rainfall-based runoff is generated from areas with low TI which shed water towards the stream network (zones of moisture saturation). The Lyambezi sub-catchments which lie on the central part of the Chobe-Linyanti showed moderate TI i.e. moderate retention of moisture. Therefore, when dry local hydrological conditions prevail, the Lake Lyambezi area is likely to progressively dry out before the major streams dry, because it is an area of moderate moisture saturation and therefore more vulnerable to climatic changes/variability.

Within the Caprivi sub-basin, areas of runoff generation are usually those of relatively high elevation with steep slope compared to their surroundings i.e. areas of lower TI. However, large scale floods in the sub-basin are driven by major rivers which swells up as a result of discharge received from the rainfall events that occurred in the catchments in Angola and Zambia. It is reported that in the Caprivi sub-basin the streams (zones of moisture saturation) receive flood water first and subsequently generate runoff as a consequence of overtopping of banks. When the banks are overtopped flooding becomes a function of distance from stream network (Gumindoga 2008). When the Zambezi banks are overtopped by flood waters, depending on the wetness of the season, the runoff will flow into Lake Lyambezi via the Chobe River and as overland flow via the Bukalo-Isuma flow path.

The sediment transportation index is showed in Figure 5-3(c) and it represents areas of sediment deposition and potential sediment source areas. The lower sediment index values show sediment source areas while the higher sediment index values represent areas of sediment deposition. Thus the Caprivi sub-basin is predominantly a source area of sediments based on the sediment transportation index, while the local stream network represents the area of sediment deposition. However, sedimentation is not a challenge to water resources management, due to the characteristic presence of Kalahari sands that are associated with higher infiltration rates, and local vegetation also reduces the risk of sedimentation and potential for soil erosion at local scale.

## 5.2 Inter-annual Lake Lyambezi area variations

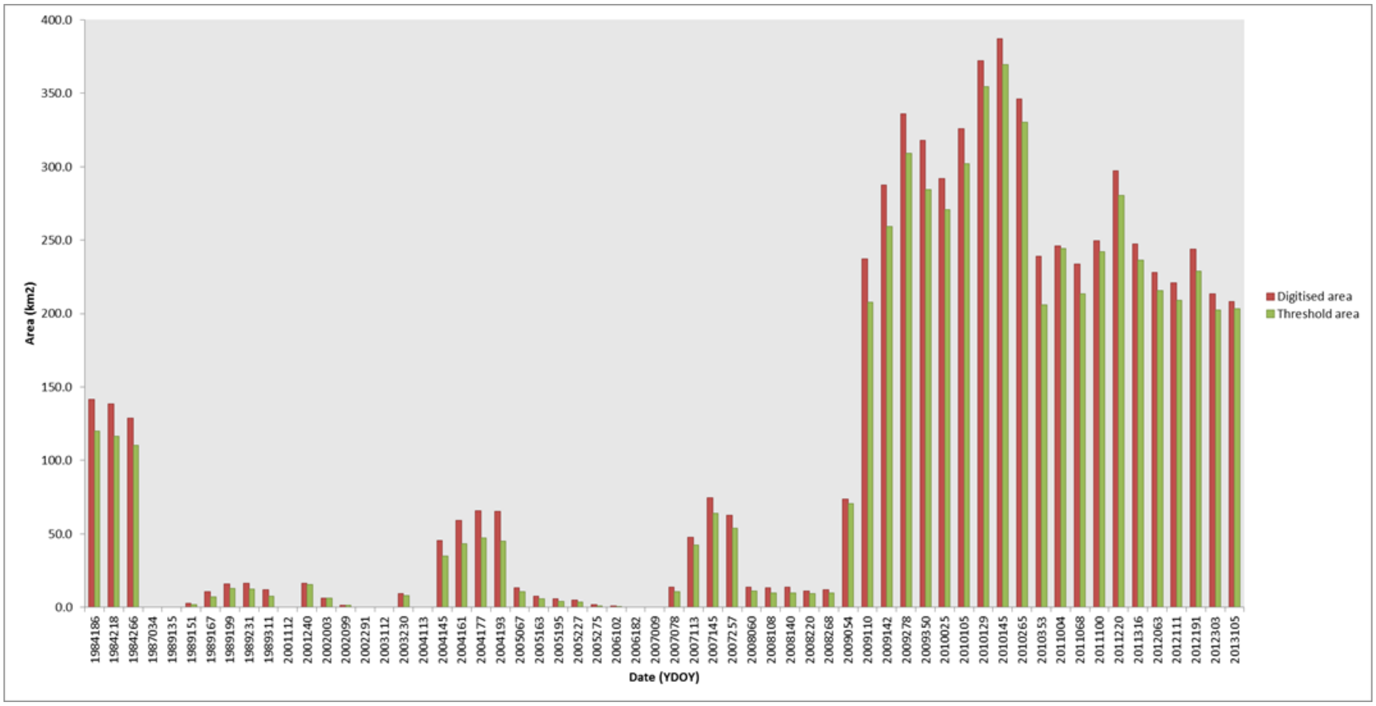


**Figure 5-4 Lake Lyambezi area variation**

Figure 5-4 shows the areal variations of Lake Lyambezi from day 186 of 1984 to day 105 of 2013. Hence, it can be observed that Lake Lyambezi exhibits a wide range of intra-annual and inter annual variations. With reference to the area based on the best threshold, the lake reduced in area from approximately 120 $km^2$ to 110 $km^2$ between day 186 and day 266 of 1984. This was equivalent to an area deficit of 10 $km^2$ within 80 days. The lake continually shrunk and was completely desiccated in late 1985. After the lake dried up, land use on the lake bed shifted to crop farming.

A dry lake bed was observed from satellite images acquired on day 34 of 1987 and day 135 of 1989 respectively, implying that the lake remained desiccated. However, a partially inundated lake was observed on the satellite scene acquired on day 151 of 1989, after subsequent image analysis, a lake area of approximately 1.8 $km^2$ was obtained. The onset of inflow into the lake area via the Chobe is estimated to be day 148 of 1989. Limitations in ascertaining the actual day of lake inundation onset were due to the unavailability of satellite imagery data at a daily temporal scale and lack of water level data. Nevertheless, the floods continued to rise and the lake area expanded to a maximum of 12.8 $km^2$ on day 199 of 1989. Subsequently the lake area started decreasing as the floods receded and reached an area of 7.6 $km^2$ on day 311 of 1989, and the lake dried up again in 1990. This was in agreement with a report by Schlettwein *et al*., (1991) that the lake was inundated for 8 months in 1989 to an area of 200 ha (2 $km^2$) before drying up again. These authors estimate the onset of filling up of the lake to be in March which lied between day 60 and 90 of 1989. The disagreement between these two findings was in the magnitude of area inundated and the onset of filling of lake in 1989. In this study, a time series analysis of lake area variations was performed; hence, several stages of the lake area variations were captured. Therefore, the lake area coverage reported by Schlettwein *et al*., (1991) represents one of the lake area variations only.

Since drying up again in 1990, the lake bed remained desiccated for over 10 consecutive years, until when the region went through a wet phase during 2001. Therefore, in 2001 the lake was inundated again. An analysis of available satellite imagery showed that on day 112 of 2001, the lake bed was completely dry, while on day 240 of the same year the lake was inundated, covering an area of 15.8 $km^2$. The lake received inflow via the Chobe and the onset of the filling up is estimated to be day 140 of 2001 and the area is estimated to have been at maximum between day 190 and 230 of 2001. This estimation was made based on the lake response and lake behavior exhibited in 1989, which was the year the lake, was inundated for the first time since drying up in late 1985. When the lake filled up in 2001, it showed little resilience after the floods receded and it continuously decreased in area from 15.8 $km^2$ on day 240 of 2001 to 6.5 $km^2$ and 1.4 $km^2$ on days 3 and 99 of 2002 respectively. The lake completely dried up again in 2002 as it was not inundated by floods on that year and a dry lake bed was observed on the satellite imagery acquired on day 291 of 2002.

The lake was inundated again by floods in 2003. An analysis of the satellite scene acquired on day 112 of 2003 showed that the lake bed was still completely dry but on day 230 of the same year, the lake was inundated, covering an area of 8.1 $km^2$ as shown in Figure 5-4. Therefore, the onset of the filling up was estimated to between days 140 and 155 of 2003 and the lake area was estimated to have been at maximum between days 170 and 230 of 2003. The lake dried up again and this is proved by a dry lake bed that was observed on the satellite image acquired on day 113 of 2004.

In 2004, the Caprivi region received high floods, and the lake was massively inundated. On day 113 of 2004, the lake bed was still dry while on day 145 of 2004, it was robust and having an area coverage of 34.9 $km^2$. The lake received inflow first via the Zambezi and the onset of the filling was on day 122 of 2004. As the flood levels increased, the lake received more inflow via the Chobe River and attained a maximum area of 47.2 $km^2$ on day 177 of 2004. The lake area started decreasing after the floods receded, and the downward trend continued through to 2005, which was characterised by low floods. The lake area decreased from 10.6 $km^2$ to 5.8 $km^2$ between day 67 and day 167 of 2005. The period between these days represents the annual flood period. Therefore, this downward trend in lake areal extent during the flood period of 2005 implies that the lake was not recharged by flood waters that year. Instead, the lake continually shrunk and had area coverage of 2 $km^2$ and 0.4 $km^2$ on day 275 of 2005 and day 102 of 2006 respectively. Subsequently, the lake desiccated, and a dry lake bed was observed on the satellite image acquired on day 182 of 2006.

The lake remained dry through to the beginning of 2007 as observed on the satellite image acquired on day 9 of 2007. However, the region went through a new wet phase and the lake received floods waters via the Chobe with the onset of filling up being on day 76 of 2007. The lake area on day 78 of 2007 was 10.9 $km^2$ and it continued to increase until it reached a recorded maximum of 64.1 on day 145 of the same year as shown in Figure 5-4. The actual maximum area attained in 2007 was likely to have not been captured due to the unavailability of satellite images at a daily temporal scale. When the floods started receding, the lake area decreased and it covered an area of 53.7 $km^2$on day 257 of 2007. The lake area of 11.4 $km^2$ was recorded on day 60 of 2008, and an incidence of low floods in the same year resulted in the lake not receiving a novel flood pulse. However, the lake never desiccated and exhibited resilience as the lake area varied minimally, changing from 10 $km^2$ on day 108 of 2008 to 9.8 $km^2$ on day 268 of the same year.

During the year 2009, the lake never dried up and the Caprivi region received relatively high floods. Hence the Zambezi River impacted upon the lake by contributing water inflow via the

Chobe River and as overland flow coming from the Bukalo-Isuma flood flow path, which was linked to the lake via the Kalengwe channel. Since 2009, as shown in Figure 5-4, the intra-annual lake area variation assumed a wide range, covering an area of 70.9 $km^2$ on day 78 of 2009 and reaching a maximum area of 309.1 $km^2$ on day 278 of the same year. After the floods, the lake area decreased to 284.3 $km^2$ on day 350 of 2009. In 2009, the lake also received a second flood pulse from the Kwando. As a result of this, it is likely that a second peak in area coverage occurred, but it was not captured due to unavailability of imagery at an adequate temporal scale. The region continued to go through a very wet phase until 2010 where the lake attained an overall recorded maximum area of 369.5 $km^2$ on day 145 of 2010. Since 2011, the flood intensities have reduced and the lake responded by a exhibiting a downward trend in areal extent. The lake area reached a maximum of 280.2 $km^2$ on day 220 of 2011 while it reached a maximum of 228.9 $km^2$ during the floods of 2011 and 2012 respectively. The lake area extent on day 105 of 2013 was 203.4 $km^2$.

