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SPATIAL AND TEMPORAL VARIATION OF INUNDATION IN THE OKAVANGO DELTA, BOTSWANA; WITH SPECIAL REFERENCE TO AREAS USED FOR FLOOD RECESSION CULTIVATION

By

Kobamelo Dikgola

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Supervisor: Prof Dominic Mazvimavi

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Spatial and temporal variation of inundation in the Okavango Delta, Botswana; with special reference to areas used for flood recession cultivation

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Keywords

Okavango Delta

Floodplains

Inundation

Rainfall Variability

Flow Variability

Flow Distribution

Outflows Trigger

Change Detection

Trends

Cyclicity

Frequency Analysis

Abstract

Spatial and Temporal Variation of Inundation in the Okavango Delta, Botswana; With Special Reference to Areas Used for Flood Recession Cultivation

Kobamelo Dikgola

PhD Thesis, Department of Earth Sciences, University of the Western Cape

The Okavango Delta is recognized as one of the famous inland wetlands and its sustainable use is important for socio-economic development of Botswana. The Okavango delta comprises permanent swamps, seasonal swamps, and drylands on islands within the delta and the surrounding areas, sustained by Okavango river inflows from upstream and local rainfall. The Okavango River splits into several distributary channels within the delta. Areas which are flooded annually vary in response to varying inflows into the delta. Peak inflows into the delta occur during the February to May period. Due to the low gradient over the delta, these inflows move slowly resulting in peak outflows from the delta occurring during the June to August period. The inundated area over the entire delta increases from May until it reaches maximum in August and starts to decrease from September, reaching minimum inundated area in the months of December and January. The incoming flood wave into the delta and maximum inundation is out of phase with the local rainfall season.

Communities living within and around the delta derive their livelihoods from tourism, hunting, fishing, livestock rearing, and crop production. Crop production is carried out on drylands and within floodplains. Some of the households take advantage of the increase in soil moisture arising from this inundation along floodplains to cultivate their crops as the floods recede. This practice is locally referred to as *molapo* farming which highly depends on inundation of floodplains. The availability of floodplain inundation highly depends on the magnitude of inflows into the delta and the local rainfall which are highly variable resulting in uncertainty regarding successful crop production, availability of livestock grazing areas, and uncertainty in reliance on the wetlands resources such as fishing. The uncertainty experienced in timing of extreme events which cause flooding of resulting in water reaching areas or floodplains where it

is not wanted, and also uncertainity in timing of low flows, therefore water not reaching some parts of the delta.

Several hydrological studies have been carried out with the aim of improving the understanding of the spatial and temporal dynamics of flows throughout the delta including predicting areas that are likely to be inundated each year. The significant gap addressed by this research is to improve the understanding of the spatial and temporal influence of magnitude and timing of flows on floodplain inundation. Local rainfall on the delta is highly variable over time and space due to its convective nature. This research also addresses the rainfall temporal and spatial variations and its implications on floodplain inundation. The knowledge about spatial extent and duration of floodplain inundation should assist in predicting each year the viability of *molapo* farming. Three research site, Shorobe, Tubu and Xobe are selected as case studies to understand the dynamics of floodplain inundation induced either by inflows or local rainfall.

Local rainfall during the December to March period enables the crops to reach maturity. The onset of the rainy season is very important in supporting sowing of crop seeds. Local rainfall on the delta varies considerably. Aerial rainfall interpolation shows a change in rainfall magnitudes over space in different rainfall months, i.e different parts of the delta receive different rainfall magnitudes in different months of the rainy season. The spatial variation is mainly associated with the migration of the ITCZ southwards first through East Africa during October and November and down over Southern Africa in December to February. The movement of the ITCZ brings rainfall concentration on the northern and eastern parts of the Okavango Delta during December to January and bringing rainfall concentration to the northwestern part of the delta around February. However, rainfall spatial correlation between stations can be poor even within the first 150 km therefore implying neighboring places do not experience floodplain inundation by rainfall at the same time. The poor spatial correlation of rainfall between neighboring stations reflects the erratic nature of rainfall in the Okavango Delta characterised by localized thunderstorms. Change detection shows change points in rainfall which can be associated with ENSO episodes. A change point is identified in 1976 and 1977 which can be associated with the El Nino episodes during those years and two change points identified in 1999 and 2004 which can be associated with the La Nina episodes, therefore rainfall induced floodplain inundation can

also be associated with wet and dry ENSO episodes. Rainfall does not show any significant trends except for an increasing trend on 10th percentile of Shakawe rainfall. Rainfall also does not show any cyclic behavior. Rainfall over the Okavango Delta can be divided into three unique homogenious sub-regions; sub-region 1: the northern part following the GEV probability distribution and being the region with highest rainfall amounts; sub-region 2: the lower northern and the outlet parts of the Okavango Delta following the GPA distribution with moderate rainfall; and sub-region 3: the middle part of the delta extending to the western and the eastern fringes of the delta, following the P3 distribution and having the lowest rainfall.

The main characteristic that defines the Okavango Delta flows at Mohembo is its cyclic behavior. Three significant cycles are identified, close to 10, 20 and 40 years. No significant trends are identified, only a decreasing trend in minimum flows. Change points are identified in 1979 and 1988 and these can be explained by the existing cyclicity since no major land use changes have taken place in the Okavango River Basin upstream before 1989. The existence of cyclicity in Okavango River flows at Mohembo also explains the periodic wetting and drying of different floodplains in the delta. A long period of low flows was experienced from 1983 until 2003 and floodplain inundation extent was greatly reduced, more especially during the 1993-2003. During the 1993-2003 period, flows could no longer reach Maun Bridge along Thamalakne River, therefore leaving *molapo* floodplains around Boteti River, Gomoti River and Thaoge River to dry out. The 10 and 40 year return floods are important as they indicate the probability of a flood magnitude which has potential to result in major inundation in the Okavango Delta. Therefore, flood magnitudes with recurrence interval 10 and 40 years have high probability of occurring and can cause major floodplain inundation as they can be above the 2009 flood of 969 m^3/s, which was the return of major inundation of Okavango Delta floodplains after a long period of dryness.

The Ngoqa-Maunachira distributary channel of the Okavango River receives 32% of flow volumes entering the Okavango Delta at Mohembo. 12 % of the Mohembo flow volumes reach the Jao-Boro distributary whilst 1% is received by the Thaoge distributary. Therefore more inundation is experienced along the Ngoqa-Maunachira system compared to the other two. Only about 2% of the Mohembo flow volumes leave the Okavango Delta through Boteti River. Long

term shifting of flow direction amongst reaches along the Okavango Delta distributaries is evident more especially along the Ngoqa-Maunachira River system. This results in shifting of inundation. Sub-surface water respond significantly to local rainfall and inflows with high soil moisture conditions retained at 60 cm and 100 cm below the ground.

Declaration

I declare that this thesis

"Spatial and Temporal Variation of Inundation in the Okavango Delta, Botswana; With Special Reference to Areas Used for Flood Recession Cultivation"

is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Kobamelo Dikgola February 2015

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Dedication

I dedicate this thesis to my late grandmother

Mosadifela Setlhoko Dikgola

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List of Abbreviations

AMIN	Annual Minimum Series
AMS	Annual Maximum Series
BRT	Buishand Range Test
CDF	Cummulative Distribution Function
DGS	Departemnt of Geological Surveys
DWA	Department of Water Affairs
DMS	Department of Meteorological Services
ENSO	El-Nino Southren Oscillation
EPSMO	Environmental Protection and Sustainable Management of the Okavango River Basin
EV1	Extreme Value Type 1
EXP	Exponetial
FDC	Flow Duration Curve
GEV	Generalised Extreme Value
GPA	Generalised Pareto
GNO	Generalised Normal
GLO	Generalised Logistic
ITCZ	Inter-Tropical Convergence Zone
KEP	Kgalagadi Early Pearl
KS	Kolmogorov-Smirnov
OD	Okavango Delta
ODMP	Okavango Delta Management Plan
OKACOM	Okavango River Basin Commission
ORB	Okavango River Basin
ORI	Okavango Research Institute
ODRS	Okavango Delta Ramsar Site
MEP	Mean Excess Plot
MK	Mann Kendall
MOZ	Makgadikgadi-Okavango-Zambezi
P3	Pearson Type 3
PDS	Partial Duration Series
POT	Peak Over Threshold
PT	Petit Test

SNHT	Standard Normal Homegeinty Test
SST	Sea Surface Temperature
TDA	Transboundary Diagnostic Analysis
TTT	Tropical Temperate Troughs
WMO	World Meteorological Organisation

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Glossary of terms

Antecedent conditions: The conditions existing prior to the occurrence of an event: e.g; preceding soil moisture conditions prior to the arrival of an annual flood wave.

Blockage: Channel flow confinement and obstruction by vegetation causing slow water movement

Burfication: Splitting of the main channel into smaller distributary channels

Climate Change: A significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years.

Delta fringe: A riparian zone in the edge of the wetland

Distributary: A channel that branches off and flows away from the main stream channel

Inundation: The overspreading of flood water covering a surface

Flood wave: A distinct rise in water levels culminating in a crest and followed by recession to low water levels

Flood peak: The crest or the highest value of an inflow at any point in the delta resulting from the propagation of Okavango river inflows down a low gradient throughout the entire delta.

Floodplain: A flat land adjacent to a river stretching from the banks of a channel to an enclosing valley wall, this area tends to be inundated during high flows. This is where flood recession (molapo) cultivation takes place.

Flow propagation: The movement of a flood wave along channels

Hydroperiod: The seasonal pattern of the water level that results from the water budget and the storage capacity of a wetland

Peizometer: A small diameter borehole used to measure groundwater levels

Riparian zone: An area in the immediate vicinity of the channels, this includes the floodplains, extending further into the drylands. The riparian zone functioning is assumed to be highly influenced by the wetland

Sub-Surface Water: Water beneath the ground surface

1: INTRODUCTION

1.1 Background

The Okavango River Basin (ORB) is an endorheic basin shared by Angola, Botswana and Namibia. The river runs for 1,100 km from central Angola where it is referred to as the Cubango river, through Namibia where it is called Kavango river, and finally into Botswana as the Okavango river. The total basin area is about 530,000 km^2. Runoff is generated on the sub-humid Benguela Plateau in southern Angola at an altitude of 1,780 m above sea level and flows southward to the semi-arid Namibia and most of the water entering the Okavango Delta in Botswana is lost to evapotranspiration (Andersson *et al.*, 2003). Mean annual rainfall over the Okavango River basin ranges from the highest 1,200 mm/yr in Angola, 550 mm/yr in Namibia to 450 mm/yr in Botswana. The ORB has two main rivers in Angola, Cubango and Cuito which flow southwards through savanna woodlands and tropical forests into the semi-arid Kalahari along the boundary of Namibia and Botswana. After passing the border between Angola and Namibia, the Cubango River is called the Kavango and is joined by the Omotako River in Namibia. The Omatako River begins in a plateau in the central part of Namibia. The Kavango and the Cuito Rivers then join to form the Okavango River (Figure 1.1). The Okavango River enters Botswana at Mohembo at an altitude of 980 m above mean sea level, it then splits into several distributary channels as it drains into the Okavango Delta (Figure 1.1), a large swamp area caused by tectonic activities. Altitude declines by 65 m from Mohembo to Maun over a distance of 260 km (Ellery & McCarthy, 1994). The ORB is made of two distinctive parts, the upper part characterised by a typical river system and the lower part characterised by a wetland.

The area of the Okavango River Basin which is responsible for perennial surface water flows is much smaller than the total extent of the basin based on topography (TDA, 2011) and thus creating a challenge in the delimitation of the ORB especially on the downstream part of the Okavango Delta. In respect of topography, the ORB thus includes areas historically drained by the now fossil Omotako River in Namibia, the Okavango Delta spillover through the Selinda Channel which connects to the Chobe River system through the Kwando/Linyanti River and the Okavango Delta outflows drained by the Thamalakane-Boteti Rivers subsequently connecting to the Makgadikgadi pans. The Makgadikgadi pans are connected to the Nata River Basin which

drains the western part of Zimbabwe. The delimitation of the ORB is usually limited to the parts of the basin in Angola and Namibia, and the panhandle/delta/Boteti river complex in Botswana (TDA, 2011)

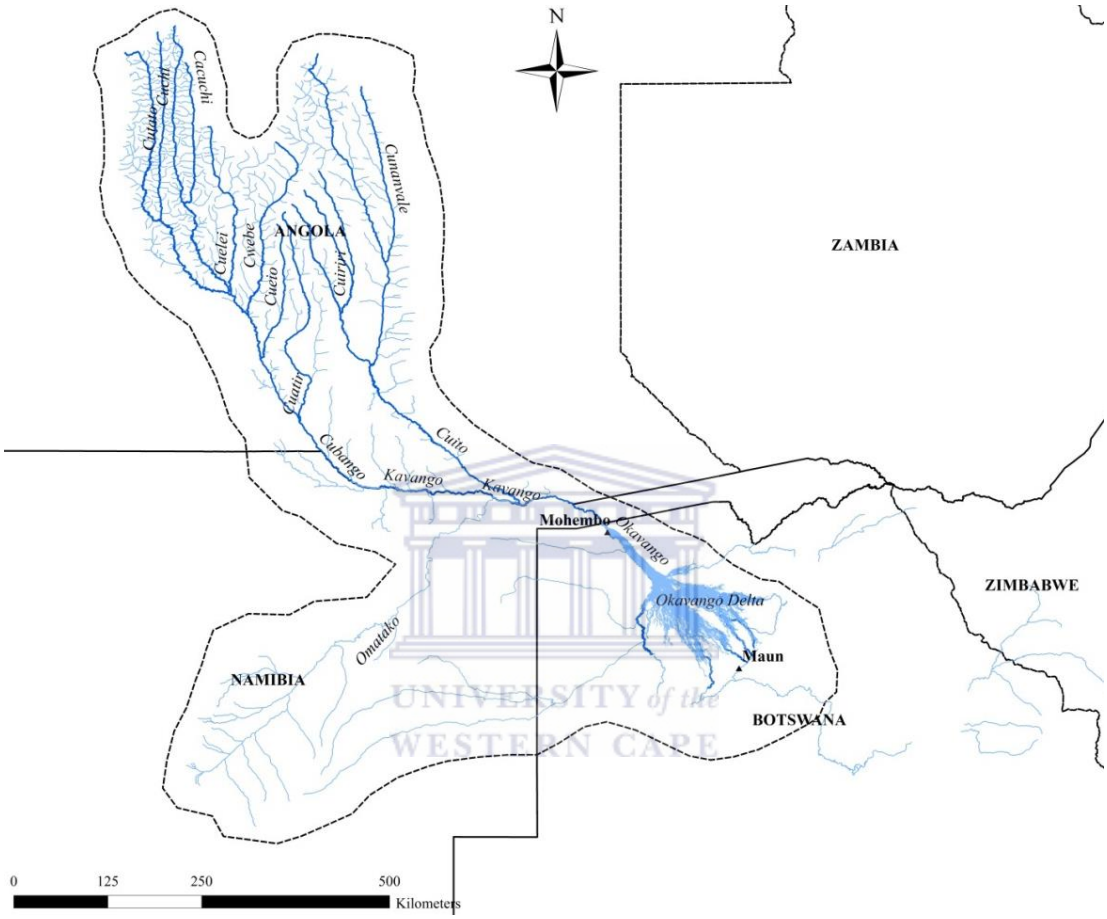


Figure 1.1: The Okavango Delta as part of the Okavango River Basin, shared between three countries, Angola, Botswana and Namibia. Mohembo is where Okavango River inflow is gauged.

The flood peak from upstream in Angola reaches the Okavango delta at the end of the local rainy season in April resulting in variation in floodplain inundation extent in the wetland. The inundated area varies annually from 4,000-6,000 km^2 to a maximum of 6,000-12,000 km^2 (Wolski *et al.*, 2006). A considerable amount of flood water recharges groundwater throughout and on the fringes of the permanent swamps (Gumbricht *et al.*, 2004). According to Gumbricht *et al.*, (2004) and Wolski *et al.*, (2006) summer rains slightly contribute to the rising of the groundwater table. Local rains which occur in the austral summer, between October and March rarely induce flooding, except during extremely high rainfall years. The local rains only

influence the variability of the inundated area by wetting the system before the high inflows arrive into the Delta (Wolski *et al.*, 2006). A combination of inflow, local rainfall and antecedent wetness conditions causes variation of the inundated area and outflows from the delta (Gumbricht *et al.*, 2004).

1.2 Literature review

The Okavango Delta is a wetland of national and international interest and therefore has attracted a lot of research in all fields. In terms of hydrology and understanding the flooding and inundation in the delta, Dincer *et al*., (1987) developed a simple mathematical model to understand flow distribution amongst the main distributary channels, simulated as cells represented by a reservoir with triangular cross section, along the flow line of the distributary system. The Okavango Research Group at the University of the Witwatersrand in Johannesburg, South Africa, carried out a substantial research work in the Okavango Delta for over 20 years, on different disciplines which mainly emphasizes the role of sediment transport, vegetation, hydrological and geochemical processes on shaping and functioning of the Okavango ecosystem (McCarthy *et al.*, 1988; McCarthy *et al.*, 1993; McCarthy *et al.*, 1997; McCarthy *et al.*, 1998; McCarthy *et al.*, 2000; McCarthy *et al.*, 2003; McCarthy *et al.*, 2004; Gumbricht *et al.*, 2001; Gumbricht *et al.*, 2004; Gumbricht *et al.*, 2005). Gieske (1997) modelled the outflow from the Jao/Boro river system. The research explained the role of both long term (over 10 years shallow groundwater levels) and short term (memory of one year or less of peak rain and flood events) antecedent conditions in sustaining the Okavango wetland. The results showed that the Okavango Delta outflows are entirely linked to climatic variations. Wolski *et al*., (2006) developed a hybrid model to estimate flooding in the Okavango delta. The model overcomes the problem of simplicity of previously developed models by introducing a better representation of surface water-groundwater interactions. The model predicted the minimum to maximum inundated area due to an annual flood event. The Department of Water Affairs (DWA), through the Okavango Delta Management Plan project configured the MIKE SHE/MIKE 11 model for the Okavango Delta (ODMP, 2006). The model simulated flows in the delta and is useful for management purposes. There are still limitations in understanding the role of spatially distributed rainfall in inundation of floodplains, the distribution and influence of incoming flows in inundating specific floodplains in the delta which is critical for livelihood activities.

1.2.1 Local rainfall on the Okavango Delta

The Okavango River inflows contribute about 75% of the water in the Okavango Delta while the local rainfall supplies about 25% (Andersson *et al.*, 2003). This result in inundation mostly caused by Okavango river inflows and to a smaller extent the contribution by local rainfall (Bartsch *et al.*, 2009). Spatial and temporal variations of inundation extent in the Okavango Delta have seasonal variability (Wolski *et al.*, 2008; Bartsch *et al.*, 2009). Annual rainfall over the delta varies from 300-1,000mm/year (McCarthy, 2005). Local rainfall is characterized by convective thunderstorms that are highly scattered with high temporal variation (Gumbricht *et al.*, 2004). Maximum inundation extent in the delta is reached around August and September, 5 – 6 months after the end of the rainy season (Bartsch *et al.*, 2009).

Due to micro-climatic difference (Milzow, 2008), variation in regional climate (McCarthy *et al.*, 2000) and tectonic movements (Wolski *et al.*, 2006) within the delta, different parts of the delta respond differently to hydrological processes. Inundation on the eastern part of the delta is mainly triggered by local rainfall, whilst the western part is mainly affected by the flood pulse (Wolski and Murray-Hudson, 2006). Localized surface flooding caused by local rainfall is often short lived because of high evaporation rates and infiltration (McCarthy 2005). Studies on inundation extent over the Okavango Delta have been conducted through the use of satellite imagery (McCarthy *et al.*, 2003) and hydrological models (Milzow 2008; McCarthy *et al.*, 2003). The extent to which flooding depends on local rainfall or the contribution of local rains on soil moisture or antecedent conditions before the arrival of the upstream inflows, have not been explored (McCarthy *et al.*, 2003).

Hydrological models are widely used for flood prediction but the challenge remains in their sensitivity to uncertainty related to spatial variability of rainfall. This uncertainty is due to lack of data on rainfall and other relevant climatic characteristics at spatial scale that could enable an accurate representation of the effects of these variables (Arnaud *et al.*, 2002). The success of hydrological models depends highly on accurate representation of catchment rainfall inputs (Hughes, 2005). Quantitative knowledge of rainfall variability, evapotranspiration and soil moisture is important for understanding surface and subsurface processes (Anagnostou, 2004).

Wolski *et al.*, (2006, 2008) used average annual rainfall of Maun and Shakawe, two stations at the two ends of the delta, approximately 260 km apart, to analyze the hydrological responses of the wetland to rainfall. This raises the question of accurate representation of rainfall spatial variability over the entire delta. Balme *et al.*, (2006) suggests that a minimum of 8 – 10 rainfall stations over an area of 10,000 km^2 is required to capture rainfall at event scale. More than 30 rainfall stations are available through out the Okavango Delta, but due to vandalism by wild animals and lack of access to stations during the wet season, some stations have missing records. Only 19 stations have reasonable rainfall records to capture the delta rainfall variation.

1.2.2 Okavango River flows, flow partitioning and inundation distribution

Flows of the Okavango River from the Angolan highlands enter the delta through the permanent swamps at the panhandle before spreading through the entire alluvial fan (Mapila *et al.*, 2006). Flows from the well watered part headwaters take 3-4 months to arrive in the delta. Consequently peak inflows in April are out of phase with the local rains that are highest during the January-February period (Wolski *et al.*, 2008). Inflows into the delta start to increase in December and reach peak flows in April and decline to their lowest level in November (Gumbricht *et al.*, 2004; Wolski *et al.*, 2006). The flood wave takes four to five months to spread across the entire delta (Gumbricht *et al.*, 2004). According to *Gumbricht et al*., (2004), about 14,000km^2 of the Okavango Delta area can be flooded at least once every 10 years. The existence of juxtaposed fluvial islands in the delta area suggests a historically larger inundation area (Gumbricht *et al.*, 2004).

The relationship between the Okavango River inflow at Mohembo and changing flooding conditions amongst the major distributaries of the delta can explain variation in inundation of floodplains (Wolski *et al.*, 2008). The relationship depends on the hydrological linkage of the distributaries with the permanently flooded part of the delta, which supplies them with water, together with prevailing antecedent conditions (Wolski *et al.*, 2008). According to McCarthy *et al.*, (2000) seasonal variations of inundated area is mainly observed in the middle (Boro) and eastern (Maunachira-Khwai) parts of the delta, while the west (Lower Thaoge) remains dry. Over the last 100 years, the main flow direction switched from Thaoge in the west towards the

east (Maunachira-Khwai) (McCarthy *et al.*, 2000) which may be linked to long-term channel aggradation process changing the underlying topography (Wolski and Hudson, 2006), and therefore resulting in more inundation in the middle and eastern part of the delta. Analysing inundation maps of the Okavango Delta, Wolski and Murray-Hudson (2006) revealed that a shift in floodwaters occurred in 1997, causing an increase in inundated area along Xudum distributary with decreased inundation along the Thaoge distributary.

Temporal changes in the distribution of flows in the Okavango Delta are climatically driven, whilst permanent changes may be associated with structural changes (Wolski and Murray-Hudson 2006). Wolski and Murray-Hudson (2006) continued to reaveal that in the 1970's, the Mboroga channel dried up. According to Wolski and Murray-Hudson (2006) the two channels, Thaoge and Mboroga dried due to blockages by debris and papyrus. However, McCarthy *et al.*, (1992) and Ellery *et al.*, (1995) suggest that the primary cause of channel blockages is the channel aggradation process by sediments. McCarthy *et al.*, (1993) also indicates that due to tectonic movement, the sinking of the Okavango grabens can potentially lead to change in flood distribution. Increased inundation in some areas along the eastern distributary (Ngoqa – Maunachira-Khwai) is sometimes observed as a result of local rainfall during the rainy season but later superimposed into the much stronger Okavango river flood wave which finally dominates the inundation variations in these areas (Wolski *et al.*, 2005). Further investigation needs to be conducted to establish how inflows determine floodplain inundation throughout the year at different parts of the delta. Channels surrounded by wide floodplains allow considerable lateral movement of water from channels into the floodplains (Wolski and Murray-Hudson, 2006).

1.2.3 Channel-floodplain interaction

When the river inflows advance into the Okavango delta, a large portion of the surface water infiltrates into the highly permeable soils along the flood front (Wolski *et al.*, 2006; Milzow *et al.*, 2009). The infiltration rate and the propagation of the flood highly depend on the prevailing groundwater table (Milzow *et al.*, 2009). Wolski *et al.*, (2006) indicate that the infiltrated water reaches the groundwater table about 3 days from the arrival of the inflows. According to Ramberg *et al.*, (2006) the infiltration is intially rapid as the flood arrives. Groundwater storage

in the delta affects the scale of inundation and determines the long- term memory and functioning of the wetland (Wolski *et al.*, 2006). Groundwater is considered a major water balance component of wetlands in semi-arid regions (Jolly *et al.*, 2008). Ramberg *et al.*, (2006) suggested that the interaction of surface water and groundwater is one of the important hydrological processes affecting the biological and biochemical processes at the hyporheic zone in wetlands (Ramberg *et al.*, 2006). During the rainy season, a small rise of groundwater occurs in the delta due to direct rainfall recharge (Wolski *et al.*, 2006). According to McCarthy, (2005) the groundwater table is shallow within the wetland in comparison to areas outside the delta. Ramberg *et al.*, (2006) found out that the magnitude and character of groundwater table changes are less pronounced away from the inundated area.

Wolski *et al.*, (2006) noted that the groundwater flow direction was towards the center of the islands from floodplains. Evapotranspiration lowers the groundwater levels on islands and creates a hydraulic gradient from the floodplain towards the center of islands (Wolski *et al.*, 2006). Wolski *et al.*, (2006) and McCarthy, (2005), generalized that there is no groundwater discharge into the channels in the entire delta. The generalization might be true for floodplain-islands groundwater flow but different for floodplain- riparian zones like in the fringes of the delta. McCarthy, (2005) indicates the possibility of groundwater flowing far out of the delta area. According to Jolly *et al.*, (2008), groundwater flow between the riparian zone and the wetland depends on gradient between the water table below the riparian zone and the amount of surface water in the wetland. Wolski *et al.*, (2006) concluded that the Okavango Delta forms a recharge wetland based on the floodplain-island groundwater flow study. Jolly *et al.*, (2008) indicates that some wetlands can be flow-through wetlands, channels gaining water from groundwater discharge on one side and losing water through groundwater recharge on the other side. The Okavango delta is characterized by shallow groundwater tables and as a result, a significant amount of water is also lost from the saturated zone through evapotranspiration (ET) (Bauer *et al.*, 2003). According to Serrat-Capdevilla *et al.*, (2011), in most arid and semi-arid regions, actual ET is very much limited by availability of water (Serrat-Capdevilla *et al.*, 2011) which is not the case in the Okavango Delta. The Okavango Delta is in a semi-arid region, characterised by annual evapotranspiration that is greater than local rainfall (Gumbricht *et al.*, 2004). 97% of the water in the delta is lost to evapotranspiration annually (Bauer *et al.*, 2004) and this plays a

major impact on the duration of floodplain inundation in the delta. The remaining water recharges groundwater or released as outflows through downstream channels (ODMP, 2006).

1.2.4 Flood recession cultivation

Flood-recession farming is practised along many rivers of the world (Senegal, Nile, Mahaweli, Tana, Indus, Hadejia, Phongolo, Kafue, Colorado, and Logone) (Saarnak, 2003). Flood-recession farming system utilises natural irrigation and fertilization of the floodplains (Saarnak, 2003). The yield from flood-recession cultivation is strongly affected by flooding patterns (Saarnak, 2003). According to Adams (1986), despite the high variability of river flows, floodplains still remain a valuable agricultural resource. The extent and duration of surface flooding is a key factor in floodplain cultivation and this is linked to depth and frequency of flooding (Adams, 1986). According to Adams (1986) a flood of long duration is likely to be followed by a series of repeated inundations, and floods with greater depth are likely to have long duration of inundation. Flood duration helps to identify flood-tolerance of different crops (Adams, 1986). The flood-tolerance helps to identify the survival of different crops under different inundation conditions, i.e whether a crop can survive waterlogging or just residual moisture conditions.

The wetlands of Okavango Delta are a major source of livelihoods for the rural communities (Kgathi *et al.*, 2005). The communities derive their livelihoods directly or indirectly from the natural resources of the Okavango Delta. Livelihood activities of local communities in the Okavango Delta include agriculture (both arable and livestock), fishing, hunting and gathering, and tourism which also create formal employment for local communities. Although tourism promotion and development in the delta is growing, arable agriculture is still ranked the most important livelihood activity for local communities in the Okavango Delta region (Kgathi *et al.*, 2007). Two systems of crop farming are practised, dryland farming and flood-recession farming which is locally reffered to as *molapo* farming (Vanderpost, 2009). In 1997 and 1998, 27% and 16% respectively, of farmers in Ngamiland, were involved in *molapo* farming practice. According to Vanderpost (2009), 48,900 hectares of land is cleared for cultivation in the Ngamiland/ Okavango region of which 75% consists of dryland fields and 25% is for flood-recession cultivation, i.e *molapo* farms. *Molapo* farming is mainly practiced in floodplains of the western and south eastern fringes of the Okavango delta mainly in Tubu and the Shorobe-

Matlapaneng area and on the distal floodplains at Xobe along Boteti River (Figure 1.2). *Molapo* farms lie on fertile soils in the floodplains, therefore resulting in higher yields than in the dryland farms. When making use of rainfed conditions only 500 kg/ha sorghum can be obtained from *molapo* cultivation whilst under optimal flooding conditions 1,800 kg/ha – 2,900 kg/ha sorghum can be obtained (Bendsen, 2002). According to Kgathi *et al.*, (2005) there is additional potential for *molapo* farming on 7,465 ha of land in the Okavango Delta.

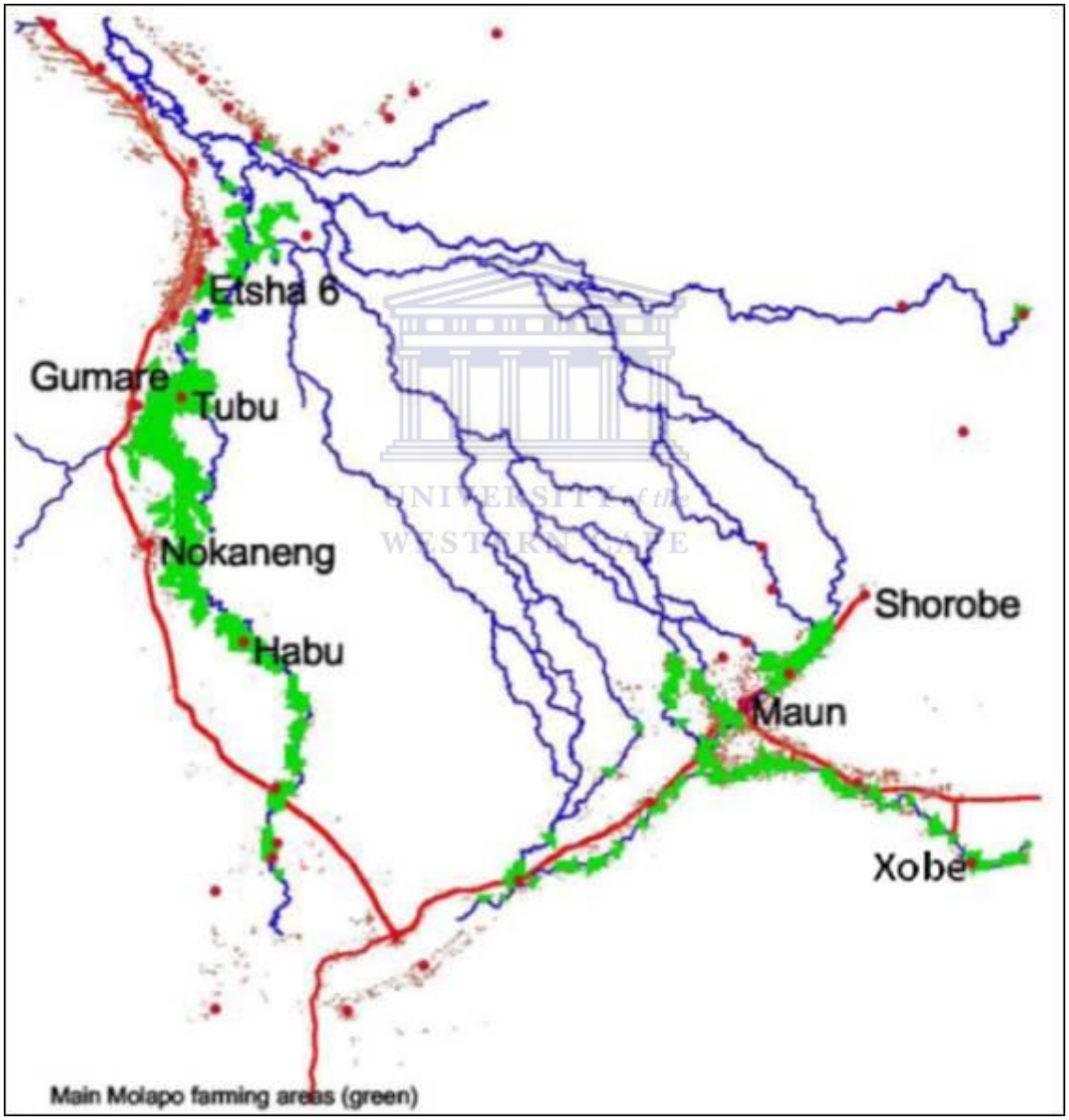


Figure 1.2: The main *molapo* farming areas in the Okavango Delta (Source; Vanderpost 2009)

Molapo farming in the Okavango delta takes place in floodplains moistened by overbank inundation, and rising groundwater table, and supplemented by rainfall (Vanderpost, 2009). According to Bensen (2002), between September and December, the Okavango water levels recede due to evapotranspiration, infiltration to groundwater and outflows. This leaves floodplains moistened and suitable for crop cultivation. Variation in inundated areas has an effect on *molapo* farming due to availability of moisture for *molapo* cultivation and this may result in *molapo* farmers having to migrate to the neighbouring places (Kgathi *et al.*, 2008) e.g. due to the drying up of the Gomoti River in the 1990s some of the Shorobe farmers migrated to Maun. According to Kgathi *et al*.,(2005), the variation of inflows into the delta affects *molapo* farming either by being too high and not receding on time, or too low and therefore reducing the moisture availability in the floodplains. From 1974 to 1978, inflows in the Okavango delta were high and this caused a large part of Shorobe *molapo* farms not being cultivated, whereas between 1986 and 1987 and in the 1990s, the *molapo* farms were not flooded and could still not be cultivated. During years when floods are low, *molapo* farmers have to depend on local rains for crop production (Kgathi *et al.*, 2005).

1.3 Scope of the study

1.3.1 Motivation

The Okavango Delta is characterized by the strong seasonality and high inter-annual variation of inflows. The permanent swamps and seasonal swamps of the delta are annually sustained by 10 km^3/yr of inflows of the Okavango River and 6 km^3/yr of local rainfalls (McCarthy, 2005). The variation of inflows into the delta results in seasonal variation of floodplain inundation in the entire delta. Defining the hydroperiod components such as frequency, duration and depth helps in understanding of wetlands inundation dynamics (Murray-Hudson *et al.*, 2014). The variations in timing, magnitudes and frequency of Okavango River inflows need to be investigated further to determine the extent to which they influence inundation on the floodplains. According to Wolski *et al.*, (2006) local rains wet the Okavango system before the arrival of the Okavango River flood wave. Although the local rains rarely cause flooding in the delta except during years of extremely high rainfall, the extent to which the rains can induce inundation in the floodplains

is still not clear. Due to the convective origin of the local rains over the delta, they are highly scattered and variable over space and time, and this variation also needs to be explored.

A significant portion of the Okavango Delta floodplains is inundated differently every year due to the seasonal flood pulse (Murray-Hudson *et al.*, 2014). Wolski *et al.*, (2005) pointed out that the inundation dynamics in the Okavango delta result from a complex interplay of Okavango river inflow, local rainfall, channel-floodplain interactions, in-channel sedimentation and human interventions both within and upstream of the delta. Due to variation in annual flood pulse, the hydroperiod in the Okavango delta has spatial and temporal variation and as a result, it determines the provision of ecosystem services at different points in time. The variation in inundation over the entire delta needs to be explored by assessing the distribution and partitioning of the flood pulse amongst the major distributaries of the delta. The extent to which the annual flood pulse travels along the distributary channels also varies depending on the magnitude of the peak flow that enters the delta through the Okavango River. An assessment of the flows can also help in understanding peak flow magnitudes that induce certain inundation distances and extents in order to trigger outflows from the delta.

1.3.2 Research objectives

1.3.2.1 Goal

The main goal of this study is to contribute towards improving understanding of floodplain inundation as a result of Okavango River inflows and local rainfall in the Okavango Delta.

1.3.2.2 Aim

The study seeks to assess the effects of spatial and temporal variation of local rainfall and Okavango River inflows on the variability of inundations of floodplains, which is important for livelihood activities in the Okavango Delta.

1.3.2.3 Specific objectives

1. To assess the effects of spatial and temporal variations of local rainfall on inundation of floodplains within the Okavango Delta.
2. To examine the characteristics of flows (timing, magnitude and duration) of the Okavango River that influence inundation in the Okavango Delta.
3. To examine the distribution and partitioning of flows within the Okavango Delta and implications on floodplain inundation in different parts of the delta.
4. To assess how spatial and temporal variations of local rainfall and Okavango river inflows and their distribution affect inundation of floodplains used for flood-recession cultivation.

1.3.2.4 Research questions

- How does the local rainfall on the Okavango delta vary over time and space, and what are the effects of these variations on floodplain inundation in the Okavango Delta?
- What are the main Okavango river flow characteristics and what are their implications on variations of floodplain inundation in the Okavango Delta?
- How does the partitioning of Okavango river inflows over the Okavango Delta influence the spatial variation of inundation in the Okavango Delta floodplains?
- How does the variation in local rainfall and flow distribution affect inundation of floodplains used for flood-recession cultivation?

1.4 Chapter synopsis

Chapter 1: Gives a general introduction of the research, background literature, the motivation of the research and objectives

Chapter 2: Gives a description of the study area

Chapter 3: Focuses on the rainfall dynamics over the Okavango Delta. The chapter assesses the spatial and temporal variation of local rainfall; spatial structure, trends, frequency and probability analysis.

Chapter 4: Evaluates the Okavango river flow characteristics. The chapter asseses the magnitudes, frequency and duration of Okavango River flows at Mohembo and the implication to long term characterization and dynamics of floodplain inundation within Okavango delta.

Chapter 5: Presents the partitioning and distribution of Okavango river inflows amongst the Okavango Delta channels and implications to floodplain inudation. The chapter further presents the triggering of outflows from the Okavango Delta also also their implication downstream floodplain inundation.

Chapter 6: Implications of spatial and temporal dynamics of local rainfall and inflows on for floodplain inundation which is important for livelihoods activities such as *molapo* farming.

Chapter 7: This chapter concludes and gives recommendations based on the findings of this study.

2: DESCRIPTION OF THE STUDY AREA

2.1 Introduction

Early Pleistocene tectonic movements formed depressions which led to some of the current large catchments which are drained by ephemeral streams and few perennial rivers (Grey and Cooke, 1977; Meier *et al.*, 2008). The Okavango Delta, located in the south-western tectonically active extension of the East African Rift Valley, is one of these basins (McCarthy, 1998). Tectonic movements along the north-east and south-west of Botswana resulted in the down-warping of the Okavango Delta and the formation of a depression that created the current Makgadikgadi Pans (Grey and Cooke 1977). The Okavango Delta is part of the former Makgadikgadi-Okavango-Zambezi system (MOZ). During the late Pleistocene, the Okavango Delta and the Makgadikgadi Pan in Botswana were covered by lakes and the Okavango and Zambezi Rivers used to control the hydrology of the Makgadikgadi Pans (Meier *et al.*, 2008). Due to tectonic movements, the Zambezi watercourse connection with the Makgadikgadi was disrupted (Meier *et al.*, 2008).