### 5.2.1 Summary of the Lake Area Variations

An analysis of the lake area variations as observed in Figure 5-4 showed that Lake Lyambezi went through seven phases of filling and drying up between 1984 and 2013. The first phase pertains to the period between 1984 and 1985, when the lake was filled since the 1950s and then it dried up in late 1985. The second phase pertains to 1989, when the lake was inundated for the first time since it dried in late 1985, but it desiccated again in 1990. The third phase which occurred during the 2001/2002 period is first time the lake re-emerged in the 21st century, before drying up again in mid-2002.

The fourth phase is represented by the inundation of the lake in 2003 and its subsequent drying up later in the same year. The fifth phase pertains to the period between 2004 and 2006, when the lake was inundated and supported a local fishery for two years before it dried up completely in 2006. The sixth phase pertains to the period between 2007 and 2008 when the lake filled up, and supported a small-scale local fishery but later shrunk to approximately 10 $km^2$. The seventh phase is the period from 2009 to 2013, when the lake expanded to an area above 200 $km^2$. Since 2009, the lake has supported a high yield subsistence fishery where the major species harvested belong to the Cichlidae, Clariidae, Characidae and Schilibeidae fish families (Peel, 2012).

## 5.3 Spatial representation of the variation in area and changing morphologies of Lake Lyambezi

Figures 5-5 and 5-6 show the spatial representation of the dynamic area variations and changing morphologies of Lake Lyambezi shown as insets in the maximum lake boundary.

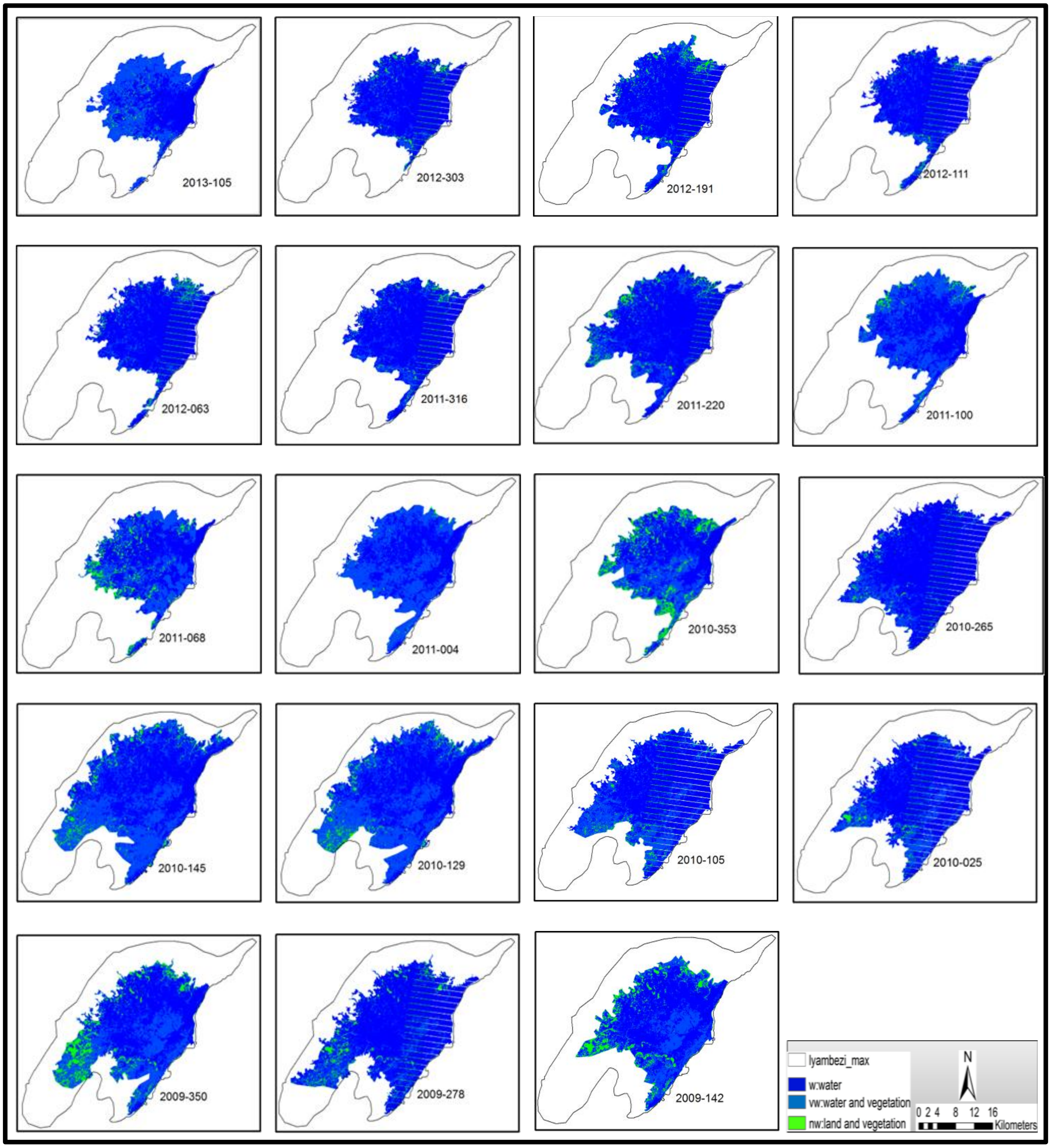


**Figure 5-5 Variation in area and morphology of Lake Lyambezi 2009-2013**

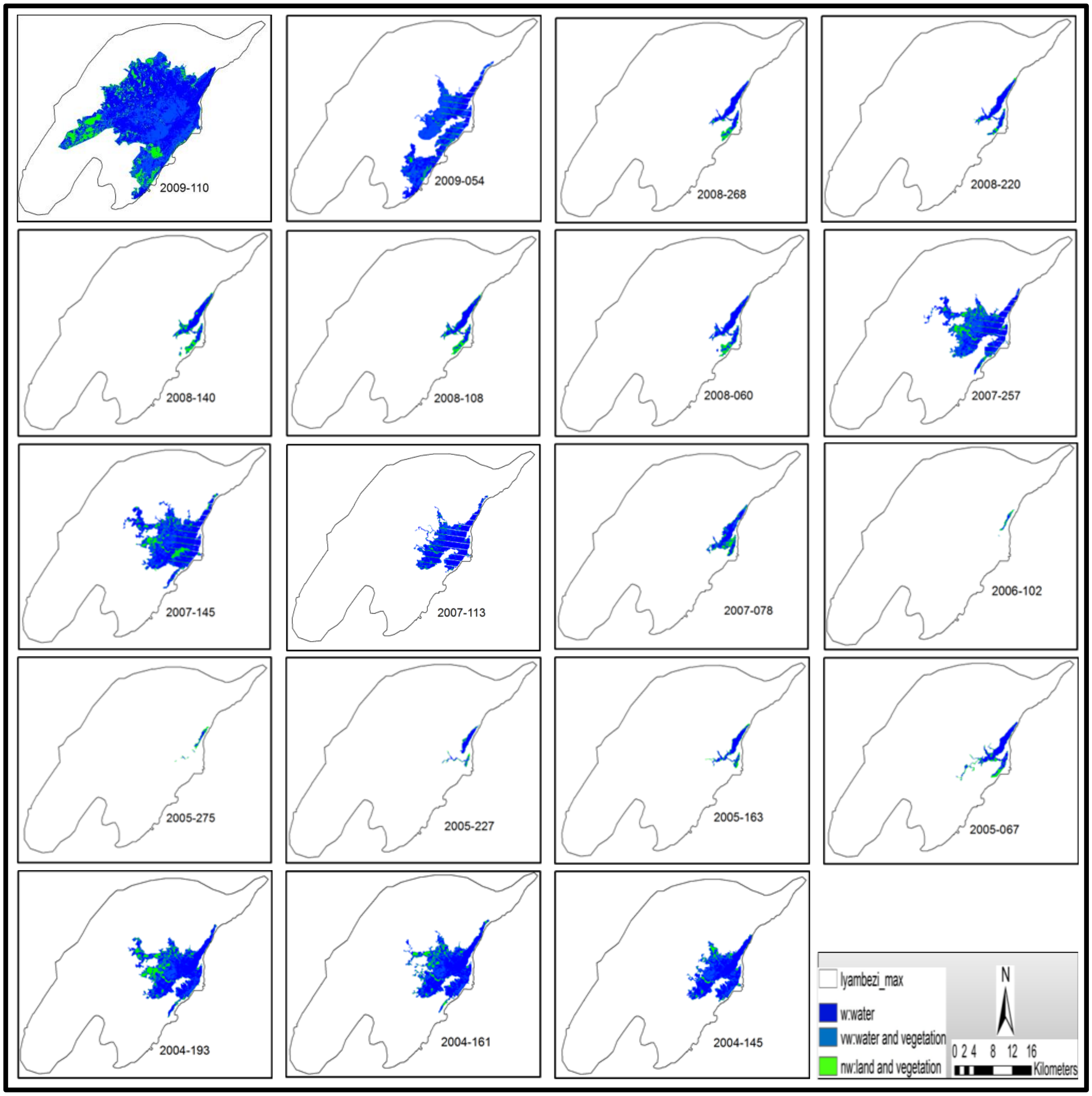


**Figure 5-6 Variation in area and morphology of Lake Lyambezi 2004-2009**

At maximum spatial extent the lake is estimated to cover an area of 590 $km^2$ as represented by the border around the actual spatial lake coverage. It can also be observed in Figures 5-5 and 5-6 that during the period 2004 and 2013 the lake exhibited a wide range of areal variations. During the fifth phase of the lake's existence since it dried up in 1985, it assumed an intermediate to very low spatial/areal coverage. The lake increased in areal extent in response to flood inflow in

2004, subsequently shrinking when the floods receded as the lake started loosing water through ET and sub-surface outflows.

During the period between 2007 and 2008 (phase six), the lake also exhibited intermediate to low spatial areal coverage. However, the transition to phase seven (2009-2013) was not characterised by a dry phase unlike transitions between other phases. The period between 2009 and 2013 was generally characterised by an existence of a very large water body with the only exception being day 54 of 2009 when the lake was of low spatial extent. Thereafter, the lake increased in areal extent reaching an annual maximum on day 278 of 2009. In 2010, the lake reached its overall recorded maximum areal extent on day 145, while the lake area began to gradually decrease in areal extent from 2011. The periods when the lake was dry were not presented because at that stage the spatial extent of the lake was none.

It can also be observed from Figure 5-5 and 5-6 that variations in lake areal extent were associated with changing lake morphologies. These morphologies can be broadly categorised into four groups based on the extent of areal coverage. When the lake has a large spatial extent, it assumes the form of a round polygon with varying finger-like extensions, and when it has an intermediate areal extent, its form is like a skewed and inverted Y. As the lake area decreases to a lower spatial coverage, it separates into two sub-bodies that are connected by small channel. When the lake area reduces a lot more towards desiccation, the lake form becomes stream-like as observed on day 275 of 2005 from Figure 5-6.

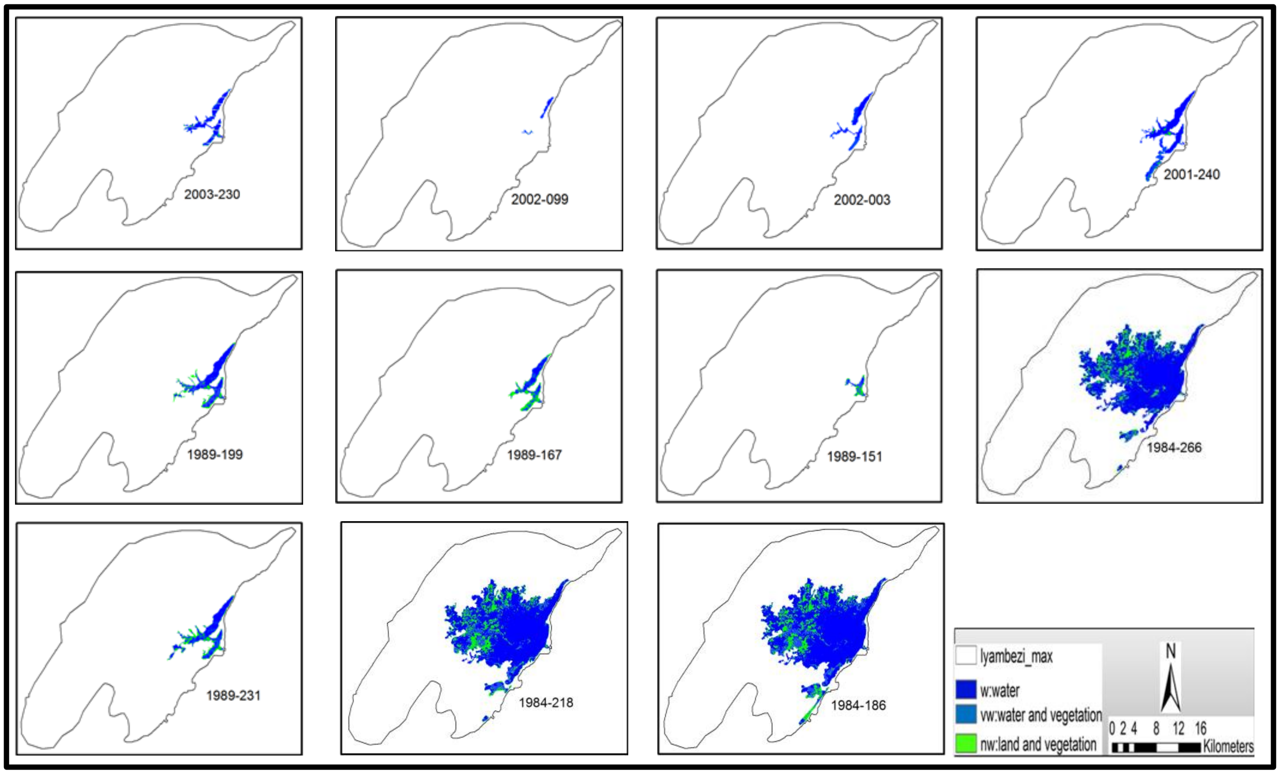


**Figure 5-7 Variation in area and morphology of Lake Lyambezi 1984 and 2003**

The Figure 5-7 shows a spatial representation of the areal variations during phases 1 to 4 of the lake's existence. During these phases, the lake area varied between large and very small spatial coverage. In 1984 (phase 1), the lake area was extensive and therefore associated with a round-like polygon with finger-like extensions. During the period 1989 to 2003 (phases 2 to 4 of the lake existence), the lake had a relatively small area coverage and its morphology was characterised by the presence of two separate small water bodies connected by a small channel as seen on the satellite scene acquired on day 230 of 2003. As the lake drifted more towards desiccation, its form changed to a short stream like shape, as observed from the satellite scene acquired on day 99 of 2002.