The Okavango Delta which is located in the northern part of Botswana in Ngamiland district (Figure 2.1), is one of the world's largest wetlands with highly variable channel morphology, flow regimes, and ecosystems. The Okavango Delta was described by Grey and Cooke (1977) as a wetland juxta-posed close to the adjacent semi-arid Makgadikgadi basin and Botswana in general. The Okavango Delta is an alluvial fan with low gradient that is mainly explained by the historic evolution and dynamism of the geomorphological processes (McCarthy and Ellery 1998) which are also responsible for the present wetland hydrology. The Okavango Delta is a wetland system with remarkable interplay of climatic, hydrological, geomorphological and biological processes that define and shape the functioning of the ecosystem. Upstream of the delta, commonly referred to as the panhandle, is a 10–15 km wide valley within which the main Okavango channel meanders for 150 km. At the end of the panhandle, the Okavango River forms a burfication, splitting into three main distributaries (Figure 2.1). During periods of high flows, water from distributaries spills to adjacent floodplains within the delta and in some cases the spilled water joins the same or different channel (Wolski and Murrary-Hodson, 2006). In some instances, the interconnection of channels causes some back flowing, e.g during high flows, the

Boro and Santantadibe Rivers that join the Thamalakane River (Figure 2.1) can cause back flow into the Gomoti RIver.

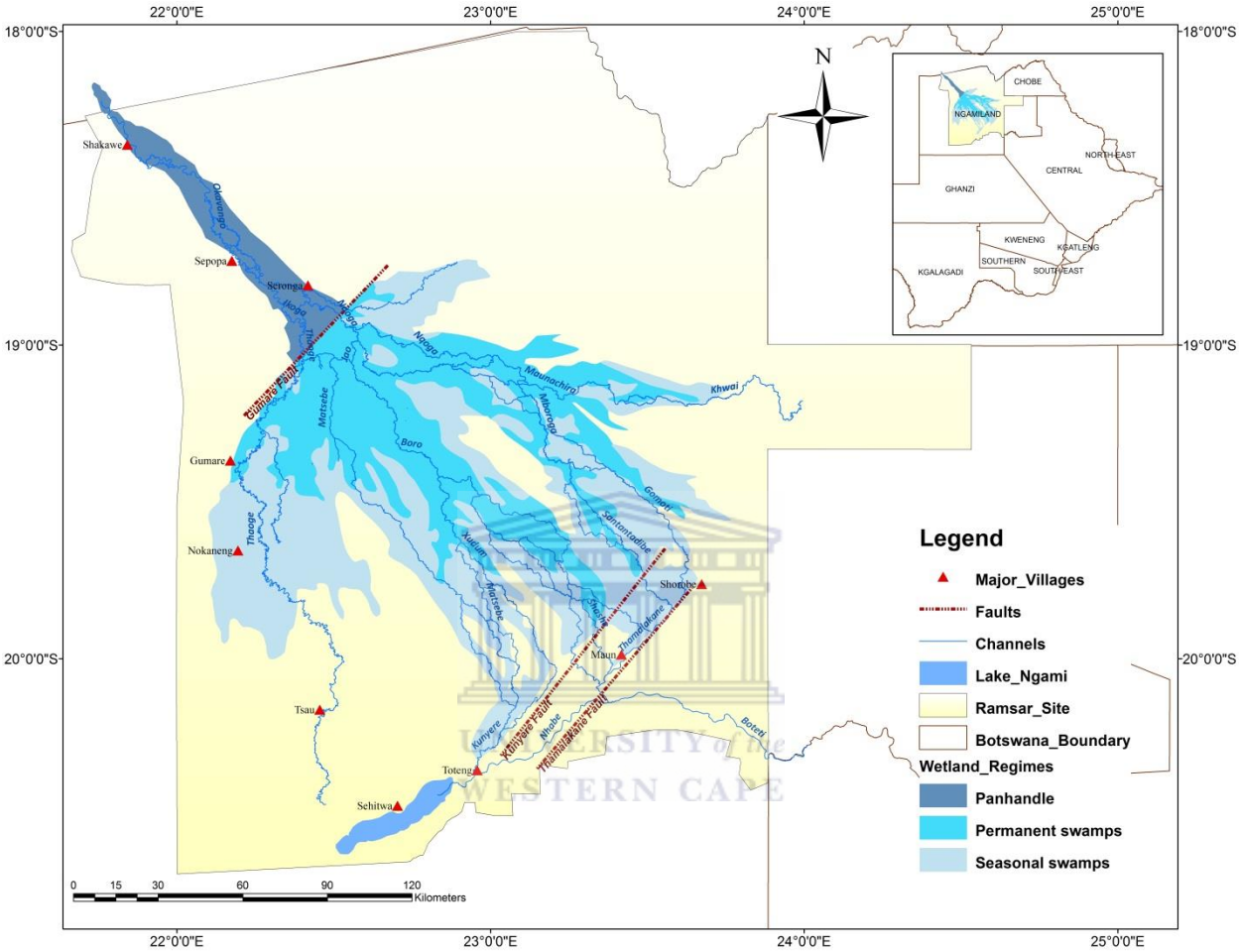


Figure 2. 1: The Okavango Delta Wetland within the Okavango Delta RAMSAR Site (ODRS), Located in Ngamiland District, Northren Part of Botswana

The delta can be classified in terms of flow regime and habitat (Figure 2.2) into the following categories; the **panhandle** which is sustained by Okavango river inflows, **permanent swamps** sustained by wet and dry season flows of the Okavango river, **seasonal swamps** sustained by seasonal flood wave entering the panhandle through the Okavango River and pulsing through the major distributaries of the delta, **occasionally flooded areas** induced by the annual flood wave during extreme wet years and local rainfall (McCarthy *et al*.,1988; Murray-Hudson *et al*.,2006 and Gumbricht *et al*., 2004). The patches of Islands which occur within the delta area and the surrounding riparian drylands are occupied by woodlands and savanna (Gumbricht *et al*., 2004).

Figure 2. 2: The major flow regimes in the Okavango Delta (Source; ODMP, 2006)

The total area for Ngamiland district is about 109, 000km^2 with the Okavango Delta Ramsar Site (ODRS) occupying 55,374km^2 (Fabricius *et al*., 2004, ODMP, 2008) The population distribution is mainly dependent on availability of water and susceptibility to water borne diseases such as malaria (TDA, 2009). According to the 2011 Botswana population census, the total population of Ngamiland district was 158,104 with the annual growth rate of 2.21% to 2.53% between 2001 and 2011, with a population density of 1.1 people/km^2 to 2.7 people/km^2 (CSO, 2011). The populations of major villages in the district as of 2011 are 55,784 for Maun, 7,827 for Gumare and 6,510 for Shakawe with growth rates of 2.45%, 2.58% and 4.02% respectively (CS0, 2011).

The growing population together with economic development calls for sustainable management of the wetland as this has the potential to cause environmental impacts on the Okavango Delta. In 1994 the three riparian states of the Okavango River Basin jointly established the Permanent Okavango River Basin Water Commision (OKACOM) with the goal to promote coordinated environmentally sustainable utilization and management of the water resource of the basin (Pinheiro *et al*., 2003). The commission helps to investigate ways in which water needs of the three countries could be accommodated in a sustainable manner and to collaborate on the management of the basin's water resources in general (OKACOM, 1994). Due to the existence

of OKACOM there is transboundary cooperation as well as integrated river and natural resources management (Jansen and Madzwamase, 2002). As one of the ways of achieving the goal of the commission, the Environmental Protection and Sustainable Management of the Okavango River basin (EPSMO) project was formed and implemented under the framework of OKACOM. The long-term objective of the project is to derive environmental benefits through collaborative management of the naturally integrated land and water resources of the ORB (TDA, 2011). An in-depth assessment of the ORB characteristics and conditions, and transboundary water resources was also conducted through a Transboundary Diagnostic Analysis (TDA) under EPSMO (TDA, 2011).

The Okavango Delta is also recognized as one of the famous inland wetlands and was in 1996 included in the Ramsar list of Wetlands of International Importance. The Ramsar Convention on Wetlands of International Importance promotes international awareness and co-operation in the conservation of threatened wetland ecosystems (Ramsar, 1971). The Ramsar Convention requires each contracting party to:

- Designate at least one wetland to be included in the 'List of Wetlands of International Importance
- Formulate plans that promote the conservation and wise use of wetlands in their territory; and
- Consult with other contracting parties regarding the implementation of the Convention's obligations, especially where a designated wetland and its associated water system extends over the territories of more than one contracting party.

The Okavango Delta is the largest RAMSAR site in the world (McCarthy *et al.*, 1998; Ashton & Neal, 2003). Based on the RAMSAR guidelines, Botswana established the Okavango Delta Management Plan (ODMP) under the framework policy from the wetlands management plan of the Botswana National Wetlands Policy and Strategy (NCSA 2000). The main objective of the ODMP is to provide data and information for management and planning. The ODMP is also expected to provide input into the overall management of the entire basin even in the future through OKACOM (Jansen and Madzwamase, 2002). In 1997 the Botswana government listed the Okavango Delta as a world heritage site (Mbaiwa 2011) and latter inscribed the 1000th site on the World Heritage list on 22 June 2014 (UNESCO, 2014)

2.2 Physical characteristics

2.2.1 Geology and soils

The following geological formation underlies the Okavango delta; the Precrambrian igneous and metarmophic rocks which include; a) Paleoproterozoic granites and amphibolites; b) Mesoproterozoic granites, metarhyolites and metabasalts; c) Neoproterozoic siliciclastic and carbonate sedimentary rocks and d) Karoo Supergroup (Mapila *et al.*, 2005) (Figure 2.3). Milzow *et al.,* (2009) noted that sands overly sedimetary and volcanic carboniferous to Jurassic karoo sequence; Neoproterozoic siliclastic and carbonate sequence and; Mesoproterozoic metavolcanic and metarhyolites; from youngest to oldest. According to Milzow *et al.,* (2009), on the southeastern part of the delta is the Ghanzi-Chobe belt of Kgwebe and Ghanzi rocks. On the Northwestern part of the delta is Damara belt. The two belts were formed during the collision of the Kalahari and Congo cratons of the Neo-Proterozoic Pan African Damara Oregency (Milzow *et al*., 2009). The Karoo Supergroup was deposited during the Permo-Carboniferous glacial episode (Obakeng 2007) and the Karoo dolerite dykes occupies the south-western part of the delta (Mapila *et al*., 2005).

Milzow *et al*., (2009) point out that overlying the bedrock are soil groups collectively known as Kalahari beds. The soils are classified as deltaic and windborne sand and silt of Cenozoic age (Milzow *et al.*, 2009). The soil classification of the Okavango Delta is defined by sediments transported by the river, deposition in the rift basin and also input of aeolian sands (Mapila *et al.*, 2005). Mapila *et al*., (2005) also pointed out that the Kalahari sands in the delta are a result of weathering from proterozoic ganitoids, gabbros and volcanic ortho-metamorphic rocks which are exposed in northren Botswana. Other sudies suggest that the Kalahari sands are a result of an accumulation of local weathering of pre-Kalahari lithology (Thomas and Shaw 1991). According to Hutchins *et al.,* (1976) the Kalahari beds can be up to 300 m in thickness. On the distal parts of the delta are detrius deposits of hard lenses of calcrete and silcrete duricrusts, formed as a result of cementation of sands by silica and carbon rich waters (Milzow *et al*., 2009). The silcrete and calcrete deposits occur 20 m below the surface. They are also found near surface and outcropping on channels.

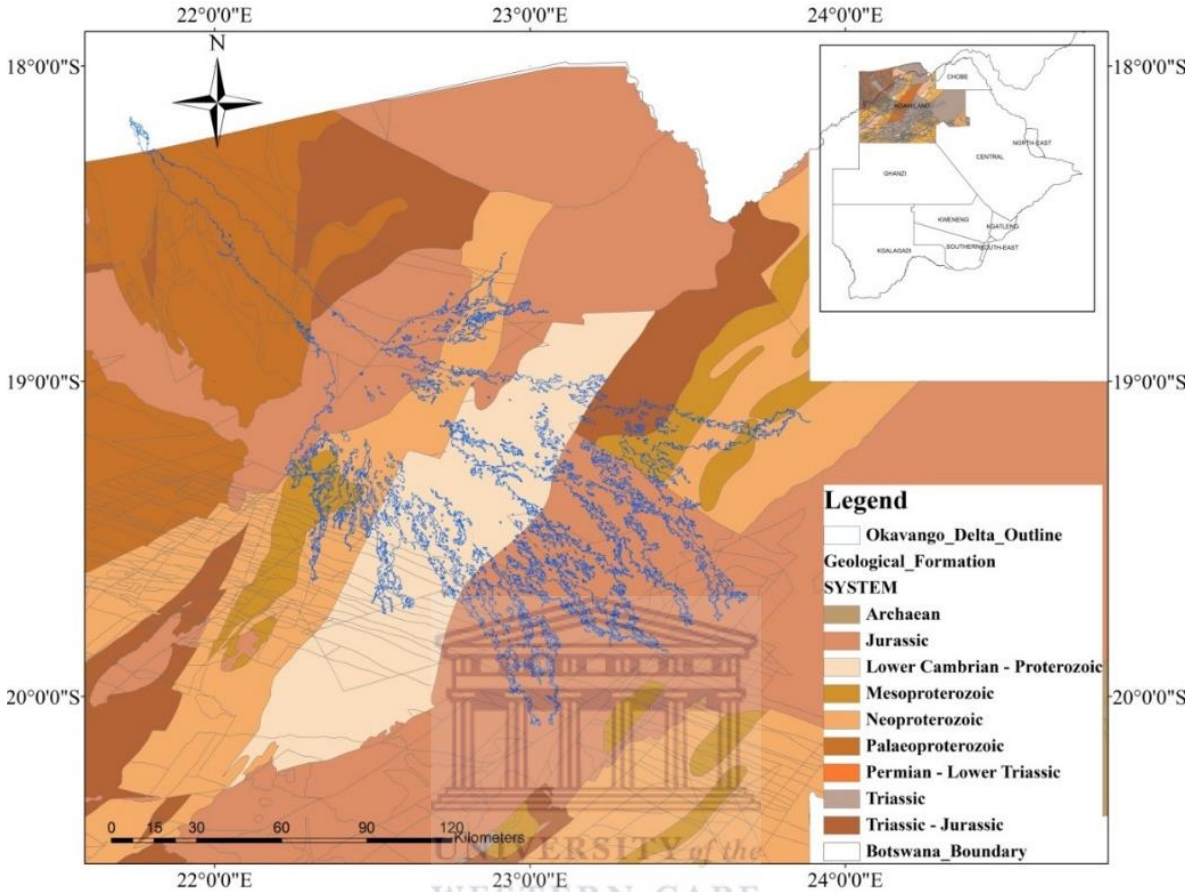


Figure 2. 3: Geology Map of Ngamilang District of Botswana, showing geological systems underlying the Okavango Delta

2.2.2 Geomorphology and topography

The Okavango Delta is a low gradient alluvial fan with a gradient of 1:3400 (McCarthy *et al.*, 1998; Wolski *et al.*, 2005; Gumbricht and McCarthy, 2001). Gumbricht *et al.*, (2001) indicated that the topography of the Okavango Delta tells a lot about the local tectonic movements and the history of sediments. Two major grabens form the Okavango delta, one before the Gumare faults, occupied by what is commonly referred to as the panhandle and the other one bounded by the Kunyere and Thamalakane fault, occupied by the delta (Mapila *et al.*, 2005; McCarthy, 2004). The panhandle is an erosional feature cut as a result of northern uplift of the Gumare fault (Gumbricht *et al.*, 2001). The distribution of water in the fan is a result of neo-tectonic activity and sedimentation (McCarthy *et al.*, 1993). According to McCarthy *et al.*, (1998) sediment load plays an important role in the termination of channels and formation of new channel routes by

blocking and paving new channel routes, causing water redistribution (McCarthy *et al.*, 1993). The sediment load consists of mainly Kalahari sands transported as bedload deposited in the alluvial fan. The sediment load is deposited along meandering river system and result in the formation of alluvial ridges (McCarthy *et al.*, 1998). Leakages from the main channel causes channel bed aggradation and giving rise to secondary distributary channel system (McCarthy *et al.*, 1998).

Gumbricht *et al.*, (2001) suggested that the local hydrology in the Okavango Delta is mainly defined by channel flows confined by vegetation blockages. According to Kurugundla (2003) three types of blockages occur and play a distinct role in influencing partitioning of flows. **Surface blockages** are predominantly formed as a result of pilling up of dried plant material of mostly papyrus culms. The materials float on the channels and get clogged over time at narrow sections. Water passes underneath the clogged material and during high flow the material causes water logging and results in the water changing direction or forming another flow path. **Papyrus shafts** are uprooted due to elephant movement. The high velocity of water during the high flood season uproots papyrus. The papyrus then gets anchored onto the shallow channel bed assisted by the sediments thus blocking the flows. Papyrus shafts acting as ducts obstruct the flows and eventually results in lateral spills. In the distal channels with significantly reduced flows, the papyrus becomes permanently anchored developing into thick shafts. **Flanked papyrus and encroaching hippo grass** in the fringes of the flowing streams have a tendency of flanking the inner bank wall narrowing the streams making navigation difficult. High flows push the floating vegetation towards the banks but the vegetation is moved back to the inner channel during the off flood season, then slowing down the flows as passing smoothly through the vegetation.The shifting of channels results in the decay of wetlands and formation of islands. The shifting of channels also results in shifting of floodplain inundation.

2.2.3 Climate

Rainfall over the Okavango Delta occurs between the months of October to April with an average annual rainfall of 490 mm/yr. The Okavango Delta region is semi-arid, although the rainfall in the area is moderate compared to the rest of the country. The delta has high annual

evapotranspiration (ET) rates of 2172 mm/yr which is four times the annual rainfall (Gumbricht *et al.*, 2004). Maximum temperatures range between 30 ^{o}C and 35 ^{o}C in summer (November to January) and minimum temperatures range between 3 ^{o}C and 12 ^{o}C in winter (May to July.)

2.2.4 Hydrology

Peak inflows reach the lower end of the Okavango Delta (OD) in June/July and recede from August onwards due to evapotranspiration and infiltration and declining river flows. Low lying flood plains on the lower part of the delta (Thaoge, Thamalakane, Gomoti, Santantadibe) and especially in the Boro-Shorobe floodplain, are frequently inundated. Maximum inundation occurs during July to September and minimum inundation is observed in December to February. The delay of the peak flow from upstream in Angola, flowing 600 km down into the delta, and the slow propagation of the flood down a low gradient within the delta, result in inundation within the delta being out of phase with the rainy season (Wolski *et al.*, 2008) (Figure 2.4). The average daily Okavango River inflows at Mohembo is about 300 m^3/s. 2% of the inflows into the Okavango Delta leaves the wetland as surface flows and and very little as groundwater flows (McCarthy 2006).

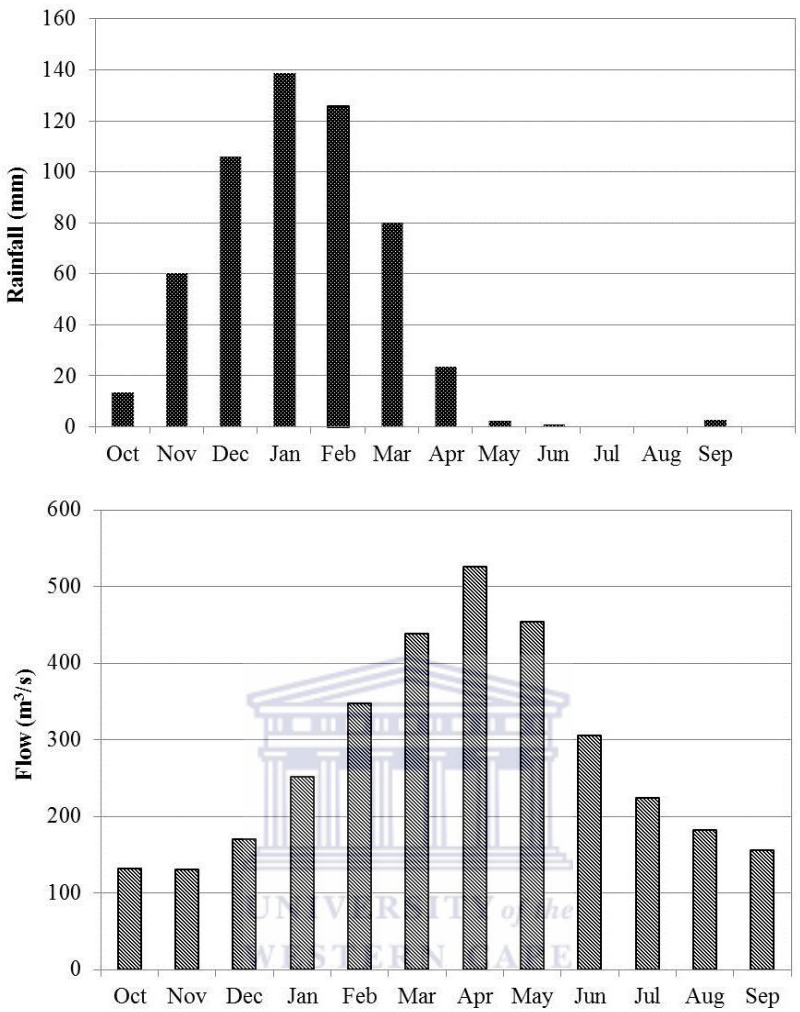


Figure 2. 4: An illustration of flows at Mohembo out of phase with local rainfall at Shakawe upstream of the Okavango Delta

2.2.5 Hydrogeology

Three major aquifer formations exist in the Okavango Delta; the basement rocks, Karoo and Kalahari group sediments. The aquifers in the Kalahari beds are shallow and are important for understanding the hydrogeology of the Okavango Delta (Milzow *et al.*, 2009). Milzow *et al.*, (2009) indicates that the following major faults in the Okavango delta; Kunyere, Thamalakane and Gumare play an importanat role in the lithological formation of the Kalahari beds. McCarthy *et al.*, (2005) suggested that the basement rock beneath the delta is highly fractured as a result of faulting, and therefore groundwater leaves the delta through these pathways. Milzow *et al.*, (2009) considers groundwater flow to be mainly vertical on large scale. Groundwater recharge is

mounded in the center of the delta (McCarthy 2006). The groundwater table is shalow below the Okavango Delta at about 1m- 6m deep and becomes deeper away from the wetland.