## 5.4 Dynamic thresholding and segmentation for the delineation of the lake

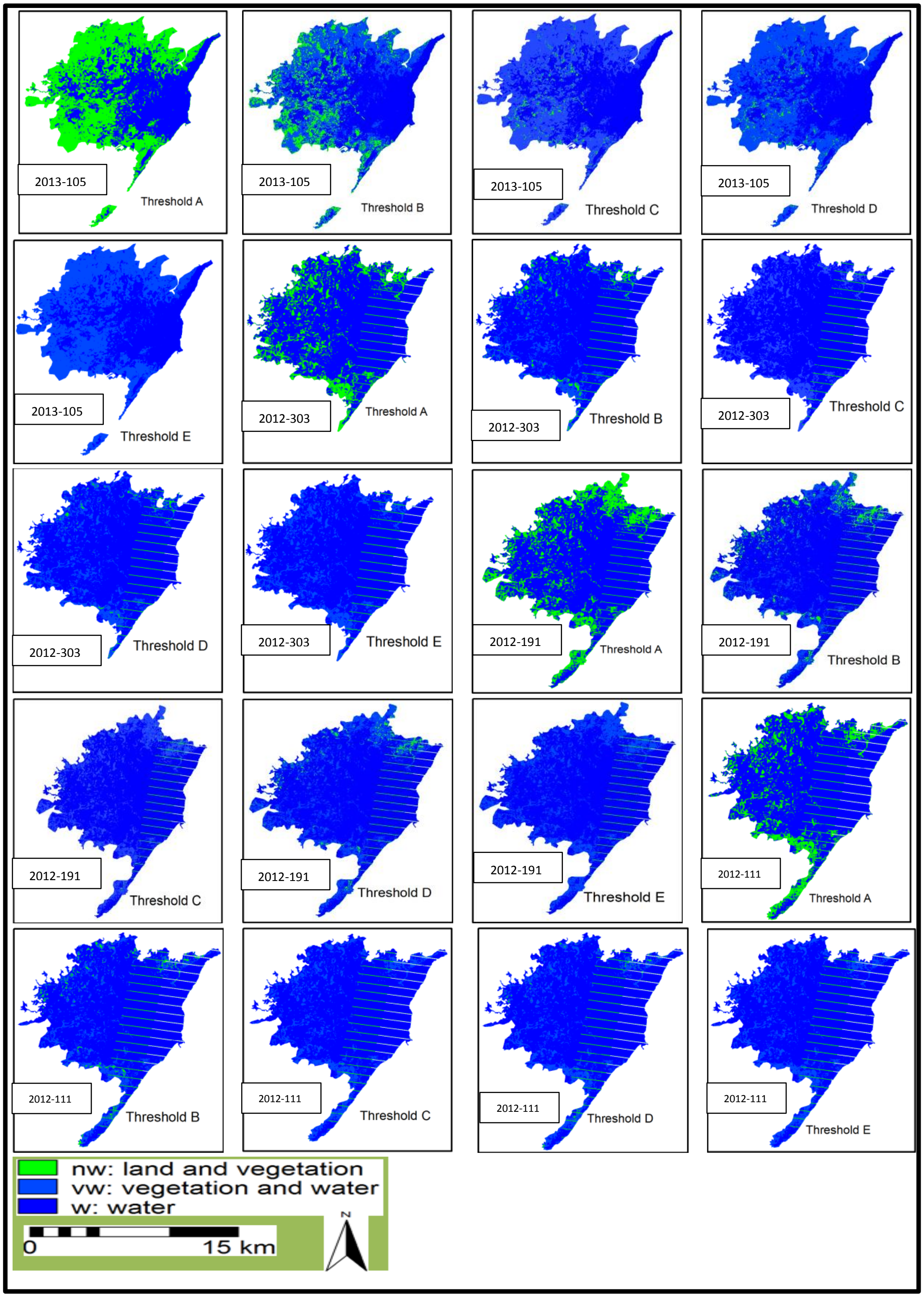


**Figure 5-8 Dynamic thresholding performance (2012 and 2013 images)**

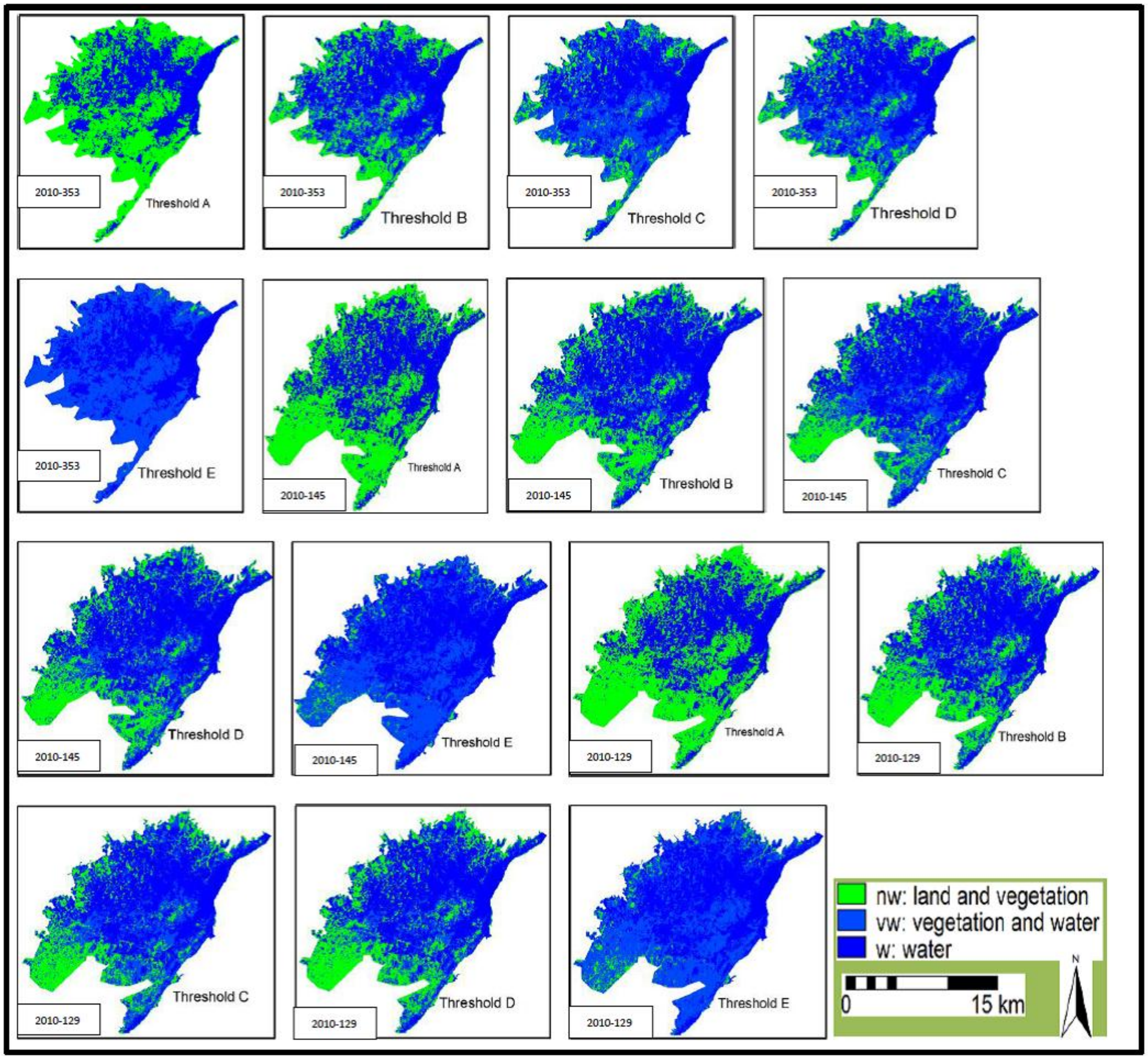


**Figure 5-9 Dynamic thresholding performance (2010 images)**

Figures 5-8 and 5-9 show the spatial representation of the spectral classes of the lake features and the varied efficiency of dynamic thresholding for the segmentation of these spectral classes on satellite imagery acquired on different days of the years 2010, 2012 and 2013. The lake has three spectral classes, namely open water, vegetation and water, and land and vegetation, while the rest of the satellite scene predominantly has the spectral class of land and vegetation but there are some water features present as the region has rivers and wetlands. Since the characteristics of similar spectral classes vary in different satellite scenes, i.e. in scenes acquired at intra and inter-annual temporal scales. The application of manual dynamic thresholding (threshold A-E) in the segmentation of spectral classes when delineating the lake area resulted in varied segmentation accuracy. Thus, for the segmentation of the given spectral classes, a better accuracy was achieved by different thresholds. Figures 5-8 shows the results of dynamic thresholding applied for the segmentation of spectral classes on satellite scenes acquired at inter and intra-annual temporal scale. It can be seen that the spatial coverage of each spectral class varies on each satellite. On the other hand, Figure 5-9 shows the intra-annual variations in the areal coverage of the spectral features of the lake. The spectral classes; water, vegetation and water, and land and vegetation e.g. on satellite scene acquired on day 105 of 2013 had a different area extent based on thresholds A-E. These spatial area variations are attributed to the varied ability of different thresholds in the segmentation of the spectral classes. And on the fact that each spectral class exhibit varied characteristics on different satellite images

## 5.5 Comparison of lake area derived from digitising and thresholding

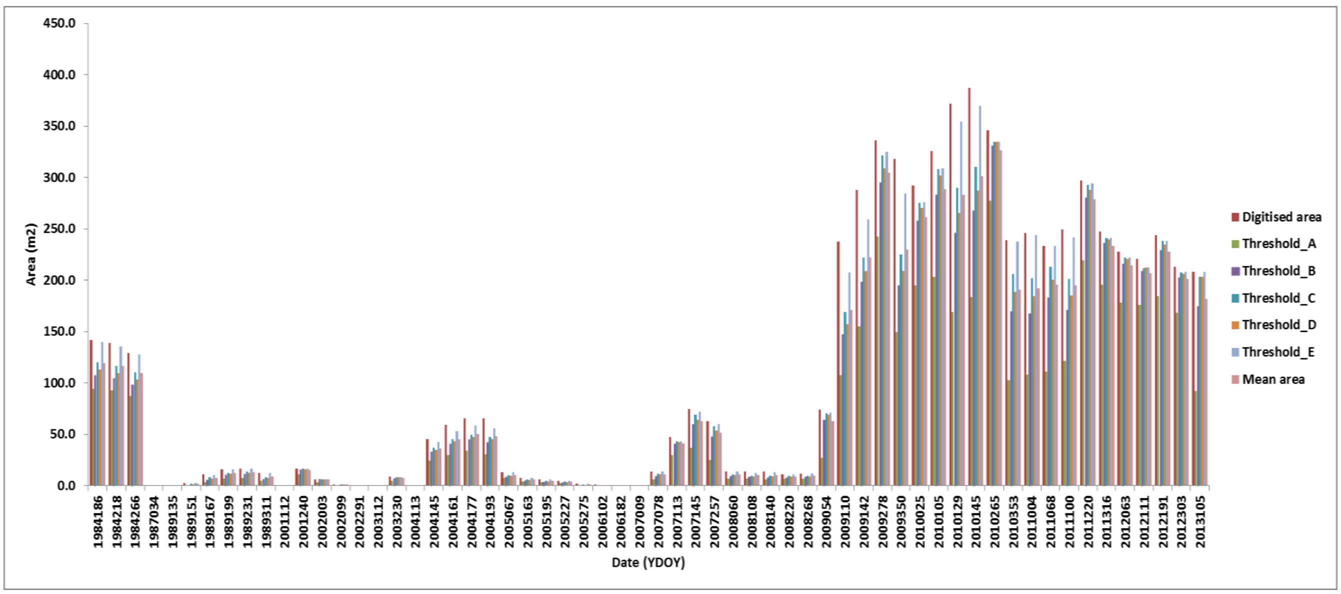


**Figure 5-10 Lake area variations obtained from dynamic thresholding**

Dynamic thresholding for the segmentation of spectral classes of the lake resulted in varied accuracy. This implies that dynamic threshold achieved varied efficiency when removing the noise of land features and in expressing the lake in terms of water coverage only. Therefore, each dynamic threshold resulted in a different estimate of the lake area.

It is observed from Figure 5-10 that overall, the largest lake area on each satellite scene was obtained based on the digitising methods, as this area includes land features engulfed by the water and shoreline. It is also observed that with respect to the thresholding methods, the least lake area was obtained based on threshold A, while the largest lake area was obtained based on threshold E. Overall, based on the trend of lake area variations, for each satellite scene the smallest to largest lake area was obtained from the thresholds A, B, D, C and E respectively.

### 5.5.1 Comparison of the means of areas obtained from dynamic thresholds of MNDWI

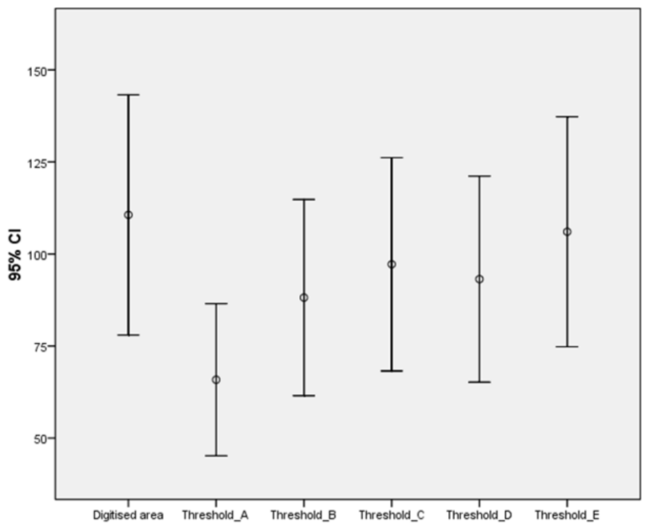


**Figure 5-11 Error bars of the mean areas obtained by using different thresholds for segmentation**

Since the lake area was calculated based on digitising and dynamic thresholding of MNDWI, a test for differences in the means of the lake area was performed at 95% confidence interval using the one-sample t-test. It is observed from Figure 5-8 that there is an overlap in the error bars representing the possible range of the means of the lake area calculated based on different methods. The overlap in the error bars of means of the lake area implies that these means are not statistically different. Hence, it can be stated with 95% confidence that there are no significant differences between the estimates of lake area obtained based on the different methods. Therefore, the best way to represent the area of Lake Lyambezi on each satellite scene, is by calculating the average the lake area (Figure 5-10) obtained based on all the methods that were used i.e. methods of digitising and use of dynamic thresholds for MNDWI.

## 5.6 Accuracy assessment of segmentation of spectral classes

**Table 5-1 Error matrix based on the efficiency of dynamic thresholding**

| | | | | | |
|---|---|---|---|---|---|
| **Threshold A** | | | | | |
| | Non-water | Water | Total | Users' accuracy | |
| non-water | 15 | 4 | 19 | 0.79 | |
| water | 1 | 5 | 6 | 0.83 | |
| Total | 16 | 9 | 25 | | |
| Producers' accuracy | 0.94 | 0.56 | Overall accuracy | 0.8 | |
| Kappa | | | | 0.53 | |
| **Threshold B** | | | | | |
| Spectral class | Land/vegetation | Vegetation/water | Water | Total | Users' accuracy |
| Land/vegetation | 6 | 3 | 0 | 9 | 0.67 |
| Vegetation/water | 2 | 4 | 4 | 10 | 0.40 |
| water | 1 | 0 | 5 | 6 | 0.83 |
| Total | 9 | 7 | 9 | 25 | |
| Producers' accuracy | 0.67 | 0.57 | 0.56 | overall accuracy | 0.6 |
| Kappa | | | | | 0.4 |
| **Threshold C** | | | | | |
| Spectral class | Land/vegetation | Vegetation/water | Water | Total | Users' accuracy |
| Land/vegetation | 5 | 1 | 0 | 6 | 0.83 |
| Vegetation/water | 5 | 6 | 4 | 15 | 0.40 |
| Water | 1 | 0 | 5 | 6 | 0.83 |
| Total | 11 | 7 | 9 | 27 | |
| Producers' accuracy | 0.45 | 0.86 | 0.56 | overall accuracy | 0.59 |
| Kappa | | | | | 0.41 |
| **Threshold D** | | | | | |
| Spectral class | Land/vegetation | Vegetation/ water | Water | Total | Users' accuracy |
| Land/vegetation | 5 | 1 | 0 | 6 | 0.83 |
| Vegetation/water | 3 | 6 | 4 | 13 | 0.46 |
| Water | 1 | 0 | 5 | 6 | 0.83 |
| Total | 9 | 7 | 9 | 25 | |
| Producers' accuracy | 0.56 | 0.86 | 0.56 | overall accuracy | 0.64 |
| Kappa | | | | | 0.47 |
| **Threshold E** | | | | | |
| Spectral class | Land/vegetation | Vegetation/ water | water | Total | Users' accuracy |
| Land/vegetation | 0 | 0 | 0 | 0 | 0 |
| Vegetation/water | 10 | 7 | 4 | 21 | 0.33 |
| Water | 1 | 0 | 5 | 6 | 0.83 |
| Total | 11 | 7 | 9 | 27 | |
| Producers' accuracy | 0 | 1 | 0.56 | overall accuracy | 0.48 |
| Kappa | | | | | 0.28 |

Table 5-1 shows the error matrix for the dynamic thresholds used in the segmentation of spectral classes on the satellite scene acquired on day 105 of 2013. It is observed from the error matrix results that threshold D achieved an overall accuracy of 64% and had an agreement of 47% as determined by a Kappa statistic, while threshold A achieved an overall accuracy of 80% and a Kappa statistic of 53%. However, threshold A was not taken as the best because it combined into one, the spectral classes relating to water/vegetation and land/vegetation. Alternatively, for this satellite scene, threshold D was taken as the best dynamic threshold because it performed better among the thresholds that included the all three spectral classes constituting the lake area. The rest of the thresholds achieved an overall accuracy of ≤60% and a Kappa ≤41. The Kappa statistic achieved by dynamic thresholds was generally categorised as poor to good, where a Kappa >40% is poor, while a Kappa in the range 40<K>70 is regarded as good (Ismail and Jusoff, 2008).

## 5.7 The link between error matrix and ground features of Lake Lyambezi

The lake is characterised by a distinct presence of pelagos, aquatic and fringing vegetation.

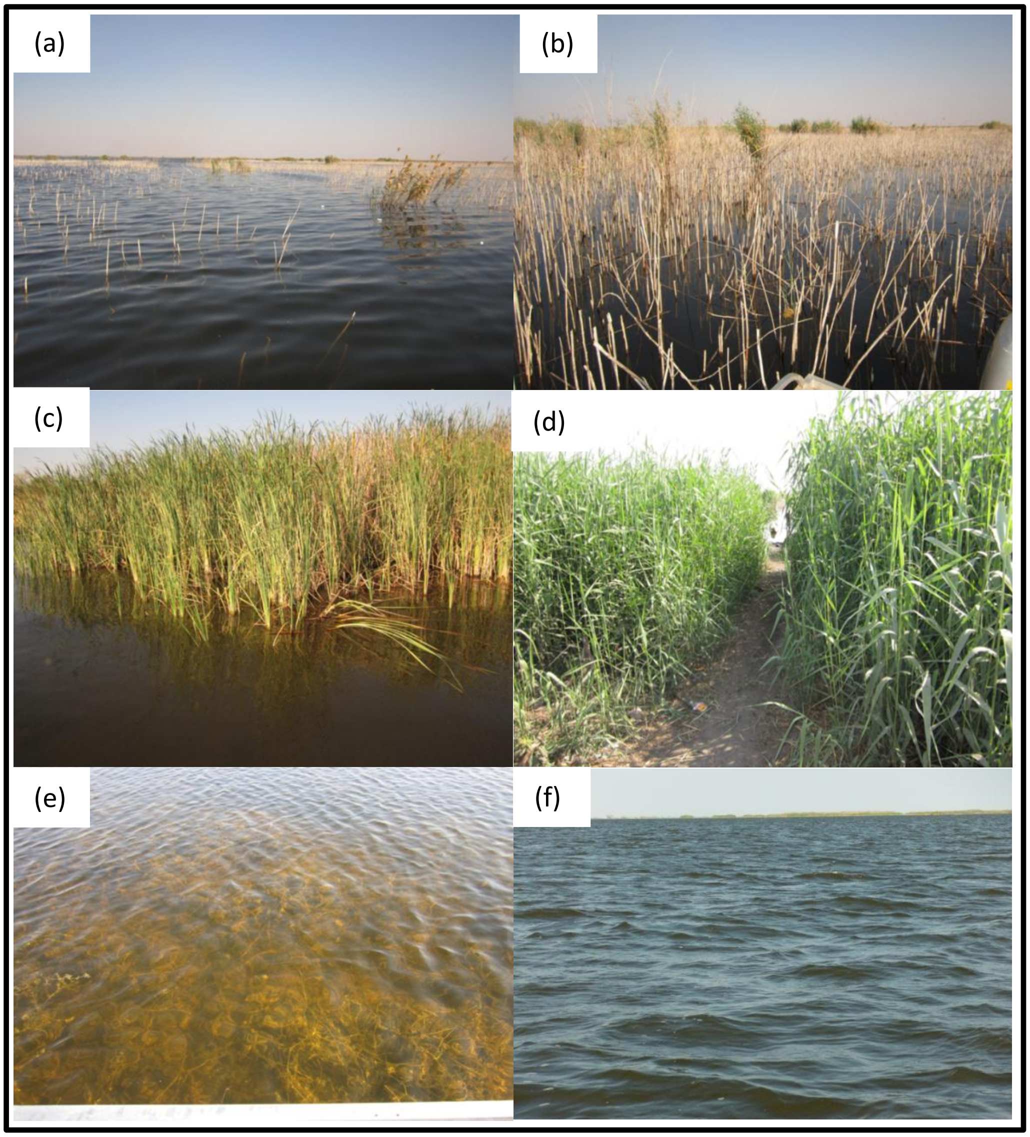


**Figure 5-12 Spectral features of Lake Lyambezi**

Figure 5-12 shows the pictures exhibiting the spectral classes constituting the lake area of Lyambezi. It can be observed that there is a strong presence of out cropping vegetation predominantly comprised of the common reed (*Phragmites australis*), as shown in Figure 5-12

(a) and (b), and dense patches of bulrush (*Typha latifolia*), as shown in Figure 5-12 (c). The outcropping vegetation occurs in the lake area where water depth varies from <1m and <3m. Part (d) of Figure 5-12 on the other hand shows a presence of thickly vegetated pelagos (land features). Part (e) shows the open water characterised by a presence of thick patches of submerged vegetation comprised predominantly by the African oxygen elodea (*Lagarosiphon major*), which is also known as the oxygen weed. The African elodea weed can grow up to 6 metres deep in the open water hence it is growing in the lake area of <1 to 5m depth. Finally part (f) shows the clear open water, where aquatic vegetation is markedly absent, and has a depth of between 1 and 7m.

The use of the MNDWI in the delineation of Lake Lyambezi resulted in low to moderate overall accuracy, with an overall accuracy that ranged between 48% and 80%. This is not in agreement with the high accuracy of approximately 97% reported when using the MNDWI to delineate open water bodies (Hui *et al*., 2008; Ji *et al*., 2009). In most studies, the MDNWI has been used on Landsat TM and ETM+ images. In this study, it was used both on Landsat TM, ETM+ and Landsat 8 OLI. Also, the error matrix was based on Landsat 8 OLI because this was the latest image and hence the only one that was be ground-truthed.

The generally lower accuracy achieved when delineating Lake Lyambezi is not, however, attributed to the differences in the Landsat sensors but to the physical characteristics of the lake. Before it dried, Lake Lyambezi was reported to be comprised of open water body with an extensive reed bed throughout the lake (Seaman *et al*., 1978). Lake Lyambezi is a highly productive system characterised by open water with vast patches of submerged vegetation dominated by the African oxygen elodea vegetation. There is also extensive reed growth throughout the lake, while the areas towards west and south-west are characterised by vast, dense reed outcroppings dividing the lake into parts of open water. There is also a marked presence of thickly vegetated pelagos, some of which serve as temporary residence for the fisherfolks. Therefore, the lower accuracy achieved by using MNDWI while delineating Lake Lyambezi is attributed to the vast presence of submerged and out-cropping vegetation. The lower accuracy on MNDWI thresholds was attributed to the high chlorophyll count, implying that the lake exhibited some characteristics similar to those of a forest.

## 5.8 The hydrological components affecting Lyambezi

### 5.8.1 Regional hydrographs

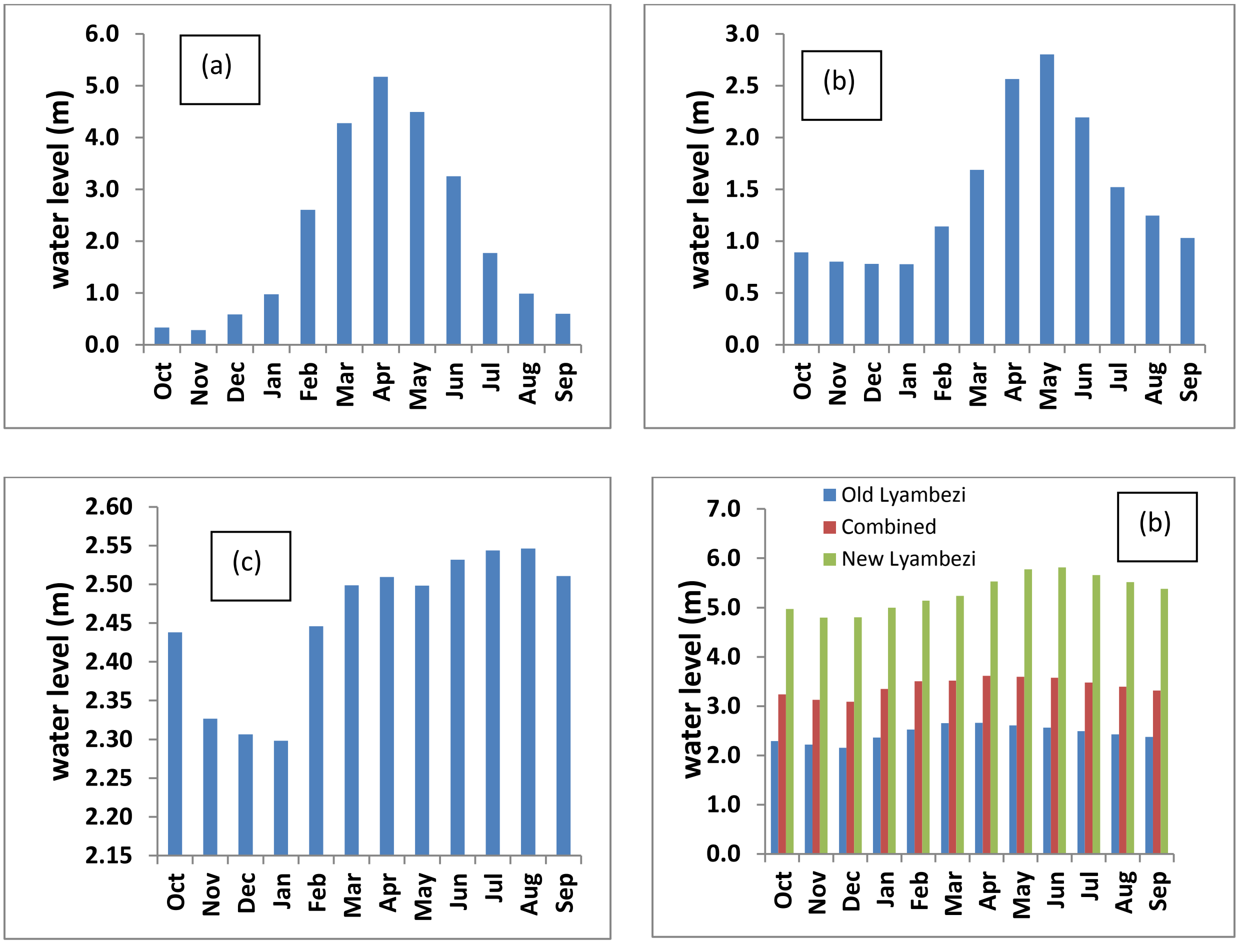


**Figure 5-13 Long-term monthly average; (a) Zambezi (b) Chobe (c) Kwando (d) Lake Lyambezi**

Figure 5-12 shows the long-term average monthly water levels (discharge in metric units) of the rivers and the Lake Lyambezi. The Zambezi is the major river that contributes flood pulse to both the Zambezi and the Chobe-Linyanti (*location of Lake Lyambezi*) wetland systems, and the shape of its hydrograph is closely related to the Chobe River average monthly hydrograph. This is because the Chobe is closely linked to the Zambezi, acting as a tributary characterised by a periodic east to west directional flow during the flood season with a delayed peak (May peak) in floods as compared to the Zambezi (April peak). The long-term average monthly hydrograph of the Kwando River shows moderate to little inter-annual variation compared to the other rivers.