2.2.6 Land cover

The Okavango Delta is characterized by patches of vegetation with high temporal and spatial variation depending on wetting and drying of the delta. Vegetation experiences long term successional changes and short term seasonal changes (Ringrose *et al.*, 2005). McCarthy *et al.*, (2005) classified the delta into 12 ecoregions ranging from rivers to dry woodland. On average, 14,000 km^2 of the delta is flooded every decade, but 9,000 km^2 can be classified as the actual wetland containing and surrounded by islands with dry woodland and savannah (Gumbricht *et al.*, 2004). Permanent water bodies are occupied by *papyrus* and *vossia*, with floodplains occupied by different grass classes and; islands and the riparian dryland occupied by *mopane* and acacia (Gumbricht *et al.*, 2004). Murray-Hudson *et al.*, (2011) categorized the Okavango Delta floodplains into the following four categories: a) Dry Floodplain grassland include annual grasses such as *Urochloa mosambicensis*, *Chloris virgate*, *Ipomoea coptica*, and *Pechuel-Loeschea leubnitziae* and are sustained by the annual flood for less than a month and therefore essentially sustained by local rainfall. During years when the floodplains are not inundated, shrub and small tree species get established. b) Seasonally flooded grassland, are flooded between one and five months and include grass species such as, *Nicolasia costata*, *Nidorella resedifolia*, *Eragrostis Lappula*, *Setaria sphacelata* and some sledges. c) Seasonally flooded sledgeland, is flooded for five to eight months, and comprises sledges such as *Eleocharis dulcis* and *Cyperus articulatus*, aquatic grasses such as *Leersia hexandra* and *Oryza longistaminata* and water-tolerant herbs such as *Ludwigia stolonifera* and *Persicaria limbata*. d) Seasonal Aquatic communities, mainly occupied by sledges, floating leaves and submerged herbs (Murray-Hudson *et al.*, 2011). The growth of riparian trees is partially sustained by groundwater uptake with those in dry floodplains depending on local rainfall rather than the flood event for renewal of leaf growth (Ringrose, 2003). Ringrose (2003) classified the riaparian woodland into; a) the dense tall woodlands of *C. imberbe* and *A. erioloba* trees and ; b) less dense wooded woodland comprised of *T. prunioides*, *A. erioloba* trees mixed with shrubland comprised of *A. fleckii*, *C. megalobotrys* and *L. capassa*.

2.2.7 Land use

Land use patterns vary due to the ever changing natural conditions and livelihood strategies. The land use distribution pattern is mainly shaped by water availability, presence of waterborne diseases, soil quality and range land availability, and ethnicity (Bensen and Meyer 2002). Government policies and developmental plans also play a role in land use spatial coverage. Subsistence farming, arable dryland, floodplain farming (*molapo*) and livestock farming are important land use activities in Okavango Delta area. Dryland farming is practised along the panhandle and distal drylands, whilst *molapo* is along the western and south-eastern fringes of the delta. Livestock farming distribution is determined by access to grazing land and natural surface water availability. This results in livestock being concentrated along the permanent open water sources along the fringes of the delta (Benson and Meyer, 2002). Tourism development is another major land use activity in the Okavango Delta. The establishment of the Moremi Game Reserve (Figure 2.5) as a protected area is a major tourist attraction in the delta. According to Mbaiwa (2005), 5% of Botswana's GDP is drawn from tourism with most of it derived from the Okavango delta. Although tourism has a significant contribution to the country's economy, it comes with environmental impacts and creates some socio-economic conflicts (Mbaiwa 2003).

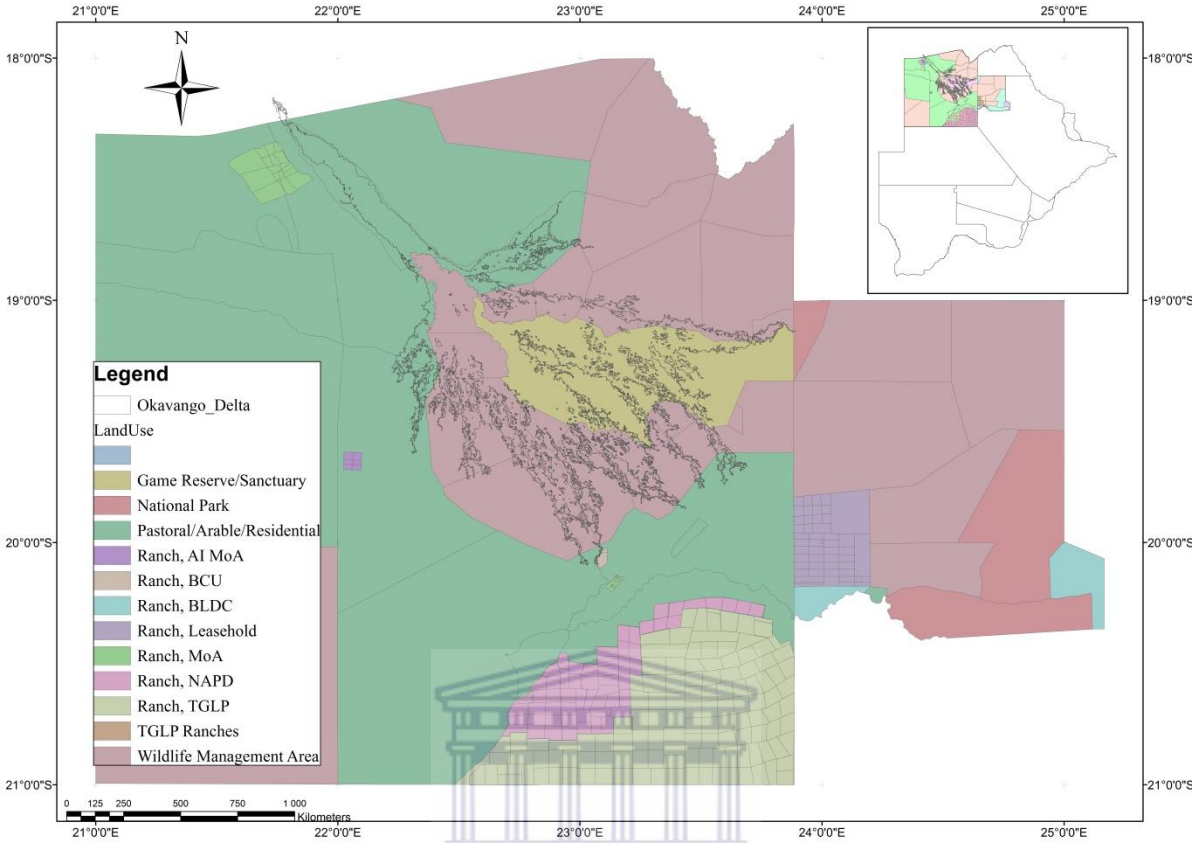


Figure 2. 5: Landuse Map of Ngamiland District, Botswana showing the Okavango Delta occupied by Game reserve, Wildlife Management Areas and Ranches

2.3 Wetland ecosystem services

Ecosystem services provided by wetlands include biodiversity support, flood abatement, water quality improvement, human livelihood support, mitigation of climate change, and groundwater recharge (Zedler, 2003; Wang *et al.*, 2006) depending on the characteristics of the wetland. Wetlands ecosystems provide both direct and indirect services and therefore it is important that they are conserved. Direct services provided by wetlands include, water supply, both animal and plant products whilst indirect services are obtained from the ecosystem functions including, flood mitigation, and groundwater recharge. Human uses of wetland ecosystems mostly cause alteration to the wetlands (Wang *et al.*, 2006). It is therefore important to understand the wetland ecosystem response to impacts of human livelihood activities as they play a critical role in shaping the ecosystem functioning. In developing countries, most rural communities depend

directly on ecosystem services. Although difficult to attach economic value to ecosystem services, it is important to include ecosystem services decisions when making plans (Korsgard and Schou 2010).

The Okavango Delta is a complex and dynamic ecosystem driven by different factors. Sediment transport and deposition influences channels and changes the floodplain inundation. According to Ellery and McCarthy (1994), evapotranspiration causes accumulation of dissolved silica, calcium carbonates and magnesium carbonates below the surface. Deforestation may result in salinization of surface water (Ellery and McCarthy 1994). All the above mentioned factors influence the temporal and spatial occurrences and diversity of habitats. Bauer *et al.,* (2006) points out that wetlands are valuable and diverse ecosystems and therefore they require large amounts of water for their natural processes and functioning, causing conflicts between human water use and demand, and the wetland natural water use. Bauer *et al.,* (2006) further points out that the ecosystem value of wetlands and their value to human use depend on the flooded area, it is therefore important to understand flooding dynamics. Okavango delta habitats are occupied by a variety of plants and animal species. According to Merron and Burton (1995), the panhandle, permanent streams and swamps have a higher species richness compared to seasonal floodplains and drylands. The spatial and temporal variations in flooding patterns cause changes in pattern of ecological succession of inhabitat plants and dependent animals (Ramberg *et al.,* 2006). Adapted plants species benefit from accumulated and mobilized nutrients by flood waters (Ramberg *et al.,* 2006). Communities are therefore encouraged to practice natural resource management for wildlife conservation and tourism development.

3: RAINFALL SPATIAL AND TEMPORAL CHARACTERISTICS

3.1 Introduction

The specific objective addressed in this chapter is to assess the effects of spatial and temporal variations of local rainfall on inundation of floodplains within the Okavango Delta. The main focus of this chapter is to assess how rainfall over the Okavango Delta varies with time and to evaluate the implication of the variation on floodplain inundation. An assessment of the variability of rainfall over the entire Okavango Delta is carried out. Time series of monthly rainfall and annual rainfall, for 19 stations (Figure 3.1) spread over the entire Okavango Delta, are used for analysis in this chapter. Analysis of rainfall spatial patterns is carried out to depict the spatial variation of rainfall and therefore a picture of possible spatial variation of floodplain inundation due to local rainfall can be obtained. Rainfall trend analysis is conducted in order to assess the possible association of floodplain inundation with long term increase or decrease in rainfall. To assess the possibility of shifts from wetness to dryness of floodplains and the association with rainfall shifts, change detection is conducted. Regional Frequency Analysis (RFA) is conducted for rainfall regionalization and to investigate the probability of occurrence of different rainfall elements associated with varying floodplain inundation conditions.

Precipitation is the major factor controlling the hydrological cycle of a region and varies considerably over space and time (Dunne and Leopold, 1995; Baigorria *et al.*, 2007). An understanding in rainfall of an area is the most important component of hydrology that helps to conceptualize the behavior of nature and climate change (Maragatham, 2012). Rainfall is key to water resources, agricultural and ecosystem management (Maragatham, 2012) and; seasonal and annual rainfall totals are used for decision making on water resources and agricultural management (Dunne and Leopold, 1995). Although agricultural systems have been changing in response to spatial and temporal variations of rainfall, farmers still face risks related to rainfall variations due to shortage of climate information to capture the magnitude and direction of variation (Baigorria *et al.*, 2007). Many studies on understanding rainfall variation specifically in southren Africa have been carried out, (Kampata *et al.*, 2008; Mazvimavi, 2010; Ngongondo *et*

al., 2011). Different results and conclusions from these studies suggest that it is essential to carry out studies at different spatial and temporal scales using different methods to complement each other. According to Barua *et al.*, (2012), recent studies have shown the importance of analyzing hydroclimatic variations at local scales than at global scale, as trends vary from one scale to another.

The spatial and temporal distribution of rainfall has an effect on the occurrence of floods or droughts (Baigorria *et al.*, 2007). It is important to quantify the amount of rainfall over an area and the accuracy of rainfall estimates over an area depends on the distribution and density of rain gauges (Mishra, 2013). Low gauge density is still a problem in many regions of the world including southren Africa and this, results in uncertainty in the estimation of areal rainfall of a region. Bacchi *et al.*, (1995) suggested that a combined use of both satellite and point measurements of rainfall leads to a more accurate accounting of rainfall spatial distribution. Satellite derived rainfall estimates are useful for overcoming the problems resulting from low gauge density especially in the tropics where rainfall is convective with high temporal and spatial variations (Collischonn *et al.*, 2008). There has been some success in the use of satellite derived rainfall in simulating streamflows, however rain-gauge measurements are still needed for calibration and ground truthing. The time interval is another important factor in the determination of spatial distribution of rainfall. Seasonal and annual rainfall totals are reliable for decision making on water resources management or agricultural decisions such as choice of crops (Dunne and Leopold, 1995). According to Bacchi *et al.*, (1995) estimating areal rainfall from point measurements over a short time scale such as few minutes or hours can result in significant errors and therefore relationships between point measurements are best investigated at monthly and annual time intervals.

3.2 Rainfall circulation pattern

The atmospheric circulation pattern over southern Africa determines the moisture sources in Botswana and hence the rainfall variation and origin over the Okavango Delta. Generally, the interaction of three air masses, which are the cold dry air from the southern Atlantic Ocean, warm moist air from the southern Indian Ocean, and the warm moist air from the equatorial Atlantic Ocean plays an important role in the climate of the Okavango River Basin (Wolski *et*

al., 2014). The El Nino- Southern Oscillation (ENSO) remains the most dominant perturbation responsible for rainfall pattern over southern Africa (Nicholson and Entekhabi, 1986). According to Nicholson and Entekhabi (1986), Goddard and Graham (1999) and Nicholson *et al.*, (2001) the interannual variability of summer rainfalls over southern African is strongly influenced by the ENSO phenomenon, Sea Surface Temperature (SST) and Southern Oscillation Index (SOI) changes in the tropical Pacific, southern Atlantic and SST variations of the Indian Ocean. Nicholson *et al.*, (2001) point out that studies have indicated that droughts in Botswana occur as a result of Pacific ENSO episodes although Kenabatho *et al.*, (2012) found out that there is strong correlation between Botswana rainfall pattern and atmospheric temperature than ENSO indices. The two opposite phases of ENSO, La Nina (the cold phase) and El Nino (the warm phase) are differently correlated to rainfall pattern over eastern and southern Africa, with east African rainfall pattern positively correlated to El Nino and negatively correlated to southern Africa rainfall pattern. The La Nina event of 1999-2000 caused devastating floods over southern Africa due to the Tropical Cyclone Eline weather system associated with the SST anomaly over the Indian Ocean (Reason and Keibel, 2004). Hart (2012), concluded that spatial and temporal rainfall variations over southern Africa generally are a result of variation in moisture from the tropical and subtropical Indian Ocean, and the southeast Atlantic Ocean.

The seasonal variation of rainfall in the Okavango River Basin depends on the movement of the Inter-Tropical Convergence Zone (ITCZ). Seasonal shifts of two major convergence zones; the Inter-Tropical Convergence Zone (ITCZ) and the Congo Air Boundary (CAB), influence the variability of rainfall in eastern and southern Africa (Nicholson, 2000). The ITCZ and the CAB separates the southeast and northeast monsoon that influence rainfall over different parts of Africa (Nicholson, 2001). According to Ratna *et al.*, (2013), the southern most position of the Inter-Tropical Convergence Zone (ITCZ) has a major influence on seasonal rainfalls over the northern part of the region. Summer rainfall in eastern and southern Africa is dominated by the ITCZ when this migrates southwards first through east Africa during October and November and down over southern Africa in December to February (Goddard and Graham 1999). During the austral summer, cloud bands associated with the Tropical Temperate Troughs (TTT) from northwest to southeast surrounded by south Indian convergence zone, develop at a synoptic scale bringing large amounts of rainfall over southern Africa (Washington and Todd; 1999; Todd and

Washington 2000; Hart, 2012; Ratna *et al.*, 2013). The cloud bands commonly referred to as TTT are formed as a result of mid latitude baroclinic wave in austral summer and moisture advection and convergence supplied by the flux form Indian and Atlantic Ocean (Macron *et al.*, 2014). Hart *et al.*, (2010) also indicates the moisture flux from tropical southeastern Atlantic support formation of TTT over the Kalahari during summer. The TTT are the main daily rainfall producing weather system over southern Africa during the summer season (Ratna *et al.*, 2013). The spatial and temporal variation of rainfall over southern Africa is highly influenced by the TTT. Ratna *et al.*, (2013) and Hart (2012), concluded that the frequency, position and intensity of TTT influences intra-seasonal and inter-annual rainfall variation over the region.

3.3 Materials and methods

3.3.1 Rainfall datasets

Rainfall data for 19 stations (Figure 3.1) within the Okavango Delta are used in this analysis, with two stations Maun and Shakawe having a long record from 1921 and 1931 respectively to 2012.The data were collected from the Department of Meteorological Services (DMS) and Department of Water Affairs (DWA) of Botswana. Flooding in the delta creates problems of accessing and installing rainfall stations or to collect data during high flow season. Therefore some monitoring stations have short record lengths and missing data.

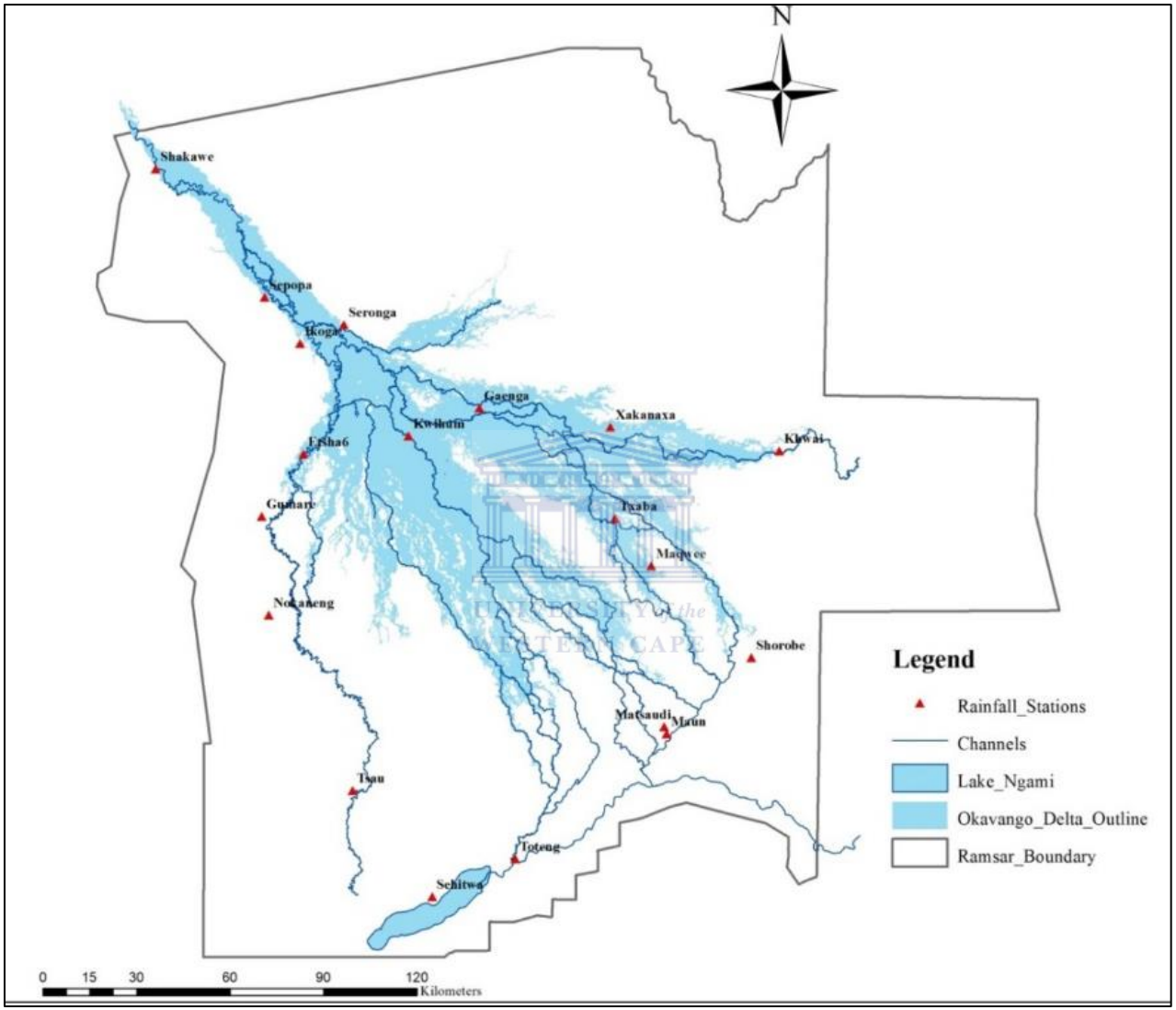


Figure 3.1: Rainfall Stations spread throughout the Okavango Delta within the ODRS; used for analysis in this chapter.

3.3.2 Data quality control

Data quality analysis is important before using such data. This reveals outliers which can cause problems in identifying characteristic features of rainfall time series. Outliers result from a lot of reasons including several days' accumulation of missing observations. It is therefore important to be cautions to determine whether outliers are truly erroneous as this may result in biased analysis. Neighbouring stations may be used for comparison. Although graphical assesment may be used to reveal outliers, statistical tests are important (WMO 2009). In this study, the outliers are screened using the Tukey Fence (Zhou *et al.*, 2006). This statistical technique uses Inter-quartile range (IQR) to set a Tukey fence. The data are sorted into ascending sequence to obtain Q1 and Q3, the lower and upper quartile points, and the difference between Q3 and Q1, (Q3−Q1) is named IQR. The Tukey fence is the range from Q1−1.5 * IQR to Q3+ 1.5* IQR. The values outside the fence are considered to be outliers.

3.3.3 Assessment of spatial pattern of rainfall

Rainfall stations within a given area are expected to have similar rainfall characteristics. It is important to determine spatial correlation to understand the relationship between rainfall stations in a given area. Further rainfall interpolation can be based on the relationship established from spatial correlation. According to Sen *et al.*, (2001), estimation of spatial distribution from point measurements in a given area depends on the relationship between the point measurements. To examine the spatial structure of rainfall in the Okavango Delta the following methods are used.

3.3.3.1 Pearson correlation

The Pearson correlation coefficient is computed between stations and the following assumptions are considered;

- Two data sets for stations closer to each other should show stronger correlation
- The correlation is homogeneous and isotropic and therefore a function of distance only

The Pearson correlation coefficient is given by;

$$\boldsymbol{r} = \frac{\sum_{i=1}^{n}\left((\boldsymbol{X}_i - \bar{\boldsymbol{X}})(\boldsymbol{Y}_i - \bar{\boldsymbol{Y}})\right)}{\sqrt{\sum_{i=1}^{n}(\boldsymbol{X}_i - \bar{\boldsymbol{X}})^2 \sum_{i=1}^{n}(\boldsymbol{Y}_i - \bar{\boldsymbol{Y}})^2}} \tag{3.1}$$

Where $\boldsymbol{r}$ is the correlation coefficient between two stations with rainfall observations $\boldsymbol{X_i}$ and $\boldsymbol{Y_i}$, and mean rainfall $\bar{X}$ and $\bar{Y}$. A scatter plot of *r* against *d*, the euclidean distance between stations (Habib *et al.*, 2001) will enable an assessment of how distance between stations influences the relationship between their rainfalls.

3.3.3.2 Kriging

Ordinary kriging is used for aerial interpolation of monthly and annual rainfall. Kriging is one of the commonly used geostatistical approaches and has been widely used as a reliable estimation method. Kriging quantifies spatial autocorrelation and spatial configuration amongst measured points around the prediction location. Kriging assumes that data comes from a stationary stochastic process (Li and Heap 2008, Nas 2009, Ngongondo *et al.*, 2011).

3.3.4 Change detection

Homogeneous rainfall records are required for water resources decision making. A homogeneous data series of a rainfall station means the measurements are recorded or taken at a time using the same instruments under the same environmental conditions (Kang and Yusof, 2012). In some cases data of a station are not comparable for different periods due to possible changes in observational procedure, exposure or location of the rain gauge. Although rainfall measuring institutions aim to archive information about the sites and instruments used, sometimes these are not documented. The extent to which the rain gauge site influences the measured amount of rainfall remains uncertain. Graphical methods such as double mass curve can be used to test homogeneity of station data series. It is important to use statistical approaches to test significant departure from homogeneity (Buishand 1982). Therefore different statistical approaches are used to test homogeneity of records (Buishand 1982). Three statistical methods are used to test for homogeneity in the annual rainfall series; The Cummulative Deviation method (Buishand Range Test) by Buishand (1982) , the Standard Normal Homogeinety Test (SNHT) by Alexandersson (1986), and the Pettit Test (Pettit 1979). The SHNT is powerfull at detecting change at the

beginning and end of series, whilst Buishand Range test and Pettit test are powerful in identifying break point in the middle of the series (Kang and Yusof, 2012).

It is assumed that the annual values Y_i of the variable being analysed are independent, identically distributed and form a homogeneous series under the null hypothesis. Under the alternative hypothesis the series is considered to have a break in the mean and inhomogeneous. Given Y_i, the testing variable, where i is the year from 1 to n, $\bar{Y}$ is the mean and s is the standard deviation (Kang and Yusof, 2012).

3.3.4.1 Buishand Range Test (BRT)

This test uses the sum S^*_j, of the deviations of observations Y_i from their mean $\bar{Y}$. The partial sum is given by;

$$S_j^* = \sum_{i=1}^{j} (Y_i - \bar{Y}), \qquad j = 1,2,\ldots n \tag{3.2}$$

The value of S_j^* fluctuates around zero if the series is homogeneous. When S_j^* reaches a maximum (negative shift) or minimum (positive shift), then the year j has a break. The significance of the shift can be tested with the 'rescaled adjusted range' R, given by;

$$R = \frac{\left(\max\limits_{0 \le j \le n} S_j^* - \min\limits_{0 \le j \le n} S_j^*\right)}{s} \tag{3.3}$$

The values of $R/\sqrt{n}$ are compared to critical values given by Buishand (1982). If the value of $R/\sqrt{n}$ is greater than the critical value then the series is considered non-homogenious

3.3.4.2 Standard Normal Homogeneity Test (SHNT)

A *T(j)* statistic is used to compare the mean of the the first *j* years with the last of (*n-j*). The test statistic is written as (Kang and Yusof, 2012; Alexandersson, 1986);

$$T = j\overline{z}_1 + (n-j)\overline{z}_2, \qquad 1 \le j \le n$$

(3.4)

Where $\overline{z}_1$ and $\overline{z}_2$ are averages of the z_i values before and after the shift given by

$$\overline{z_1} = \frac{1}{j}\sum_{i=1}^{n}\frac{(Y_i - \bar{Y})}{s} \;\; and \;\; \overline{z_2} = \frac{1}{n-j}\sum_{i=j+1}^{n}\frac{(Y_i - \bar{Y})}{s}$$

(3.5)

To consider the series non-homogenious, the test statistic, ***T***, should be greater than the critical value at a certain critical level depending on the sample size and the year *j* is a change point if the value of *T* is maximum.

$$\boldsymbol{T_0 = \max_{1 \le j \le n} |T_j|}$$

(3.6)

3.3.4.3 Pettit Test (PT)

Pettit test is a non-parametric test that requires no assumption about the distribution of the data. This test is based on the rank, r_i of the Y_i.The ranks $r_1, \ldots, r_n$ of the $Y_1, \ldots, Y_n$ are used to calculate the statistics; U_j

$$U_j = 2\sum_{i=1}^{j} r_i - j(n+1) \qquad j = 1, \ldots n$$

(3.7)

If a break occurs in year *k*, then the statistic is maximal or minimal near the year *k*;

$$U_k = \max_{1 \le j \le n} |U_j|$$

(3.8)

The value is compared with the critical value given by Pettit (1979) for the selected significant level.

3.3.5 Trend analysis

3.3.5.1 Mann-Kendall test and Sen slope estimates

The Mann-Kendall (MK) test has been widely applied in various trend detection studies including some in southern Africa; e.g Kampata *et al.*, (2008) on the headstreams of Zambezi river basin in Zambia, Mazvimavi, (2010) on annual rainfall in Zimbabwe, and Ngongondo *et al.*, (2011) on Malawi rainfall. Although MK is a non-parametric method, it is considered more powerful than many parametric methods as it is insensitive to missing data and can tolerate outliers in the data (Ngongondo *et al.*, 2011; Barua *et al.*, 2012). Mann-Kendal test computational procedure considers n values of a random variable X and X_i and X_j as subsets of the variable at time i and j respectively where $i= 1, 2, 3, \ldots, n$ and $j= i+1, i+2, i+3, \ldots, n$ and $j>i$. Then the Mann-Kendall statistic (S) is given by;

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(X_j - X_i) \tag{3.9}$$

$$\text{Where } sgn(X_j - X_i) = \begin{cases} 1 \; if \; X_j - X_i > 0 \\ 0 \; if \; X_j - X_i = 0 \\ -1 \; if \; X_j - X_i < 0 \end{cases}$$

A positive value of S is an indicator of an increasing trend, and negative value indicates a decreasing trend. However, it is necessary to compute the probability associated with S and the sample size, n, to statistically quantify the significance of the trend.

The variance of S is computed as;

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{j=1}^{g} t_j\left(t_j - 1\right)\left(2t_j + 5\right)\right] \tag{3.10}$$

Where n is the number of data points, g is the number of tied groups in the data set (a tied group is a set of sample data having the same value) and t_j is the number of data points in the *jth* tied group, then the normalised test statistic Z is computed as follows;

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

(3.11)

The null hypothesis H_0 that there is no trend in the data, is either accepted or rejected depending on whether the computed Z statistic is less than or more than the critical value of Z-statistics of the normal distribution. This critical value has a probability of exceedance at a certain significance level, e.g at 5% significance level the critical value of Z is 1.96.

A simple non-parametric procedure developed by Sen (1968) called Sen's slope estimator can be used to identify the existence of a linear trend in a time series. The true slope; which is the change per unit time between two rainfall records can first be estimated as;

$$Q_i = \frac{X_j - X_k}{j-k} \qquad for\ \ i = 1,. \ . \ ., N$$

(3.12)

Where X_j and X_k are rainfall data values at times j and k (*for all combinations* $j>k$) respectively. Q_i is the slope between two data points. X_j and X_k with N numbers of calculated Q_i . If the time series length is n years of data, then the total number of slopes is $N= n(n-1)/2$ Q_i values are arranged in ascending order. The Sen's slope estimator is the median of the N values of Q_i . Sen's estimator is given by

$$Q = \begin{cases} Q_{[(N+1)/2]} & for\ \ N\ odd \\ \frac{1}{2}\left(Q_{[N/2]} + Q_{[(N+2)/2]}\right) & for\ N\ even \end{cases}$$

(3.13)

and Q is the true slope of a linear trend.

3.3.5.2 Quantile regression

Different trend test methods estimate rate of change in the mean of the response variable as a function of time. Quantile regression gives an opportunity to identify changes over time at any part of the distribution of the response variable i.e at any percentile value (Cade and Noon 2003). According to Chamaille-Jammes *et al.*, (2007), quantile regression has the ability to detect both negative and positive trend in extremes of the response variable, which can be non-significant from the mean effect.

The first order quantile regression model relating $Y(\theta|x)$ to X has the following form;

$$Y(\theta|x) = \beta(\theta)_0 + \beta(\theta)_1 X + \xi$$

(3.14)

Where Y is a random variable in this case being the annual rainfall time series. The θth is the quantile or percentile of Y where $X=x$. $\beta(\theta)_0$ is the intercept, $\beta(\theta)_1$ is the slope coeffiecient which is different or changes according the θth percentile or quantile, ξ is the error. The negative or positive value of $\beta(\theta)_1$, significantly different from zero, is an indication of presence of increasing or decreasing trend at the θth percentile or quantile. The θth regression quantile is estimated by minimizing the following function (Koenker and Basset 1978);

$$minimize\ \frac{1}{n}\left\{\sum_{i:y_i \geq x_i\beta} \theta|y_i - x_i\beta| + \sum_{i:y_i < x_i\beta} (1-\theta)|y_i - x_i\beta|\right\}$$

(3.15)

Where n = sample size, i=1,2,...,n, y_i = value of a random variable Y and x_i = value of a random variable X. The *quantreg* package of R available for download from http://ww.r-project.org/ developed by Koenker (2006) is used to conduct quantile regression analysis. The parameters of the quantile regression being the intercept and the slope coefficient are estimated. The t-statistic, p-value, standard errors and confidence interval are also estimated. The θth quantile of annual rainfall has an increasing or decreasing trend if the slope coefficient, $\beta(\theta)_1$ has a positive or negative value that is significantly different from zero at the 5% significance level. The 10th, 20th, and 30th percentiles are regarded to be indicators of low rainfall and the 70th, 80th and 90th percentiles are regarded to be indicators of high rainfall.

3.3.6 Detection of periodicity

Spectral analysis is used to investigate possible existence of a cyclic behaviour in the rainfall series. The standardized periodogram is estimated using Equation (3.16) (Jekins and Priestley, 1957; Fuller, 1996);

$$I_n(\omega_k) = \frac{2}{n}\left[\left(\sum_{t=1}^{n} X_t cos\omega_k t\right)^2 + \left(\sum_{t=1}^{n} X_t sin\omega_k t\right)^2\right], k = 0, 1, 2, \dots m \tag{3.16}$$

Where, X_t is equally spaced time series data, n is the number of observations in the time series and ω_k is the fourier frequency given by;

$$\omega_k = \frac{2\pi k}{n}., k = 0,1,2, \dots m \tag{3.17}$$

and m is the number of frequencies in the fourier decomposistion. The periodogram is an estimate of spectrum and the weighted moving averages of periodogram ordinates are called spectral density estimates. The Fishers Kappa and Bartlett's Kolmogorov-Smirnov statistics and the corresponding p-values are computed to test the assumption of existence of a white noise. The Fisher's Kappa test detects the presence of a cyclic behavior in a time series, i.e Fishers Kappa test whether the largest I_n value can be considered different from the mean of I_n values.

The Bartlett's Kolomogorov-Smirnov detect deviations from white noise for the range of frequencies; the sum of periodogram values from ω_1 to ω_k is divided by the sum of all periodgram values for each frequency $\omega_{k.}$. The null hypothesis of white noise is rejected for a *p*-value < α=0.05, for the computed test statistics greater that the critical values.

3.3.7 Regional frequency analysis

Frequency analysis is useful in the prediction of extreme rainfall events of selected return periods (Kusre *et al.,* (2012). Prediction of rainfall leads to informed crop planning, better assessment of crop failure due to deficit or excess rainfall and therefore resulting in better economic returns. Singh *et al.,* (2012). Regional Frequency Analysis (RFA) is considered a better approach compared to at-site analysis, for estimating frequency of rare events as it uses data from several sites to develop regional parameters (Neykov *et al.,* 2007). Regional Frequency Analysis is therefore helpful in identifying homogeneous regions to deal with the gap created by data scarcity, and therefore able to predict future events. It involves identifying and fitting data to regional probability distribution in order to assign sites to regions. The method of L-moments is also considered the best in testing hypothesis about distributions. According to Ngongondo *et al.*, (2011) the method of L-moments is considered robust, insensitive to outliers, with no sample size related limits, reliable parameter estimations and less biased than the conventional method of moments (MM) and maximum likelihood (ML) estimates. Other studies which have been conducted following the same procedure include, Parida and Moalafhi (2008) for analysis of rainfall in Botswana, Modarres (2009) regionalization of dry spells in Isfahan Privince of Iran, Nunez *et al.,* (2011), Ngongondo *et al.,*(2011) for analysis of rainfall extremes in southern Malawi and Shahzadi *et al.,* (2013) for analysis of annual maximum rainfall in Moonson region of Pakistan. RFA has the following steps;

- Data screening by L-moments and Discordancy measure
- Formation of homogeneous regions
- Selection of regional distribution
- Estimation of regional quantiles

The steps are followed as described by Hoskings and Wallis (1997). RFA is then conducted as follows;

3.3.7.1 Estimation of L-moments

According to Hosking and Wallis (1997), an alternative way of describing the shapes of probability distribution is by use of L-moments. Therefore, L-moments of each rainfall station is computed to identify homogeneity. L-moments are a linear combination of Probability Weighted Moments (PWM) and for any distribution, the *r*th L-moment λr is related to the *r*th PWM through (Hosking, 1990);

$$\lambda_{r+1} = \sum_{k=0}^{r} \beta_k (-1)^{r-k} \binom{r}{k} \binom{r+k}{k} \tag{3.18}$$

If, X_1, X_2…….X_n are data values at a given station with sample size *n*, ranked in ascending order the estimated order statistics; β_0, β_1, β_2 and β_3 are given as (Hosking, 1990);

$$\beta_0 = \frac{1}{n} \sum_{i=1}^{n} X_i \tag{3.19}$$

$$\beta_1 = \frac{1}{n} \sum_{i=1}^{n} \frac{(i-1)}{(n-1)} X_i \tag{3.20}$$

$$\beta_2 = \frac{1}{n} \sum_{i=1}^{n} \frac{(i-1)(i-2)}{(n-1)(n-2)} X_i \tag{3.21}$$

$$\beta_3 = \frac{1}{n} \sum_{i=1}^{n} \frac{(i-1)(i-2)(i-3)}{(n-1)(n-2)(n-3)} X_i \tag{3.22}$$

Where *n* is the sample size, X_i is the data value at the *i*th rank. L-moments are linear combinations of order statistics and the first four L-moments are given by;

$$\lambda_1 = \beta_0 \tag{3.23}$$

$$\lambda_2 = 2\beta_1 - \beta_0 \tag{3.24}$$

$$\lambda_3 = 6\beta_2 - 6\beta_1 + \beta_0 \tag{3.25}$$

$$\lambda_4 = 20\beta_3 - 30\beta 2 + 12\beta_1 - \beta_0 \tag{3.26}$$

The dimensionless L-moments called, L-moments Ratios are given by;

L-Coefficient of Variation (L-CV), $\tau_2 = {}^{\lambda_2}/_{\lambda_1}$

(3.27)

L-Coefficient of Skewness (L-Skew), $\tau_3 = {}^{\lambda_3}/_{\lambda_2}$

(3.28)

L-Coefficient of Kurtosis (L-Kurt), $\tau_4 = {}^{\lambda_4}/_{\lambda_2}$

(3.29)

3.3.7.2 Data screening

Data screening procedure is done to check if data is appropriate to conduct RFA (Hosking and Wallis,1997; Kumar *et al.*, 2003). A group of sites belonging to a proposed homogenious sub-region appear to be close to each other in a cloud of L-Skew and L-Kurt points in an L-moments ratio diagram. If a single site appears not to belong to the cloud, a discordancy measure (D_i) is used to decide whether to remove it from the region. The discordancy measure identifies those sites whose L-moments ratio is significantly different relative to the average L-Moment ratio of a collection of sites in a homogenious region. A site with D_i greater that 3, is considered discordant from the proposed grouping of sites (L-RAP, 2011). The *D*-Statistic is defined in terms of L-moments, therefore the discordancy measure of a given site *i* is defined as follows;

$$D_i = \frac{1}{3}(u_i - \bar{u})S^{-1}(u_i - \bar{u}) \tag{3.30}$$

Where; u_i is the vector containing L-Moment ratios of site *i;*

$$u_i = [\tau_i, \tau_{3i}, \tau_{4i}]^T \tag{3.31}$$

$\bar{u}$ is the mean of vectors;

$$\bar{u} = \frac{1}{N}\sum_{i=1}^{N} u_i \tag{3.32}$$

S is the covariance matrix of u_i;

$$S = \frac{1}{(N-1)}\sum_{i=1}^{N}(u_i - \bar{u})(u_i - \bar{u})^T \tag{3.33}$$

Depending on the size of the region, D_i indicates the how far is u_i from the centre of the region.