There is a distinct difference in the shape of the hydrographs of Kwando and Zambezi Rivers, implying that the two rivers are influenced by different hydrological factors. However, these rivers are recharged by floods from the rains that occur in the same seasons of the year in the catchments lying in Angola and Zambia. Even though these rivers are subject to the same rainfall season, the presence of the Silowana flood plains on the Kwando system serves as a flood routing entity and its sponge-like characteristics ensure that the floodwaters gradually trickle to Kwando resulting in a delayed flood event (Mendelsohn and Roberts, 1997). Thus the Kwando has a different flood regime from the Zambezi, even though in biological terms, the two rivers cannot be differentiated (van der Waal, 1980).

The long-term average monthly hydrograph of Lake Lyambezi resembles that of the Kwando albeit with very minimal inter-annual variations. The similarity in the hydrographs between these two systems cannot however, be interpreted to mean that the Kwando represents the major system drives the lake water variations. This is because there is a massive distance between the lake and the point where the Kwando is semi-gauged. Also, based on the flow direction and the location of the lake, the Kwando would potentially provide an inlet to the lake via the Linyanti River. However, the presence of broad flood plains which lie on the Mamili and southwest extent of the Chobe-Linyanti wetland systems delay or completely attenuate the flood flow into the lake. Therefore, the Kwando intermittently contributes inflow into Lake Lyambezi. These sporadic interactions between the Kwando and Lake Lyambezi are exacerbated by impacts of climate variability on water resources and by changes in local hydrology emanating from the drying out of the old Lake Lyambezi and subsequently the Linyanti River in the early-1990s. The Kwando has only contributed inflow in 2009 since the lake re-emerged, as observed from satellite imagery.

In terms of surface flow, the present lake is hydrologically closed, connecting to the rivers during the flood season only. However, the fact that it is a freshwater lake implies that there exists a base outflow point. Since both surface and subsurface flow direction is a function of topography, the subsurface outflow of Lake Lyambezi can be said to be of the eastern direction based on the modelled flow direction.

Lake Lyambezi is mostly linked to the Zambezi via the Chobe River and the Kalengwe channel depending on the extent of the floods that are driven by Zambezi River and local rainfall. The

Chobe serves as the most important system through which the Zambezi impacts the water resources of the lake. Intermittently, Zambezi also connects to the lake via the Kalengwe channel which receives flood water as overland flow through the Bukalo-Isuma flow path. An analysis of the water level peaks clearly depicts this link, with the flood peaks occurring in April, May and June for the Zambezi, Chobe and Lyambezi respectively. After the floods, the lake is disconnected from both the Zambezi and the Chobe Rivers in terms of surface flow and its water levels begin to vary independently.

### 5.8.2 The link between regional rivers and the lake

**Table 5-2 Correlation of the rivers and the Lake water levels**

| | | Zambezi | Kwando | Chobe | Lyambezi |
|---|---|---|---|---|---|
| Zambezi | Pearson Correlation | 1 | .248** | .748** | .271** |
| | Sig. (2-tailed) | | .000 | .000 | .000 |
| | N | 531 | 531 | 373 | 531 |
| Kwando | Pearson Correlation | .248** | 1 | .402** | .359** |
| | Sig. (2-tailed) | .000 | | .000 | .000 |
| | N | 531 | 531 | 373 | 531 |
| Chobe | Pearson Correlation | .748** | .402** | 1 | .645** |
| | Sig. (2-tailed) | .000 | .000 | | .000 |
| | N | 373 | 373 | 373 | 373 |
| Lyambezi | Pearson Correlation | .271** | .359** | .645** | 1 |
| | Sig. (2-tailed) | .000 | .000 | .000 | |
| | N | 531 | 531 | 373 | 531 |

**. Correlation is significant at the 0.01 level (2-tailed).

Table 5-2 shows the inter-connectedness of the regional rivers based on correlations of long-term water level records. The Kwando and the Zambezi are the major rivers in the region and are driven by the floods emanating from similar rainfall event in the catchments in Angola and Zambia (Mendelsohn and Roberts, 1997). However, the correlation between the two river systems is attributed to the difference in flood regimes. The Chobe is strongly correlated to the Zambezi, since during regional floods the Chobe acts as a tributary of the Zambezi as it changes to a reverse directional flow. When the Zambezi water levels start to recede, the Chobe River subsequently reverts to its west to east directional flow where it forms a confluence with the Zambezi at Kazungula. The Zambezi is also weakly correlated to Lake Lyambezi because the two systems are physically disconnected and linked only during the high floods. Lake Lyambezi has a good correlation with the Chobe, which serves as the primary link between the Zambezi and the lake. The Kwando is also moderately linked to Lyambezi, but most of the strength stems from the relationship between the Kwando and the old lake.

## 5.9 Perspectives for water resources management of Lake Lyambezi

### 5.9.1 Floods and rainfall variability impacts on Lake Lyambezi water resources

Figure 5-13 shows the annual maximum discharge of the Zambezi expressed in water level (m) and the annual regional rainfall. The sufficient inundation of the Lyambezi is reported to be a function of the magnitude of floods and rainfall (Schlettwein *et al.*, 1991), and an inspection of the long-term maximum discharge hydrograph of the Zambezi and rainfall is in agreement with this report.

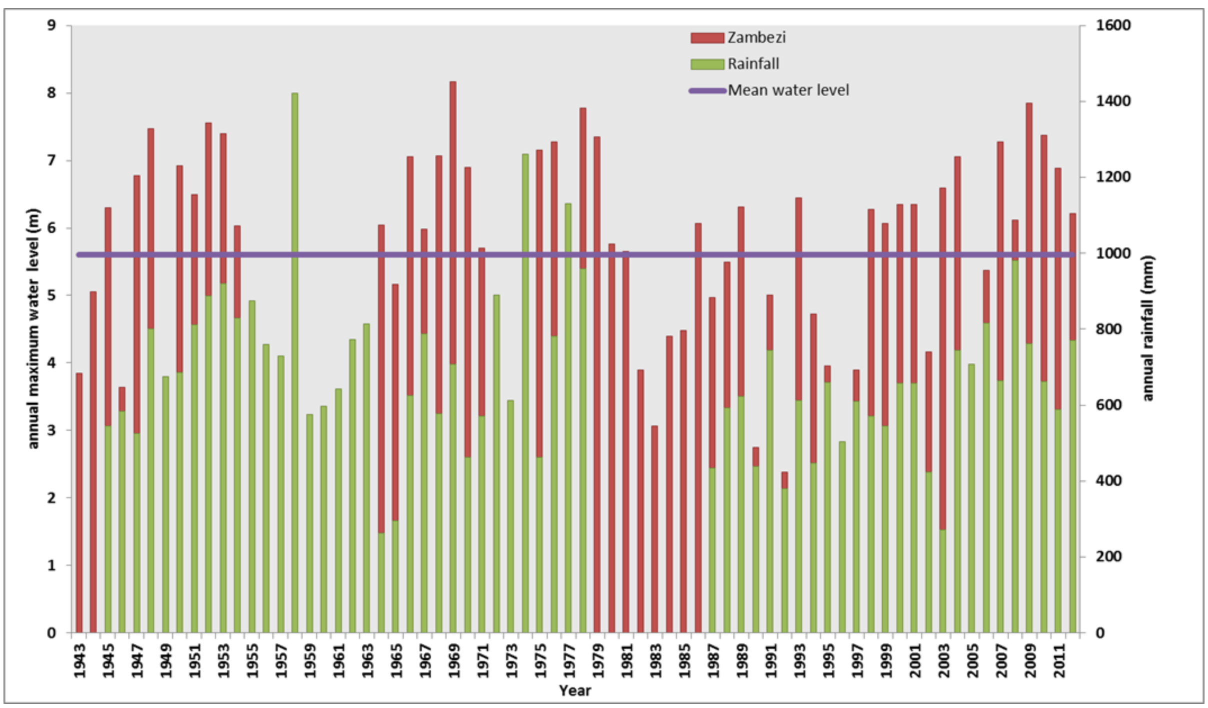


**Figure 5-13 Annual maximum Zambezi water level and annual rainfall**

Lake Lyambezi is reported to have dried up in late 1985, and it can be observed from Figure 5-13 that the desiccation of the lake was preceded by a five year period of low floods. In 1980 and 1981, the Zambezi River reached maximum water levels of 5.75 and 5.65 m which were slightly above the long-term average maximum of 5.6 m and this marked the start of the dry phase in the Caprivi sub-basin. A wet rainfall year is based on the exceedence of the long-term mean annual rainfall while for the Zambezi River discharge, a wet flood year is based on the exceedence of the long-term annual maximum discharge.

The years 1982 to 1988 were characterised by floods, with an annual maximum below the long-term average maximum, and before the end of this period the lake completely desiccated. Rainfall data for the period between 1979 and 1986 was missing, nevertheless, the period between 1979 and 1987 was reported to have been relatively dry, and characterised by annual rainfall below the 50-year average of 650mm (Pricope, 2013; Mendelsohn and Roberts, 1997). The lake dried up when the prevailing hydrological conditions for more than five consecutive years were characterised by annual rainfall and seasonal flood events of a magnitude below the long-term mean. On the other hand, the present lake was increasing in area during the wet years of 2009 and 2010. However, since 2011 the lake area has been decreasing gradually because the intensities in annual rainfall and in effective runoff decreased. Therefore, it can be deduced that generally when the lake does not receive floodwater inflow for three consecutive flood seasons it will reach the stage of severe water stress and even dry up completely.

### 5.9.2 Other factors affecting Lake Lyambezi water resources

Lake Lyambezi had an areal coverage of 110.2 $km^2$ on day 266 of 1984, but it was completely desiccated in late 1985. The causes of its drying have been attributed to the lower rainfall and the spreading reed bed that was blocking the source channels of Lake Lyambezi. However, this does explain why a lake covering an area of 110.2 $km^2$ dried up completely within a year.

Water outflow from the old and new Lake Lyambezi is limited to evapotranspiration and base outflow, the actual magnitudes of these components is unknown. Generally evapotranspiration shows a negative feedback, thus its rate decreases proportionally with the decrease in lake area extent and water level. This reduces the rate of desiccation. Therefore, the fast rate at which the lake dried up in the phase 1 of its existence is attributed to the distinct presence of *Salvinia molesta* and other alien aquatic weeds (B.C.W. van der Waal, pers comm). Where, even though the lake was shrinking, there was adequate amount of water to support plant growth and consequently high rates of ET, which increased the rate of desiccation of the lake. Alien aquatic plants are known to have a negative impact on the water resources (Williamson *et al*., 2009).

Therefore, it is important for water resources management plans to include clear strategies for aquatic weeds regulation to ensure sustainability of the present lake water resources.