3.3.7.3 Heterogeinity

To confirm that stations belong to identified homogeneous sub-region, a test statistics H termed heterogeneity measure suggested by Hosking and Wallis, (1993) is used (L-RAP, 2011). A heterogeneity measure (*H*) for L-moments ratios H1 (L-CV), H2 (L-SKEW) and H3 (L-KURT) is used to test the homogeneity of stations based on Monte Carlo simulation exercise. Heterogeneity of a region is based on variability of L-moments ratios from one site to the other compared with variation expected in a homogeneous region. 500 computer simulations are conducted fitting a 4-parameter Kappa distribution on the weighted-average regional values of L-Moments ratios of the sites. For instance if L-CV is used, then H is computed as follows;

$$H1 = \frac{(V_{L-CV} - \mu_v)}{\sigma_v} \tag{3.34}$$

where $V_{L\text{-}CV}$ is the the weighted average standard deviation. The values of mean (μ_v) and standard deviation (σ_v) are computed for 500 samples of $V_{L\text{-}CV}$ at a site. Depending on the values of H, a proposed region is; acceptably homogeneous if $H \leq 2$, possibly homogeneous if $2 < H \leq 3$ or definitely heterogeneous if $3 < H$ (L-RAP, 2011).

3.3.7.4 Cluster analysis

Clustering is one of the common approaches used for delineating homogenious regions (Kjeldsen *et al.*, 2002; Jingyi and Hall, 2004; Lin and Chen, 2006; Nyeko-Ogiramoi *et al.*, 2012). K-mean cluster is one of the widely used methods in regional frequency analysis.

Let $X = \{x_i\}; i = 1, \ldots\ldots, n$ be as set of n points to be clustered into a set of K clusters; $C = \{c_k\}; k = 1, \ldots\ldots, K$. Let u_k be the mean of cluster c_k. The squared error between u_k and the points in cluster c_k is defined as;

$$J(c_k) = \sum_{x_i \epsilon c_k} \|x_i - u_k\|^2 \tag{3.35}$$

The K-means approach finds a partition that squared error (Equation 3.35) between the empirical mean of a cluster and the points in the cluster is minimized. Finally the square error over all K clusters is minimized (Equation 3.36) (Jain 2010).

$$J(C) = \sum_{k=1}^{K} \sum_{x_i \epsilon c_k} \|x_i - u_k\|^2 \tag{3.36}$$

3.3.7.5 Distribution selection

L-Moments ratio diagrams and the Z statistics are used to identify a distribution that best fits a homogeneous sub-region. The three parameter distributions considered in this study are Gaucho, Generalized Extreme Value (GEV), Generalized Logistic (GLO), Generalized Normal (GNO), Generalized Pareto (GPA) and the Pearson 3(P3) distributions. The distributions have been proven to cover a wide range of the L-Moments ratio diagram useful for describing environmental data (L-RAP, 2011) and according to Shahzadi *et al.*, (2013) three parameter

distributions give robust regional growth curve and at-site quantile estimates. The goodness-of-fit measure is computed from;

$$Z^{Dist} = \frac{\tau_4^{Dist} - \overline{\tau_4} + \beta_4}{\sigma_4} \tag{3.37}$$

Where τ_4^{Dist} is the average of L-Kurtosis value computed from simulation of a fitted distribution, $\overline{\tau_4}$ is the average L-Kurtosis value computed from data of the region, β_4 is the bias in L-Kurtosis values and σ_4 is the standard deviation of L-Kurtosis values obtained from the simulated data. A distribution is considered the best fit if Z value is close to zero. The reasonable criteria used to select a distribution is; $|Z^{Dist}| \leq 1.64$ (Hosking and Wallis 1993; L-RAP, 2011).

3.3.7.6 Estimation of quantiles

Standardized quantiles for each homogeneous sub-region at a specified recurrence interval are estimated using regional parameters estimated by L-moments procedure, for the identified distribution. Therefore the quantiles for a station in question at specific probabilities of non-exceedance can be estimated as follows (Hosking and Wallis 1997; Kumar *et al.*, 2003; Nuñez *et al.*, 2011; Sahzadi *et al.*, 2013)

$$\hat{Q}_i(F) = \hat{\mu}_i \hat{q}(F) \tag{3.38}$$

Where $\hat{Q}_i(F)$ is the quantile function for station *i*, $\hat{\mu}_i$ is the at-station mean for station *i* and $\hat{q}(F)$ is the regional growth curve, *F* is the non-exceedance probability of the quantile.

3.4 Results

3.4.1 Data quality

All stations, except for Shakawe, Gumare, Sehitwa and Maun, in this research, contained outliers and they were set to a limit value corresponding to 1.5 x IQR or completely removed after comparing with neighbouring station. The outliers appeared as illustrated in Figure 3.2. Values

which were considered outliers were the ones which appeared extremely high or extremely low when compared with the value of the neighbouring station, such as the outlier in Ikoga, compared to Shakawe (Figure 3.2) and those kinds of outliers were preferred to be set to the limit value. Another form of an outlier is the one which appeared extremely high or low and not corresponding with the high or low of the neighbouring station, such as outliers in Shorobe compared to Maun (Figure 3.2) and those outliers were preferred to be removed. Therefore the outliers at Ikoga were set to limit and the outliers at Shorobe were removed as they were not corresponding with the high or low of Maun station. The outliers were removed as it is assumed that neighbouring stations should have the same rainfall pattern even though the magnitudes are different. The removal of outliers did not have any effect on the subsequent analysis as they were very few. The outliers in other stations were not removed as they compared well with neighbouring stations.

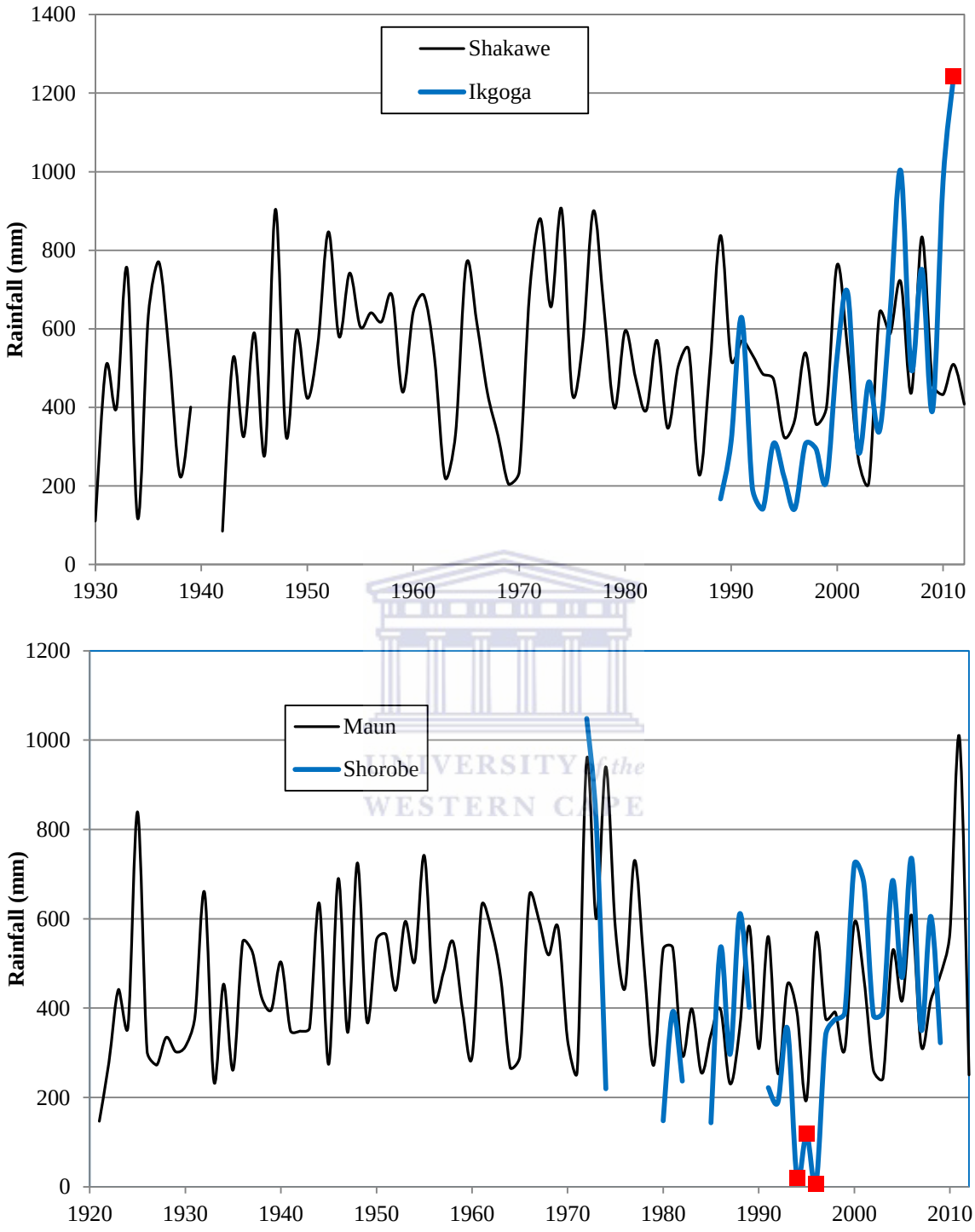


Figure 3.2: An Illustration of outlier points in red; at Ikoga rainfall station compared to Shakwe and outliers at Shorobe compared to Maun

3.4.2 Rainfall elements

Aerial rainfall and coefficient of variation interpolated by ordinary Kriging for the entire Okavango Delta Ramsar Site using the 19 rainfall stations was estimated for monthly and annual rainfall to depict the variation over space (Figure 3.3, Figure 3.4 and Figure 3.5). Aerial rainfall variation patterns can be associated with the variation floodplain inundation induced by rainfall. Monthly rainfall CVR pattern also shows how the contribution of rainfall to floodplain inundation varies from one year to the other.

3.4.2.1 Monthly rainfall

Monthly rainfall and coefficient of variation shows different patterns of spatial variation (Figure 3.3 to Figure 3.8). Monthly rainfall spatial variation (Figure 3.3, Figure 3.4 and Figure 3.5) and the association with floodplain inundation can be described as follows;

October: Rainfall increases from the western fringe of the delta towards the eastern fringe. Therefore local rains will influence subsurface soil moisture on the eastern fringe more than the rest of the delta in this month.

January and November: Within these two months rainfall increases from the lower western fringe of the delta towards the north. Rainfall will therefore contribute to subsurface soil water on the north more than the rest of the delta

February and March: Rainfall increases from the south around Maun and Shorobe areas towards the north of the delta, and therefore subsurface soil water contribution by local rains will be more in the north.

December: Low rainfall amounts are observed in the middle of the Okavango Delta, increase towards the outer western and eastern fringe, increase towards the low south and more increase towards the north. Therefore the middle part of the delta will experience less subsurface soil water contribution by rainfall than the rest of the delta.

The monthly rainfall over the Okavango Delta shows a high influence by the migration of the ITCZ from central and east Africa down to southern Africa. November and January shows similar rainfall pattern, as November is the month when the ITCZ reaches the upper part of the Okavango Delta moving downwards, whilst January is when it leaves the Okavango Delta back to central and therefore, rainfall experienced mostly on the upper part of the Okavango Delta.

During the month of December, the ITCZ is covers most parts of the delta and therefore causing rainfall in most areas. The rainfall pattern of December also shows a pattern which implies localized moisture from the center of the delta therefore causing rainfall on the outer parts. This is likely due to high temperatures causing high evapotranspiration from the delta in month of December.

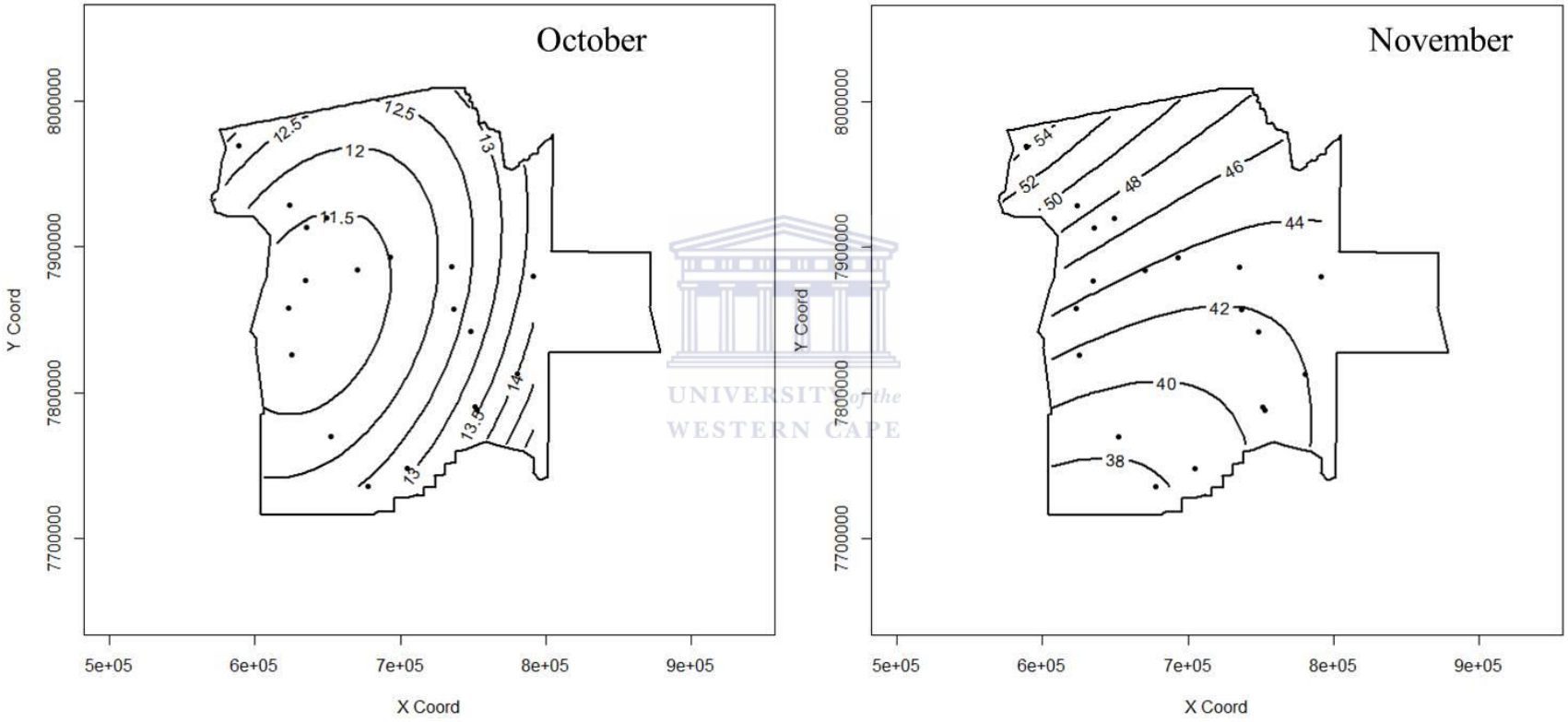


Figure 3.3 : Rainfall spatial pattern for October and Novenber (Isolines showing monthyly rainfall in mm) interpolated within the ODRS boundary using the 19 rainfall station (black dots)

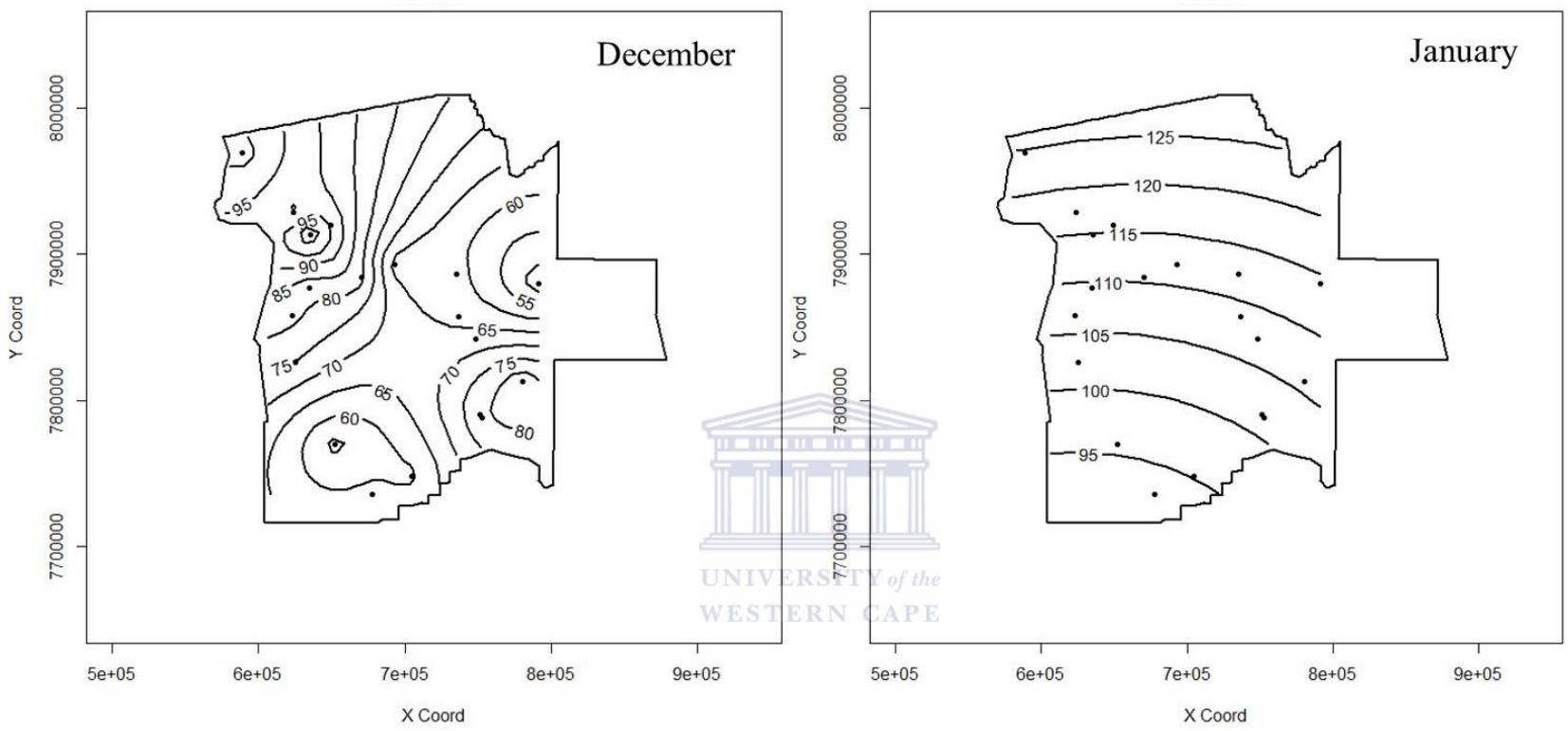


Figure 3.4: Rainfall spatial pattern for December and January (Isolines showing monthyly rainfall in mm) interpolated within the ODRS boundary using the 19 rainfall station (black dots)

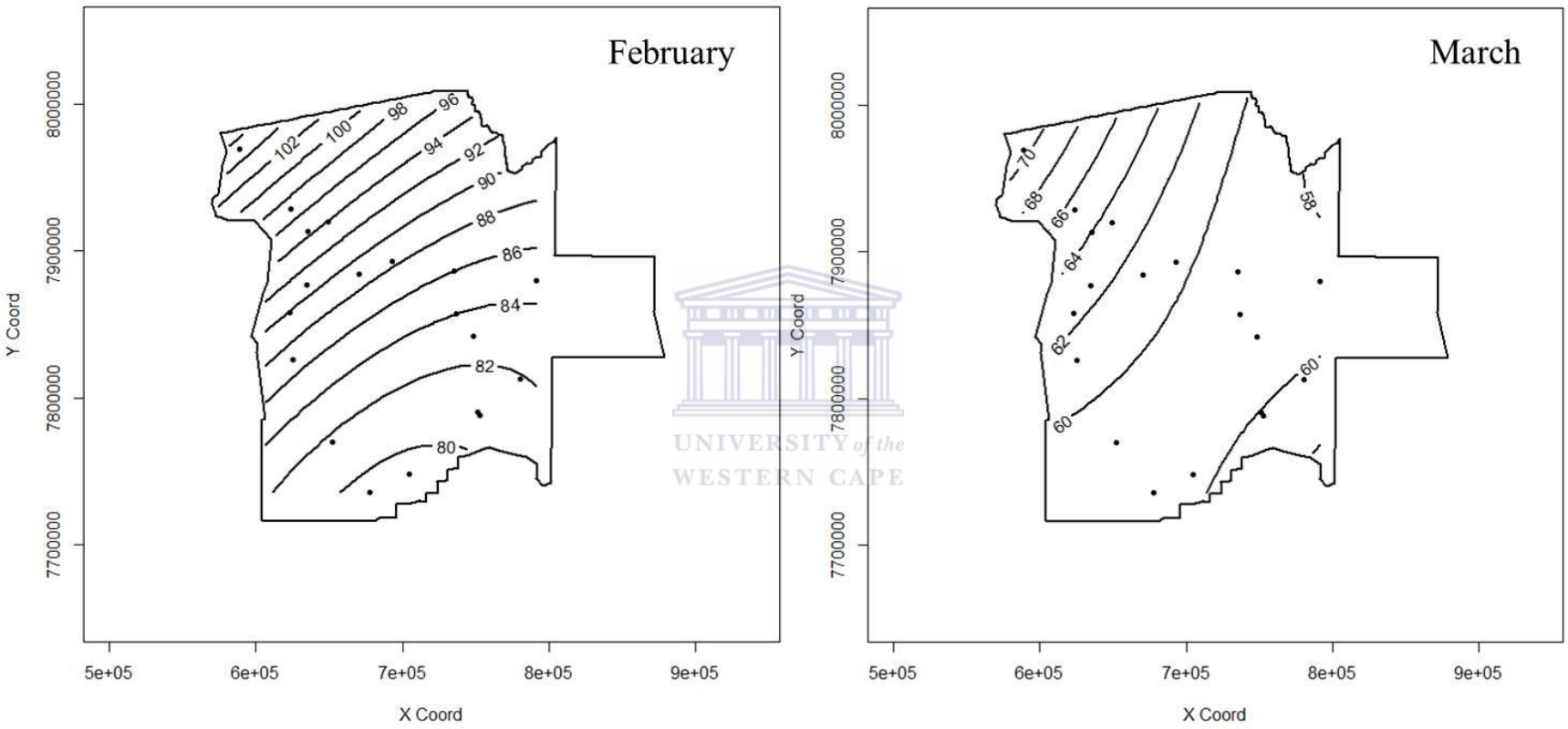


Figure 3.5: Rainfall spatial pattern for February and March (Isolines showing monthyly rainfall in mm) interpolated within the ODRS boundary using the 19 rainfall station (black dots)

Most of the rains are concentrated in the months of December, January and February, and January accounts for the highest mean rainfall of 110 mm/month for the entire delta with coefficient of variation (CVR) of 21% (Table 3.1). It is generally dry during the months of June, July and August with lowest delta-wide mean rainfall experienced in July at 0.10 mm/month (Table 3.1). Therefore the contribution of local rainfall to inundation of floodplains is expected to be highest in January and lowest in July. The highest rainfall amounts are received on the northern part of the Okavango Delta whilst lowest monthly rainfall amounts are generally received on the lower eastern and western fringes of the delta (Figure 3.3, Figure 3.4 and Figure 3.5) and again contribution of local rainfall to inundation of floodplains is expected to follow the same pattern. February shows the lowest inter-annual variation with CVR 20.9 % and July has the highest inter-annual variation with CVR of 167% (Table 3.1). This implies that the contribution of local rains to floodplain inundation over the entire Okavango Delta will vary less in Febraury compared to the rest of the months. The CRV is generally high in the middle of the delta, decreasing towards the outer parts of the Okavango Delta for the months of October, November, December, January and February whilst in March CVR is highest on the western and eastern fringes of the delta, decreasing towards the middle (Figure 3.6, Figure 3.7 and Figure 3.8). This pattern implies that contribution of local rainfall to floodplain inundation will be highly variable in the middle of the delta from one year to the other, whilst high variability will be experienced in outer fringes every year for the month of March.

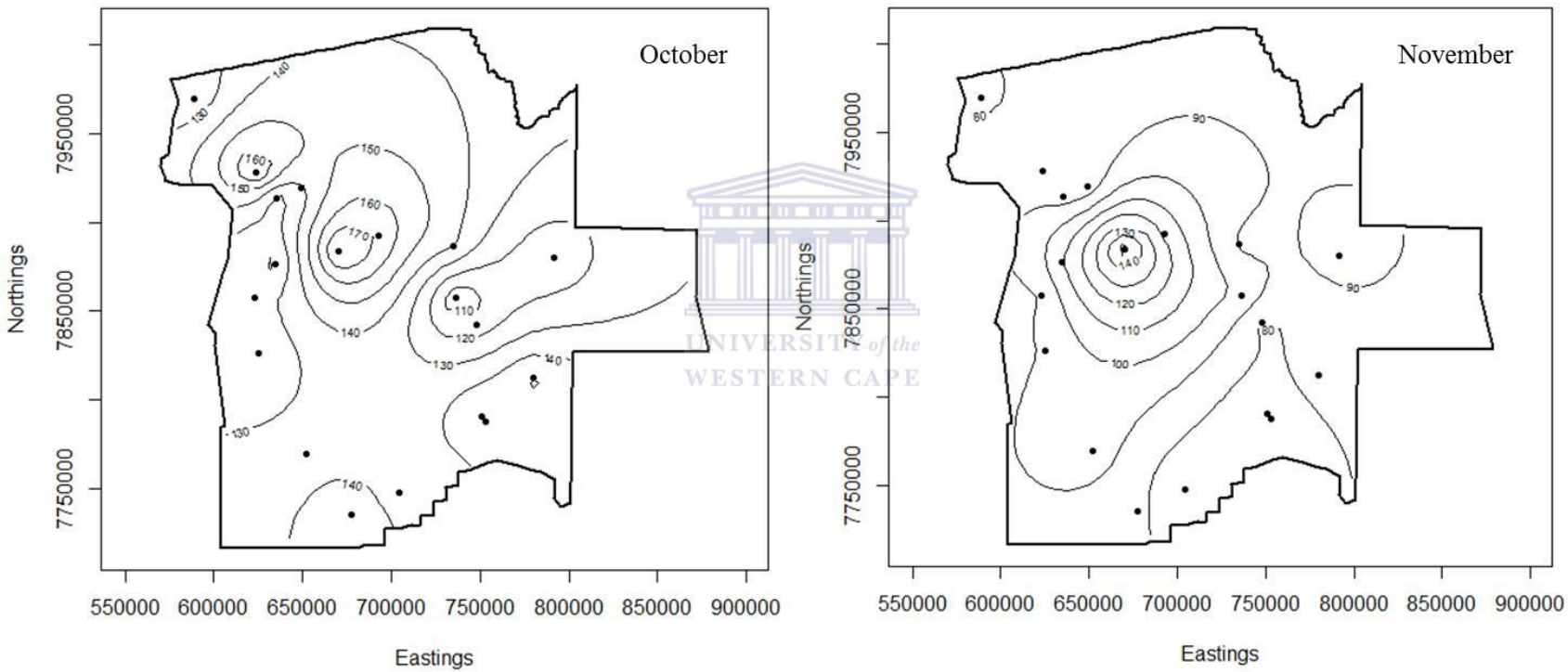


Figure 3.6: Rainy season months of October and November rainfall coefficient of variation interpolated within the ODRS boundary using the 19 stations

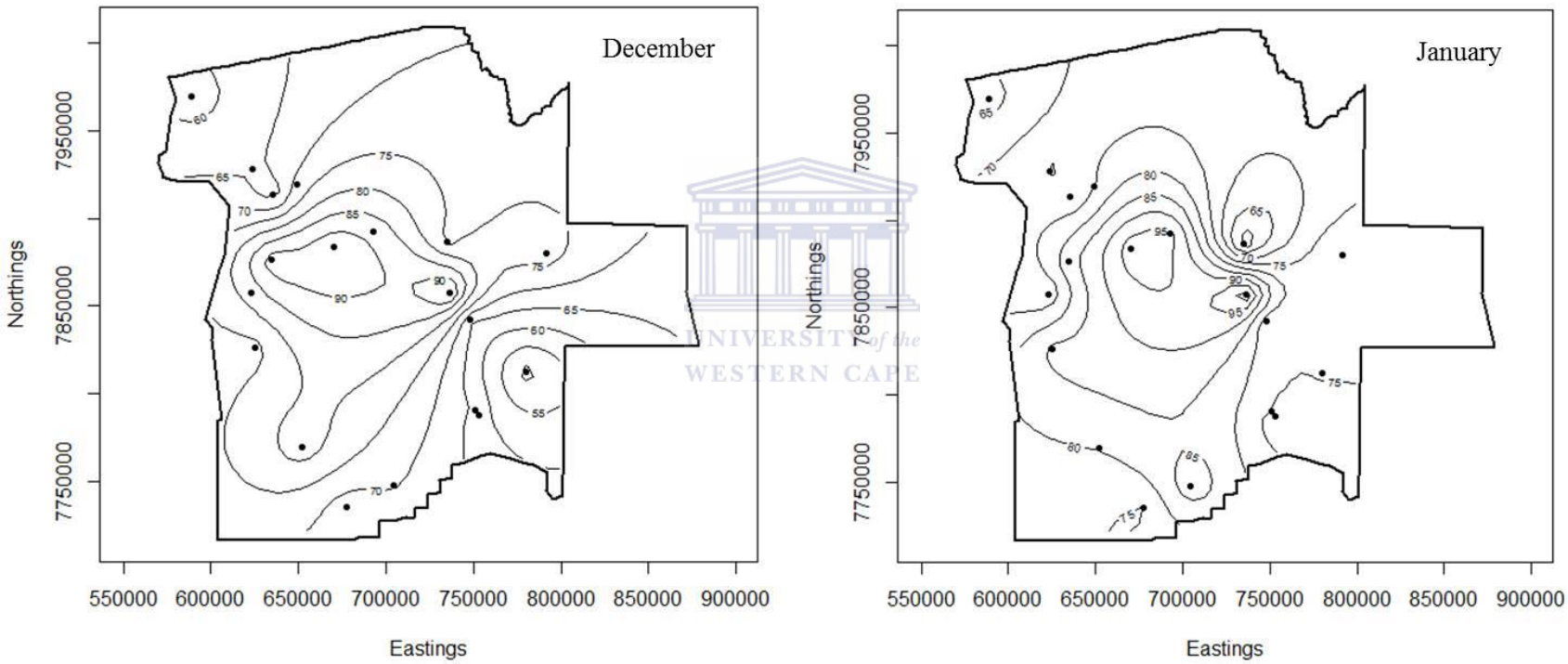


Figure 3.7: Rainy season months of December and January rainfall coefficient of variation interpolated within the ODRS boundary using the 19 stations

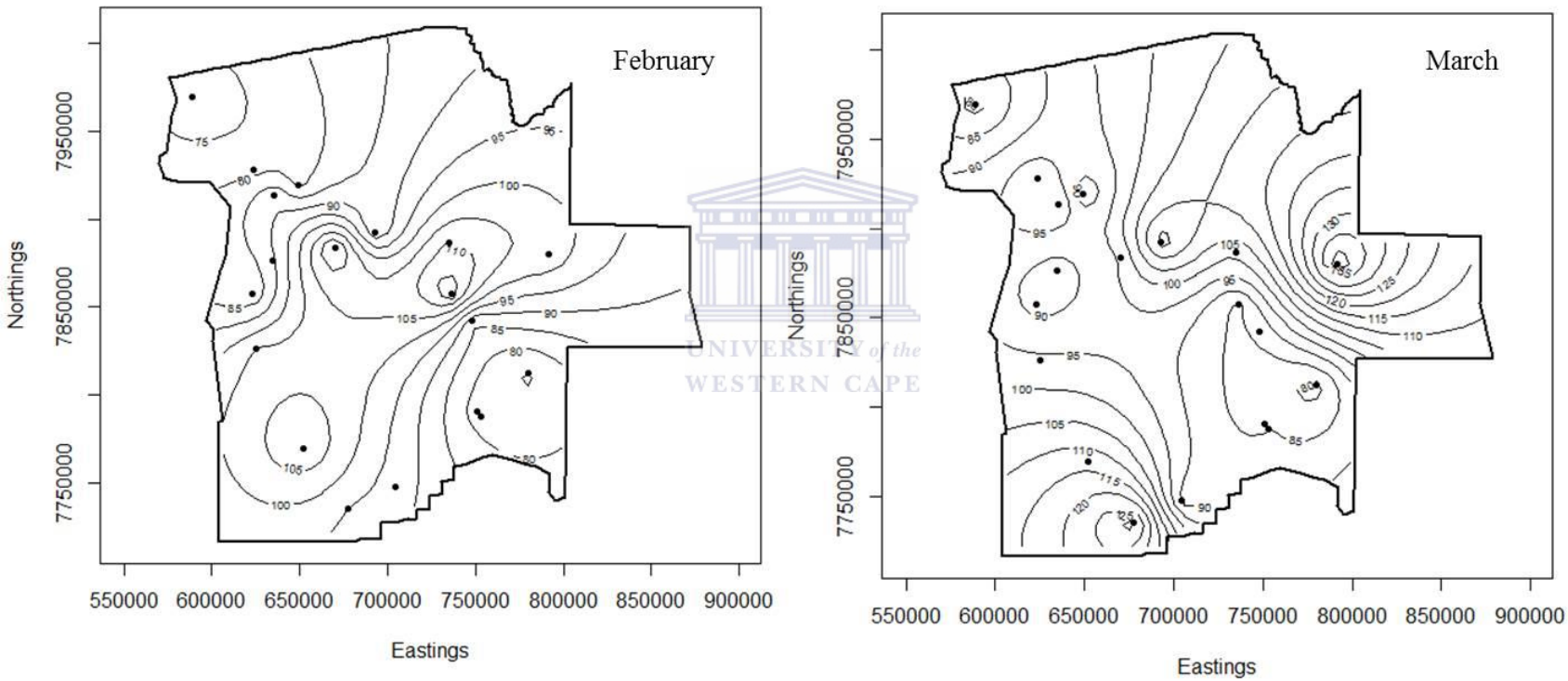


Figure 3.8: Rainy season months of February and March rainfall coefficient of variation interpolated within the ODRS boundary using the 19 stations

Table 3.1: Rainfall Summary Statistics for Okavango Delta estimated using the 19 rainfall station shown in Figure 3.2

Variable	October	November	December	January	February	March	April	May	June	July	August	September	**Annual (mm)**
Mean(mm)	**12.7**	**44.8**	**76.2**	**109.7**	**89.3**	**62.9**	**18.9**	**3.2**	**0.7**	**0.1**	**0.4**	**2.6**	**393.5**
STD (mm)	**4.9**	**13.6**	**20.1**	**26.4**	**18.6**	**16.3**	**9.0**	**2.9**	**0.7**	**0.2**	**0.6**	**1.2**	**82.8**
CVR(%)	**38.6**	**30.3**	**26.2**	**24.0**	**20.9**	**25.9**	**47.7**	**92.2**	**111.1**	**166.7**	**166.3**	**44.9**	**21.0**

3.4.2.2 Seasonal rainfall

October marks the beginning of the rainy (wet) season over the entire delta, until this reaches a maximum in January. The rainfall significantly drops from April marking the transition to the dry season with almost completely no rainfall in July, (Table 3.1). The wet season contributes 94% of the total annual rainfall and almost no rainfall in the dry season in June, July and August. The rainfall during the dry season is rather low contributing about 6% to the total annual rainfall. Generaly drier conditions are experienced in the eastern fringe of the Okavango Delta along the Ngoqa-Maunachira floodplains (Figure 3.1). The general spatial rainfall pattern shows stations on the upper part of the delta, i.e at the Panhandle; generally receiving higher rainfall during the rainy season (October-March) as compared to the rest of the delta, even though there are slight shifts in the direction of rainfall concentration from one month to the other. During the rainy season, rainfall amounts generally reduce from the north to the eastern and western fringes of the delta then increases towards Toteng and Maun (Figure 3.3, Figure 3.4 and Figure 3.5).

3.4.2.3 Annual rainfall

Average annual rainfall of the Okavango Delta is highest on the northern part with Shakawe rainfall station receiving 524 mm/year, lowest in the middle of the delta and the eastern and western fringes of the delta and moderate on outlet of the delta with 446 mm/year at Maun rainfall station (Figure 3.9). The spatial distribution of annual rainfall follows the same pattern as monthly and seasonal rainfall. Stations on the eastern fringe of the delta, along Maunachira/Khwai, recieve even lower rainfall with averages of 300 mm/year at Khwai and 275 mm/year at Txaba. Using simple arithmetic mean, the mean annual rainfall for the entire delta is 394 mm/year. The coefficient of variation is generally high, following the same pattern as annual rainfall with less variation on the northern part of the Okavango Delta, increasing towards the eastern fringe of the delta with CVR rather high reaching values of 70% (Figure 3.9).

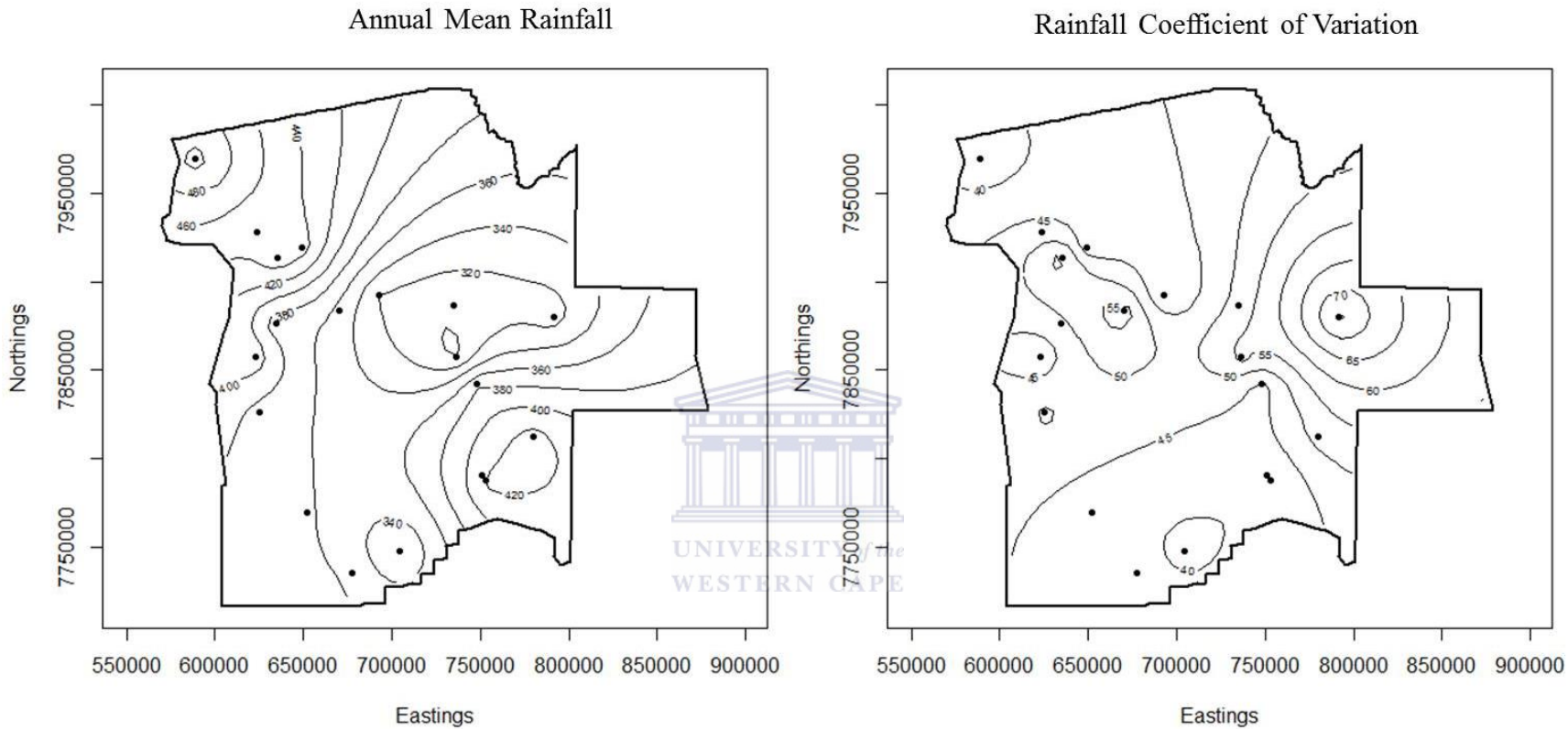


Figure 3.9: Spatial Pattern of Mean Annual Rainfall and Coefficient of Variation interpolated within the ODRS boundary using the 19 rainfall stations.