## 5.10 The Probability of exceedence and return period of floods

**Table 5-1 Probability of exceedence of regional floods**

| Rank | Year | Discharge (m) | Probability of exceedence | Return period (Yr) | Rank | Year | Discharge (m) | Probability of exceedence | Return period (Yr) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1969 | 8.2 | 0.02 | 62 | 32 | 1954 | 6.0 | 0.52 | 2 |
| 2 | 2009 | 7.9 | 0.03 | 31 | 33 | 1967 | 6.0 | 0.53 | 2 |
| 3 | 1978 | 7.8 | 0.05 | 21 | 34 | 1980 | 5.8 | 0.55 | 2 |
| 4 | 1952 | 7.6 | 0.06 | 16 | 35 | 1971 | 5.7 | 0.56 | 2 |
| 5 | 1948 | 7.5 | 0.08 | 12 | 36 | 1981 | 5.7 | 0.58 | 2 |
| 6 | 1953 | 7.4 | 0.10 | 10 | 37 | 1988 | 5.5 | 0.60 | 2 |
| 7 | 2010 | 7.4 | 0.11 | 9 | 38 | 1977 | 5.5 | 0.61 | 2 |
| 8 | 1979 | 7.4 | 0.13 | 8 | 39 | 2006 | 5.4 | 0.63 | 2 |
| 9 | 1976 | 7.3 | 0.15 | 7 | 40 | 1974 | 5.2 | 0.65 | 2 |
| 10 | 2007 | 7.3 | 0.16 | 6 | 41 | 1965 | 5.2 | 0.66 | 2 |
| 11 | 1975 | 7.2 | 0.18 | 6 | 42 | 1944 | 5.1 | 0.68 | 1 |
| 12 | 1968 | 7.1 | 0.19 | 5 | 43 | 1991 | 5.0 | 0.69 | 1 |
| 13 | 1966 | 7.1 | 0.21 | 5 | 44 | 1987 | 5.0 | 0.71 | 1 |
| 14 | 2004 | 7.1 | 0.23 | 4 | 45 | 1994 | 4.7 | 0.73 | 1 |
| 15 | 1950 | 6.9 | 0.24 | 4 | 46 | 1985 | 4.5 | 0.74 | 1 |
| 16 | 1970 | 6.9 | 0.26 | 4 | 47 | 1972 | 4.4 | 0.76 | 1 |
| 17 | 2011 | 6.9 | 0.27 | 4 | 48 | 1984 | 4.4 | 0.77 | 1 |
| 18 | 1947 | 6.8 | 0.29 | 3 | 49 | 2002 | 4.2 | 0.79 | 1 |
| 19 | 2003 | 6.6 | 0.31 | 3 | 50 | 1995 | 4.0 | 0.81 | 1 |
| 20 | 1951 | 6.5 | 0.32 | 3 | 51 | 1997 | 3.9 | 0.82 | 1 |
| 21 | 1993 | 6.4 | 0.34 | 3 | 52 | 1982 | 3.9 | 0.84 | 1 |
| 22 | 2000 | 6.4 | 0.35 | 3 | 53 | 1943 | 3.9 | 0.85 | 1 |
| 23 | 2001 | 6.4 | 0.37 | 3 | 54 | 1946 | 3.6 | 0.87 | 1 |
| 24 | 1989 | 6.3 | 0.39 | 3 | 55 | 1973 | 3.4 | 0.89 | 1 |
| 25 | 1945 | 6.3 | 0.40 | 2 | 56 | 2005 | 3.2 | 0.90 | 1 |
| 26 | 1998 | 6.3 | 0.42 | 2 | 57 | 1983 | 3.1 | 0.92 | 1 |
| 27 | 2012 | 6.2 | 0.44 | 2 | 58 | 1990 | 2.8 | 0.94 | 1 |
| 28 | 2008 | 6.1 | 0.45 | 2 | 59 | 1996 | 2.5 | 0.95 | 1 |
| 29 | 1986 | 6.1 | 0.47 | 2 | 60 | 1992 | 2.4 | 0.97 | 1 |
| 30 | 1999 | 6.1 | 0.48 | 2 | 61 | 1949 | 2.1 | 0.98 | 1 |
| 31 | 1964 | 6.0 | 0.50 | 2 | | | | | |

It can be observed from Table 5-3, that flood events of a magnitude just above the long-term maximum average are 2-year flood events with a probability of occurrence between 0.40 and 0.58 in any given year. The flood events of 1989 and 2001, which fall in the wet year category based on the multivariate ENSO index (Pricope, 2013) are 3-year flood events with a probability of occurrence of 0.39 and 0.37 in any given year respectively. During the decade 2000 to 2010, only three seasons had floods with a magnitude of less than the long-term maximum average. This implies that source floods of a magnitude above the long-term maximum average occur regularly in the Caprivi sub-basin, for the lake to be perennial; thus, its existence is more linked to rainfall variability than to flood variability.

Therefore, rainfall variability represents the greatest challenges to lake water resources management. The variability of rainfall will progressively increase as a consequence of climate change (Mirza, 2002), while in Southern Africa, oscillations between wet and dry rainfall phases have become extreme as driven by stronger El Niño or La Niña years since 1990 (Wessels *et al.*, 2004). During the last decade, most flood events exceeded the long-term maximum average threshold, while rainfall was highly variable exhibiting a wide range of oscillations between low and high annual rainfall. Consequently, during years of high rainfall, the lake subsequently exhibited robustness in the form of extensive spatial coverage.

Rainfall at local scale does not provide the most important source of inflow but it still represents the most critical factors affecting lake water resources. This is because at local scale, rainfall affects the components of infiltration rate and soil moisture content of highly permeable Kalahari sands. Hence, a wet rainfall year is characterised by water logged surface soils with micro-water pools and swamps at more localized scale, while a dry rainfall year is characterised by dry surface soils (sands). Therefore, the degree to which surface soils are water logged affects the percentage of effective runoff. Effective runoff in this case refers to the portion of Zambezi driven floods that runs as overland flow, contributing to the spatial coverage of flood water and recharge the wetland system (including Lake Lyambezi). Since, rainfall at the sub-basin precedes the floods; the wetness of the rainfall season determines the proportion of effective run-off. Hence, rainfall variability consequently influences the degree to which Zambezi-driven floods inundate the lake and may increase the chances of the Kwando-driven floods to reach the lake during the period of August/September.

# 6 CONCLUSION AND RECOMMENDATIONS

The overall objective of this study was to enhance the understanding of the spatio-temporal variations of Lake Lyambezi. The conclusion and recommendations are presented below and were based on the results.

## 6.1 Summary of findings

1. The first objective was to extract topography-based catchment characteristics in the Caprivi sub-basin. The use of SRTM 3 DEM led to the successful extraction of topography-based flow determination, which serves as a basis for further hydrological modelling and extraction of other hydrological parameters such as stream networks and the topographic index, and is important for catchment delineation. This has created confidence in the application of geo-hydrological models such as TOPMODEL for the estimation of water resources of the Lake Lyambezi.

2. The second objective was to perform a time series analysis of variations in Lake Lyambezi areal extent from remotely sensed imagery. The lake exhibited a wide range of area variation at both inter and intra-annual temporal scales and it was characterised by 7 phases of existence since 1984, based on desiccation and re-emergence of the lake. The application of MNDWI for the delineation of Lake Lyambezi based on dynamic thresholds, yielded moderate accuracy. This was attributed to the presence of thick vegetation growing on a series of pelagos and in the open water body, which gives the lake characteristics similar to that of a forest. However, the estimating the lake area on a time series basis was done successfully by applying the MNDWI. Therefore, area extent was a viable way of representing the status of the water resources of Lake Lyambezi.

3. The third objective was to investigate how the hydrological conditions at sub-basin level are related to the lake area variations. The inundation and recharge of the lake is driven by the Zambezi River floods; however, the magnitude of regional rainfall is more closely linked to the variation of the Lake Lyambezi water resources as it controls extent of spatial coverage of floods and the proportion of effective runoff.

4. The fourth objective was to test whether there is a relationship between water level variations of the Zambezi River and Lake Lyambezi. The Zambezi River is the main driver of flooding in sub-basin and constitutes the main source of seasonal inflow to Lake Lyambezi. However, the water level variations of the two systems are weakly correlated and this was attributed to the fact that the two systems are physically separate. On the other hand, Lake Lyambezi is strongly correlated to the Chobe River particularly the flood months. However, there exist a strong link in the floods peaks, where the first peak occurs in the Zambezi during April and the Chobe peak occurs in May while the flood peak of Lyambezi occurs in June. This indicates that even the correlation between the water levels of the Zambezi and Lake Lyambezi is weak; the inundation of the lake is principally driven by Zambezi floods.

5. The fifth objective was to determine the link between the probability of occurrence of floods, rainfall and dynamic changes in lake water areal extent, and the associated implication to water resources management. Based on probability of occurrence, the flood events with potential to inundate the lake and fall in the wet flood years occur regularly in the sub-basin. However, since the nature of the rainfall year controls the level of soil moisture saturation, and consequently it affects the proportion of effective runoff. Therefore, the dynamic change in lake areal extent of Lyambezi is more linked to rainfall variability than to the varying intensities of source floods.

Overall, based on the areal extent, Lake Lyambezi since 2009 holds large quantities of water resources that are capable of supporting a variety of water related livelihoods apart from the fishery.

## 6.2 Recommendations

Based on the results the following are recommend:

1. It is recommended that adequate gauging of the rivers and the lake should be done, in order to collect reliable *in situ* data, to aid the use of GIS based model for hydrological assessment and quantification of lake volume and the potential available water resources for economic development.

2. Using area as a measure, Lake Lyambezi contains massive water resources that need to be development at a local and small to enhance food security and alleviate poverty. Therefore, investigative studies should be conducted using agro-hydrological models such as ACRU 4 that are able to use a limited time series of input data to model agricultural yield against water resources availability in small catchment area. This will enhance the understanding of the potential of Lake Lyambezi to support development, augment food security and alleviate poverty.

3. A study on the feasibility of improving the effective runoff using structural development should be done. The SADC protocol on shared water resources mandates member states to adopt structural and non-structural methods to mitigate the impacts of floods. To this end, an appreciative inquiry should be made on the feasibility of creating a man-made channel that will direct water from the Kalimbeza flood plains to Lake Lyambezi via the Bukalo-Isuma and connecting to the kalengwe channel. This may be beneficial in directing excess overland flow to the lake and augment its water resources and enhance its potential for agricultural development. This will also reduce the spatial extent of floods and its associated hazards on local communities and on the operational programme of schools. The channel may be designed such that it is not directly linked to the Zambezi to avoid creating potential regional conflict, while ensuring it serves to direct overland flow to the lake.

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# APPENDICES

## Appendix 1.DynamicThresholding for the Delineation of the Water Body

### (a) The Area Calculated by using Digitising and Dynamic Thresholding

| DOY | Digitised area | Threshold_A | Threshold_B | Threshold_C | Threshold_D | Threshold_E | Mean area |
|---|---|---|---|---|---|---|---|
| 1984186 | 141.6 | 94.2 | 107.6 | 119.9 | 113.1 | 139.7 | 119.3 |
| 1984218 | 138.7 | 93.0 | 104.5 | 116.7 | 109.7 | 135.4 | 116.3 |
| 1984266 | 128.9 | 87.1 | 98.1 | 110.2 | 103.4 | 128.0 | 109.3 |
| 1987034 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1989135 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1989151 | 2.9 | 0.3 | 1.1 | 1.8 | 1.4 | 2.9 | 1.7 |
| 1989167 | 10.8 | 3.1 | 6.3 | 8.2 | 7.2 | 10.7 | 7.7 |
| 1989199 | 15.9 | 7.1 | 10.8 | 12.8 | 11.7 | 15.7 | 12.3 |
| 1989231 | 16.6 | 7.4 | 11.6 | 13.8 | 12.7 | 16.3 | 13.1 |
| 1989311 | 12.3 | 4.8 | 7.0 | 8.4 | 7.6 | 12.2 | 8.7 |
| 2001112 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2001240 | 16.6 | 10.9 | 15.8 | 16.6 | 16.1 | 16.6 | 15.4 |
| 2002003 | 6.5 | 3.2 | 6.5 | 6.5 | 6.5 | 6.5 | 5.9 |
| 2002099 | 1.4 | 0.5 | 1.3 | 1.4 | 1.4 | 1.4 | 1.2 |
| 2002291 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2003112 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2003230 | 9.3 | 5.1 | 7.6 | 8.5 | 8.1 | 8.5 | 7.8 |
| 2004113 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2004145 | 45.6 | 24.1 | 33.2 | 36.7 | 34.9 | 42.4 | 36.2 |
| 2004161 | 59.0 | 30.0 | 41.0 | 45.6 | 43.3 | 53.3 | 45.4 |
| 2004177 | 65.9 | 33.8 | 44.9 | 49.7 | 47.2 | 58.9 | 50.1 |
| 2004193 | 65.3 | 30.5 | 42.7 | 47.7 | 45.2 | 56.1 | 47.9 |
| 2005067 | 13.5 | 7.3 | 9.2 | 10.6 | 9.8 | 13.4 | 10.6 |
| 2005163 | 7.5 | 4.3 | 5.4 | 6.3 | 5.8 | 7.4 | 6.1 |
| 2005195 | 6.1 | 3.3 | 4.1 | 4.7 | 4.4 | 5.9 | 4.8 |
| 2005227 | 4.9 | 2.4 | 3.1 | 3.9 | 3.4 | 4.9 | 3.8 |
| 2005275 | 1.8 | 0.4 | 0.7 | 1.0 | 0.8 | 1.8 | 1.1 |
| 2006102 | 1.2 | 0.1 | 0.3 | 0.4 | 0.3 | 0.7 | 0.5 |
| 2006182 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2007009 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2007078 | 13.8 | 6.1 | 9.8 | 12.0 | 10.9 | 13.8 | 11.0 |
| 2007113 | 47.6 | 29.8 | 41.0 | 43.4 | 42.6 | 43.5 | 41.3 |
| 2007145 | 74.6 | 37.1 | 59.9 | 69.4 | 64.1 | 71.9 | 62.8 |
| 2007257 | 62.8 | 24.7 | 48.0 | 58.3 | 53.7 | 60.3 | 51.3 |
| 2008060 | 13.8 | 6.9 | 9.7 | 11.4 | 10.6 | 13.7 | 11.0 |
| 2008108 | 13.6 | 6.9 | 8.7 | 10.0 | 9.3 | 12.8 | 10.2 |
| 2008140 | 13.9 | 6.3 | 8.5 | 10.0 | 9.1 | 13.1 | 10.1 |
| 2008220 | 11.1 | 6.7 | 8.5 | 9.6 | 9.0 | 10.9 | 9.3 |
| 2008268 | 12.0 | 6.8 | 8.6 | 9.8 | 9.1 | 11.6 | 9.7 |
| 2009054 | 73.9 | 26.9 | 64.4 | 70.8 | 69.2 | 70.9 | 62.7 |
| 2009110 | 237.4 | 107.5 | 147.4 | 169.0 | 157.2 | 207.7 | 171.0 |
| 2009142 | 287.7 | 155.3 | 198.6 | 222.1 | 209.1 | 259.3 | 222.0 |
| 2009278 | 335.9 | 242.3 | 295.1 | 321.2 | 309.1 | 324.7 | 304.7 |
| 2009350 | 317.7 | 149.6 | 195.1 | 225.0 | 208.6 | 284.3 | 230.1 |
| 2010025 | 291.9 | 194.8 | 258.1 | 275.5 | 270.7 | 276.3 | 261.2 |
| 2010105 | 325.8 | 203.2 | 283.2 | 308.4 | 302.0 | 308.8 | 288.6 |
| 2010129 | 372.0 | 169.0 | 245.6 | 290.0 | 265.8 | 354.6 | 282.9 |
| 2010145 | 387.0 | 183.6 | 267.6 | 310.5 | 287.5 | 369.5 | 301.0 |
| 2010265 | 346.1 | 277.3 | 330.1 | 335.0 | 334.5 | 335.1 | 326.4 |
| 2010353 | 239.1 | 102.7 | 169.3 | 206.1 | 188.7 | 237.5 | 190.6 |
| 2011004 | 246.0 | 108.2 | 167.9 | 201.9 | 184.7 | 244.1 | 192.1 |
| 2011068 | 233.5 | 110.9 | 183.3 | 213.3 | 200.8 | 233.1 | 195.8 |
| 2011100 | 249.6 | 121.9 | 170.9 | 201.5 | 185.0 | 241.9 | 195.1 |
| 2011220 | 297.2 | 219.3 | 280.2 | 293.1 | 287.6 | 294.1 | 278.6 |
| 2011316 | 247.2 | 195.3 | 236.2 | 240.8 | 239.8 | 240.9 | 233.4 |
| 2012063 | 227.8 | 178.3 | 215.9 | 221.9 | 220.7 | 221.9 | 214.4 |
| 2012111 | 220.9 | 175.8 | 209.0 | 211.8 | 212.5 | 212.6 | 207.1 |
| 2012191 | 243.8 | 184.1 | 228.9 | 238.1 | 234.5 | 238.5 | 228.0 |
| 2012303 | 213.3 | 168.5 | 202.3 | 207.7 | 206.2 | 207.9 | 201.0 |
| 2013105 | 208.0 | 92.4 | 174.8 | 203.4 | 203.4 | 208.0 | 181.7 |

## (b) The Best Thresholds for the Landsat scenes

| Date (YDOY) | Best threshold | Date (YDOY) | Best threshold |
|---|---|---|---|
| 1984186 | Threshold C | 2008060 | Threshold C |
| 1984218 | Threshold C | 2008108 | Threshold C |
| 1984266 | Threshold C | 2008140 | Threshold C |
| 1989151 | Threshold C | 2008220 | Threshold C |
| 1989167 | Threshold D | 2008268 | Threshold C |
| 1989199 | Threshold C | 2009054 | Threshold E |
| 1989231 | Threshold D | 2009110 | Threshold E |
| 1989311 | Threshold D | 2009142 | Threshold E |
| 2001240 | Threshold B | 2009278 | Threshold D |
| 2002003 | Threshold D | 2009350 | Threshold E |
| 2002099 | Threshold D | 2010025 | Threshold D |
| 2003230 | Threshold D | 2010105 | Threshold D |
| 2004145 | Threshold D | 2010129 | Threshold E |
| 2004161 | Threshold D | 2010145 | Threshold E |
| 2004177 | Threshold D | 2010265 | Threshold B |
| 2004193 | Threshold D | 2010353 | Threshold C |
| 2005067 | Threshold C | 2011004 | Threshold E |
| 2005163 | Threshold D | 2011068 | Threshold C |
| 2005195 | Threshold D | 2011100 | Threshold E |
| 2005227 | Threshold C | 2011220 | Threshold B |
| 2005275 | Threshold C | 2011316 | Threshold B |
| 2006102 | Threshold C | 2012063 | Threshold B |
| 2007078 | Threshold D | 2012111 | Threshold B |
| 2007113 | Threshold D | 2012191 | Threshold B |
| 2007145 | Threshold D | 2012303 | Threshold B |
| 2007257 | Threshold D | 2013105 | Threshold D |

## (c) Comparison of the Means of Area obtained from Different Methods

**One-Sample Test**

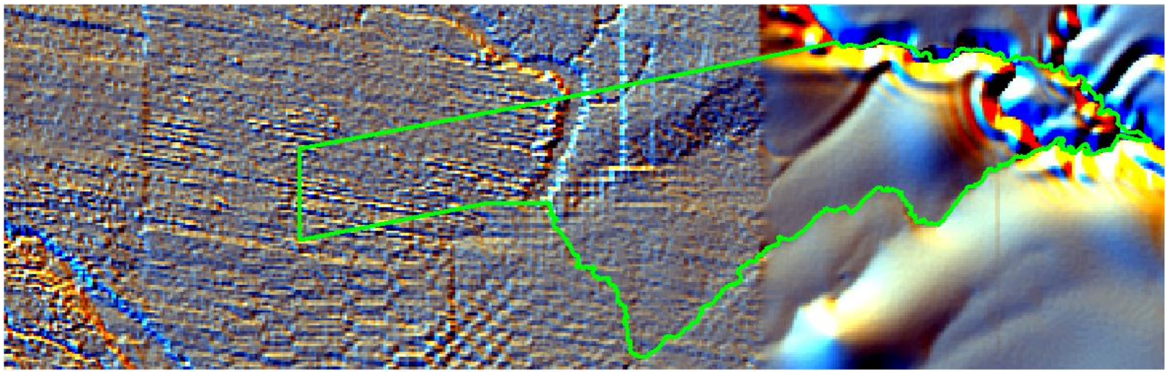
| | Test Value = 0 | | | | | |
|---|---|---|---|---|---|---|
| | | | | | 95% Confidence Interval of the Difference | |
| | t | df | Sig. (2-tailed) | Mean Difference | Lower | Upper |
| Threshold_A | 6.380 | 59 | .000 | 65.8506 | 45.198 | 86.503 |
| Threshold_B | 6.620 | 59 | .000 | 88.1589 | 61.513 | 114.805 |
| Threshold_C | 6.713 | 59 | .000 | 97.2031 | 68.229 | 126.178 |
| Threshold_D | 6.666 | 59 | .000 | 93.1697 | 65.201 | 121.138 |
| Threshold_E | 6.791 | 59 | .000 | 106.0358 | 74.790 | 137.282 |

### (d) Ground-truthing points

| X | Y | Attribute |
|---|---|---|
| 24.23207 | -17.91534 | water |
| 24.22766 | -17.91293 | land and vegetation |
| 24.21572 | -17.9088 | land and vegetation |
| 24.2319 | -17.91371 | water |
| 24.23391 | -17.91466 | water |
| 24.23425 | -17.91437 | land and vegetation |
| 24.24532 | -17.91607 | vegetation and water |
| 24.2482 | -17.92392 | vegetation and water |
| 24.23481 | -17.92205 | water |
| 24.23263 | -17.91879 | vegetation and water |
| 24.38043 | -17.92311 | vegetation and water |
| 24.33841 | -17.9514 | vegetation and water |
| 24.31959 | -17.95563 | vegetation and water |
| 24.31911 | -17.93862 | vegetation and water |
| 24.32346 | -17.92853 | water |
| 24.33787 | -17.92141 | water |
| 24.3587 | -17.91333 | water |
| 24.32392 | -17.94294 | land and vegetation |
| 24.32393 | -17.94303 | land and vegetation |
| 24.32108 | -17.94023 | land and vegetation |
| 24.31778 | -17.93883 | land and vegetation |
| 24.31562 | -17.93742 | land and vegetation |
| 24.316 | -17.93647 | land and vegetation |
| 24.31415 | -17.93108 | land and vegetation |
| 24.31415 | -17.92923 | water |
| 24.30742 | -17.92778 | land and vegetation |
| 24.30143 | -17.92842 | water |
| 24.30092 | -17.9338 | land and vegetation |
| 24.30092 | -17.9338 | land and vegetation |

## Appendix 2. DNO Hydroprocessing Outputs

### (a) Colour shadow map



### (b) The presence of sinks