3.4.2.4 Spatial correlation

Cross correlation amongst 19 stations in the Okavango delta for the individual rainy season months (October-March), monthly and annual rainfall is estimated and plotted against the Euclidian distance between the stations (Figure 3.10 and Figure 3.11). The correlation coefficients shows a very interesting pattern especially for the rainy months as it does not follow the usual clear decay with distance. For the collective rain season months and annual rainfall cross-correlation, the decay with distance is observed although it is still not very pronounced (Figure 3.11). General correlation decay is observed for all months within the first 100 km although there are cases of negative correlations even within the first 50 km (Figure 3.10 and Figure 3.11). The correlation coefficients between stations during the individual months of the rainy season shows some strong negative correlation amongst stations even at shorter distances whilst the monthly correlation is generally positive and annual interrelationship of stations also dominated by a positive correlation. The unclear influence of distance to rainfall spatial variability highlights the localized nature of rainfall. Therefore this implies rainfall contribution to inundation is localized.

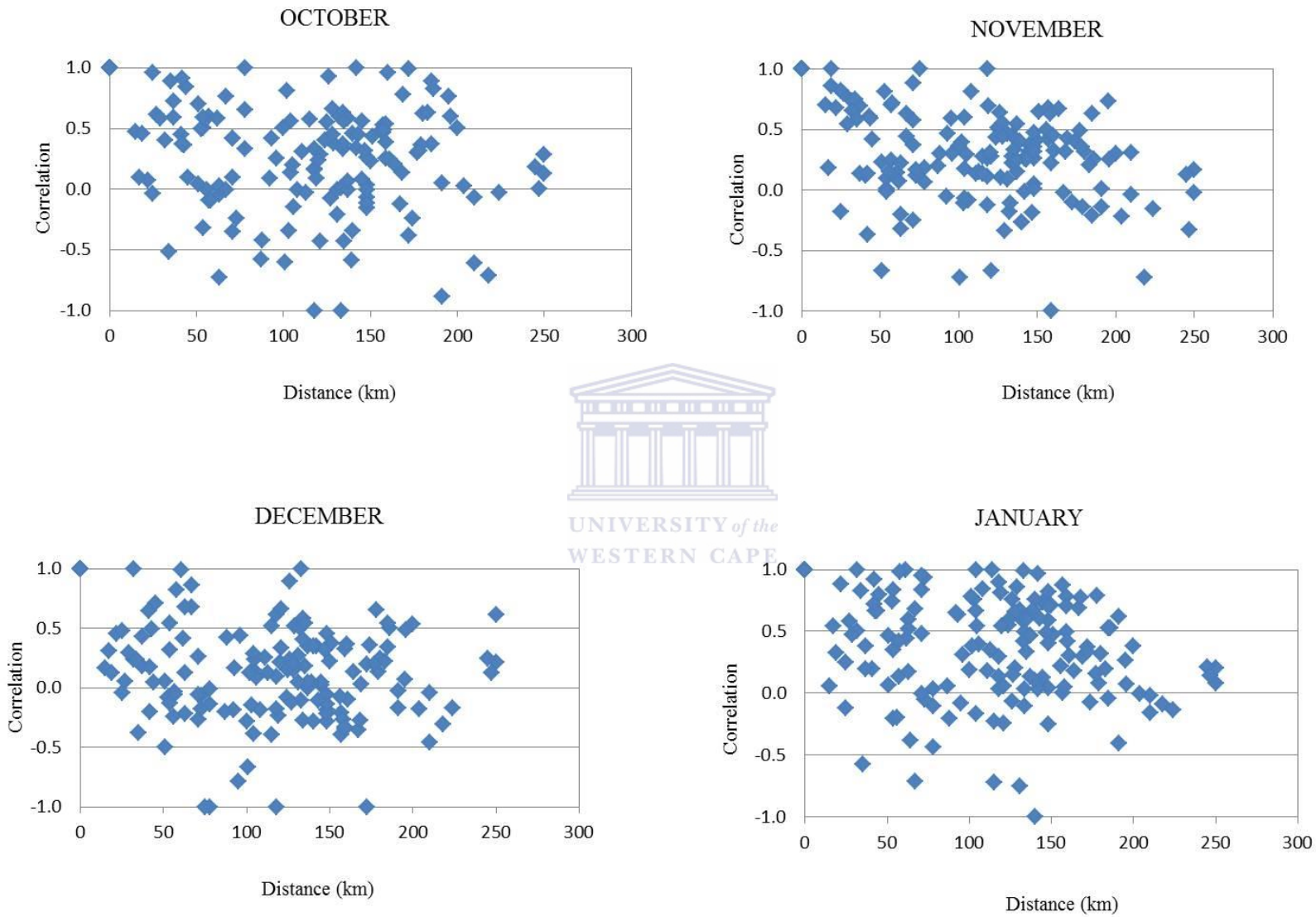


Figure 3.10: Spatial correlation of rainfall series of individual rain season months, October, November December and Januray

Figure 3. 11: Spatial correlation of rainfall series of individual rain season months (February and March), total of rain season months rainfall and annual rainfall

3.4.2.5 Long term Variation

The percentage deviation of annual rainfall from the mean of Shakawe and Maun stations is plotted in Figure 3.12. Although Figure 3.12 illustrates a tendency of a wet year to be followed by another wet year or a dry year followed by another dry year, the autocorrelation coefficients of the stations in the delta are insignificant at all lags except for those shown in Figure 3.13. Only Gaenga station shows a significant autocorrelation at lag. Etsha station shows a significant autocorrelation at lag 2 and Shakawe station has a significant autocorrelation at lag 10. This implies that rainfall over the Okavango Delta is random and erractic in time and space. Furthermore, there is no coherence in the rainfall pattern over the Okavango Delta. There is evidence of extreme rainfall events of the 1950's and early 1970's and also extreme droughts are evident in the 1920's (Figure 3.12). The CVR for annual rainfall is rather low at 21% (Table 3.1), even though there is no specific pattern in annual rainfall i.e the rainfall does not show either an increase or decreasing pattern over time, it changes from low rainfall years to high rainfall years from time to time.

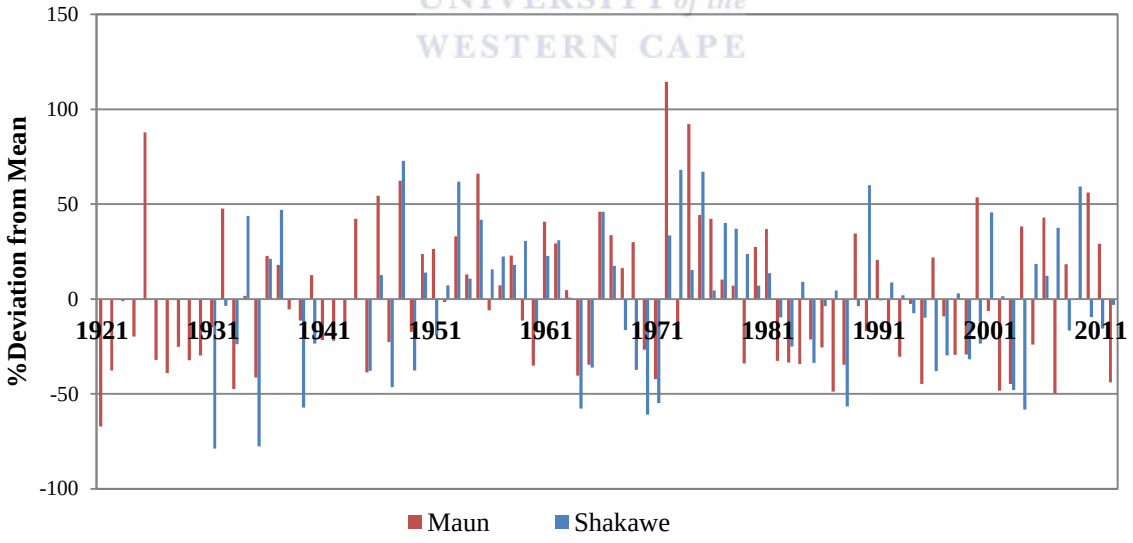


Figure 3.12: Illustration of inter-annual variations of rainfall in the Okavango Delta using Shakawe (North-Upstream) and Maun (South-Downstream) stations, 260 km appart

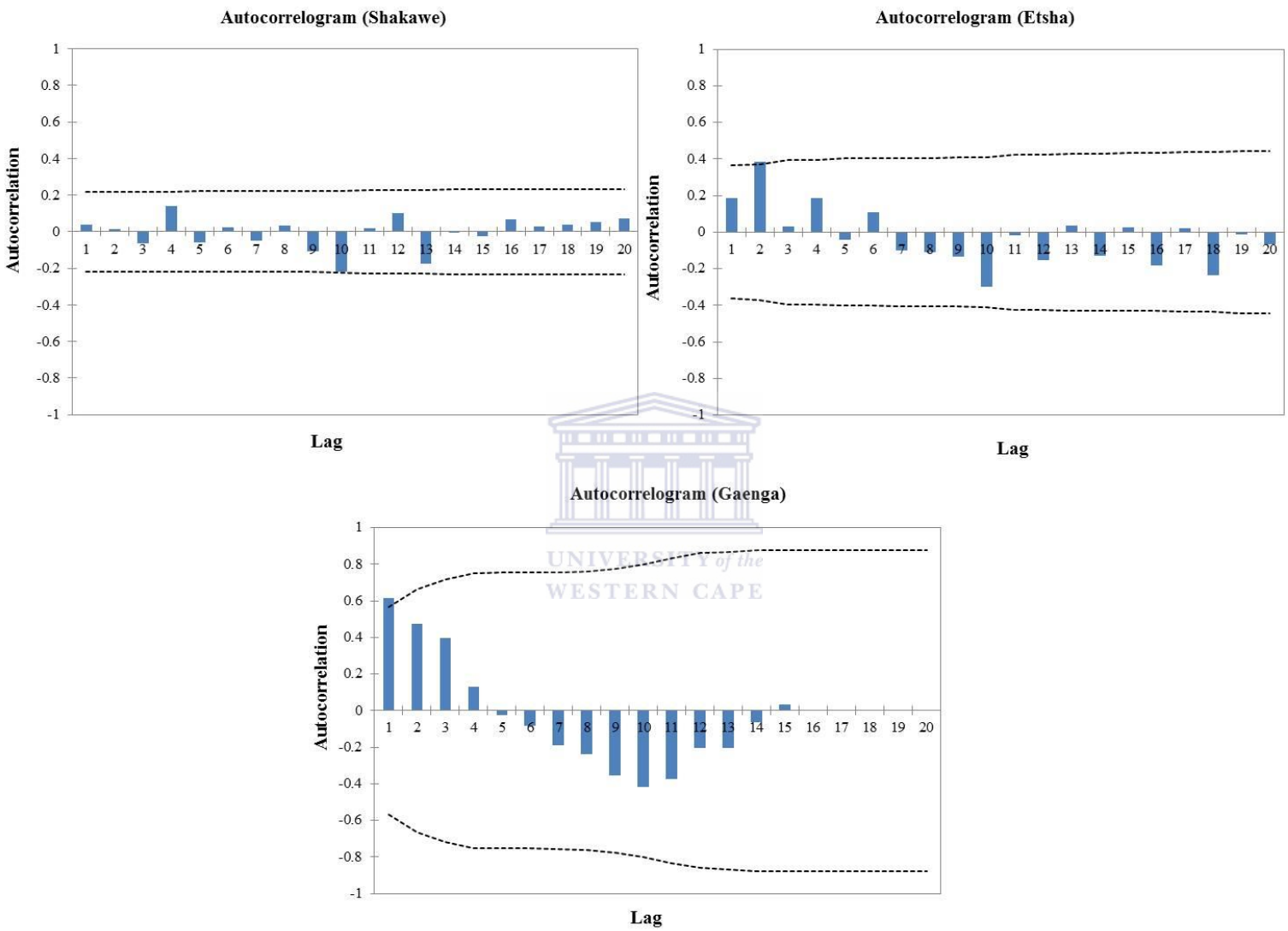


Figure 3.13: Stations with significant autocorrelation coefficients of the annul rainfall, at 5% significance level; (Dotted line showing lower and upper bound)

To illustrate periods of wet and dry years, cumulative rainfall departure from the mean of Shakawe and Maun rainfall are shown in Figure 3.14. From the two stations there is evidence of a wet period from the early 1940's to late 1950's. The area started experiencing a dry period in 1960's before a wet period started again from the early 1970's until 1981. From 1981 to 2004, it was generally a dry period again. There is a tendency of a long wet period immediately followed by a short dry period, or a long dry period followed by a short wet period (Figure 3.14).

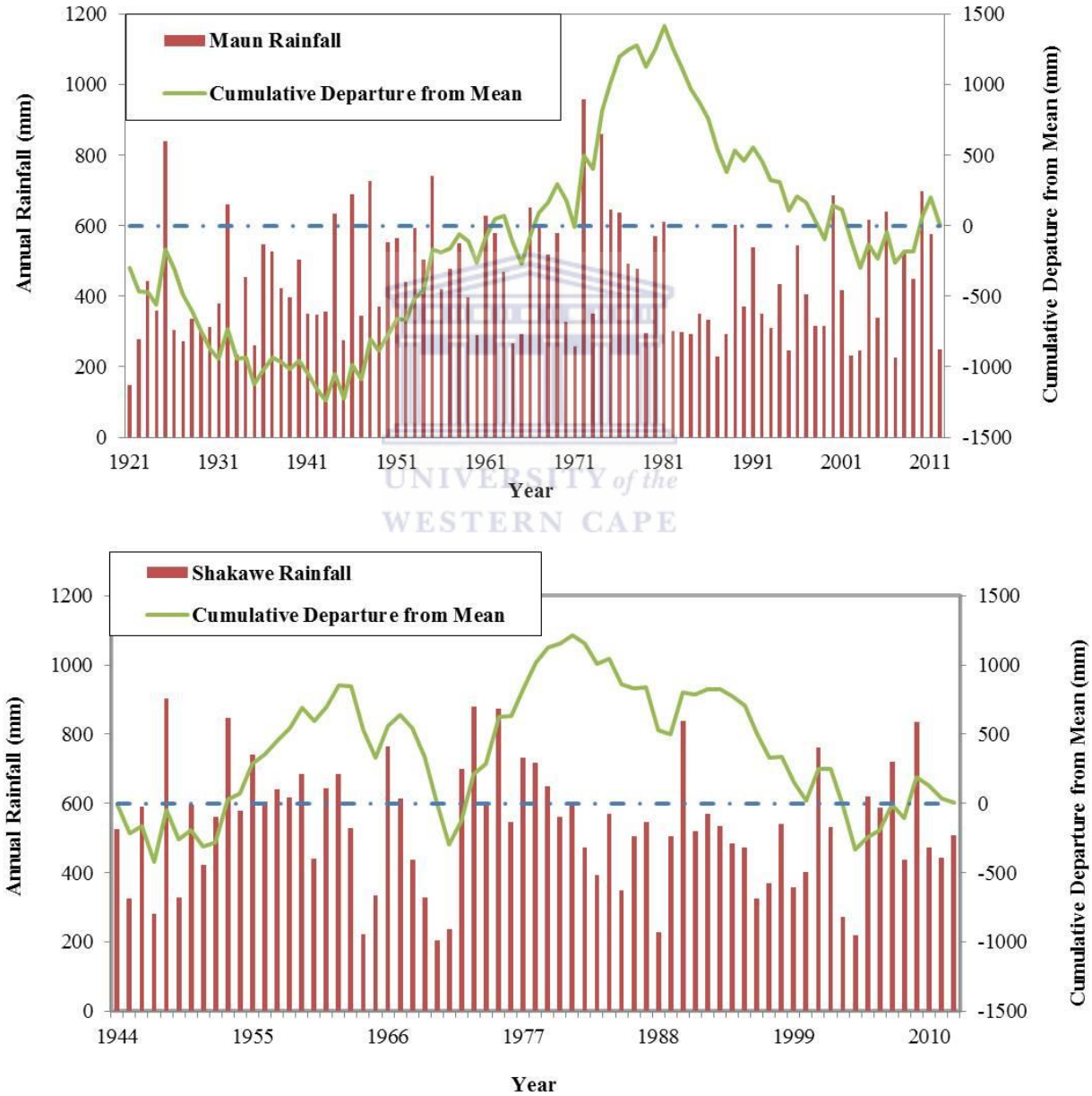


Figure 3.14: Illustration of wet and dry periods using rainfall cumulative departure of Shakawe and Maun stations

3.4.3 Identifying Change over Time

3.4.3.1 Homogeneity in Rainfall Series

Using the three homogeneity tests, Pettit test, SNHT and BR test the, *p*-value shows that 6 stations have a change point (Table 3.2). The six stations with a change in rainfall time series includes, Shakawe-B, Ikoga, Sepopa, Shorobe, Txaba and Gaenga. The tests were run for Maun and Shakawe with two sets of records; Maun-A: 1921-2012 and Maun-B:1971-2012, Shakawe-A: 1930-2012 and Shakawe-B:1970-2012 to assess the influence of record length or the starting point on the analysis. Therefore Shakawe has non-homogeneity for the 1970-2012 record (Shakawe_B) in three tests suggesting influence of record length. The *p*-values for all three tests suggest existence of change for Shakawe-B, Ikoga, Sepopa and Gaenga whilst for Shorobe the p-value for SNHT and BR suggest existence of change and for Txaba *p*-values for Pettit and BR suggested existence of change in rainfall time series (Table 3.2).

Table 3.2: *p*-value statistics and the change point identified by the three statistical tests for 19 rainfall stations in the Okavango Delta

Station	Record Length	Pettit		SNHT		BR	
		p-Value	Change Point	*p*-Value	Change Point	*p*-Value	Change Point
Shakawe_A	1930-2012	0.522	1946	0.278	1946	0.324	1946
Shakawe-B	1971-2012	0.011	1980	0.009	1978	0.026	1980
Seronga	1973-2012	0.407	1979	0.298	1978	0.116	1979
Ikoga	1989-2011	0.000	1999	0.005	2004	0.003	2004
Sepopa	1959-2012	0.014	2003	0.011	1999	0.006	1999
Etsha 6	1971-2009	0.127	1986	0.169	1986	0.573	1986
Gumare	1959-2012	0.299	1995	0.422	1999	0.047	1995
Nokaneng	1955-2009	0.138	1963	0.809	1955	0.663	1963
Tsau	1987-2012	0.318	1991	0.279	1991	0.215	1997
Sehitwa	1958-2012	0.293	1981	0.466	1981	0.176	1981
Toteng	1983-2011	0.378	1989	0.229	1985	0.286	1989
Maun_A	1921-2012	0.448	1935	0.473	1922	0.429	1943
Maun-B	1970-2012	0.295	1981	0.159	1976	0.127	1981
Matsaudi	1983-2011	0.409	1987	0.165	1987	0.264	1987
Shorobe	1972-2009	0.169	1998	0.012	1973	0.010	1999
Xakanaxa	1992-1998	0.494	1992	0.667	1995	0.509	1995
Maqwee	1992-2012	0.350	2007	0.588	2008	0.272	2007
Khwai	1992-2000	0.492	1993	0.000	1999	0.408	1999
Gaenga	1970-1985	0.002	1976	0.013	1976	0.009	1976
Txaba	1972-1984	0.003	1977	0.064	1977	0.017	1977
Khwihum	1970-1983	0.51	1978	0.753	1978	0.577	1978

To test the statistical significance of the existence of the change point suggested by the *p*-values the test statistic for Pettit, SNHT and BR were compared with the critical values. Ikoga stations showed non-homogeneity for all the three tests, Shakawe-B by both Pettit and BR, Txaba by BR and; Sepopa, Shorobe and Gaenga by SNHT. Since the three statistical tests have different strengths in identifying change at different points in the times series, a change point is identified in 1999 by Pettit test at Ikoga whilst both SNHT and BR identified a change in 2004. Both BR and Pettit identified a change in 1980 for Shakawe-B. A change point is identified 1999 at Sepopa, in 1973 at Shorobe, in 1977 at Txaba and in 1976 at Gaenga. The stations with statistically significant change point are in the northern part and in the lower eastern fringe of the Okavango Delta (Figure 3.15). The detected change in annul rainfall for stations in the north is from low to a high rainfall regime whilst for those on the eastern fringe of the delta is from high to a low rainfall regime.

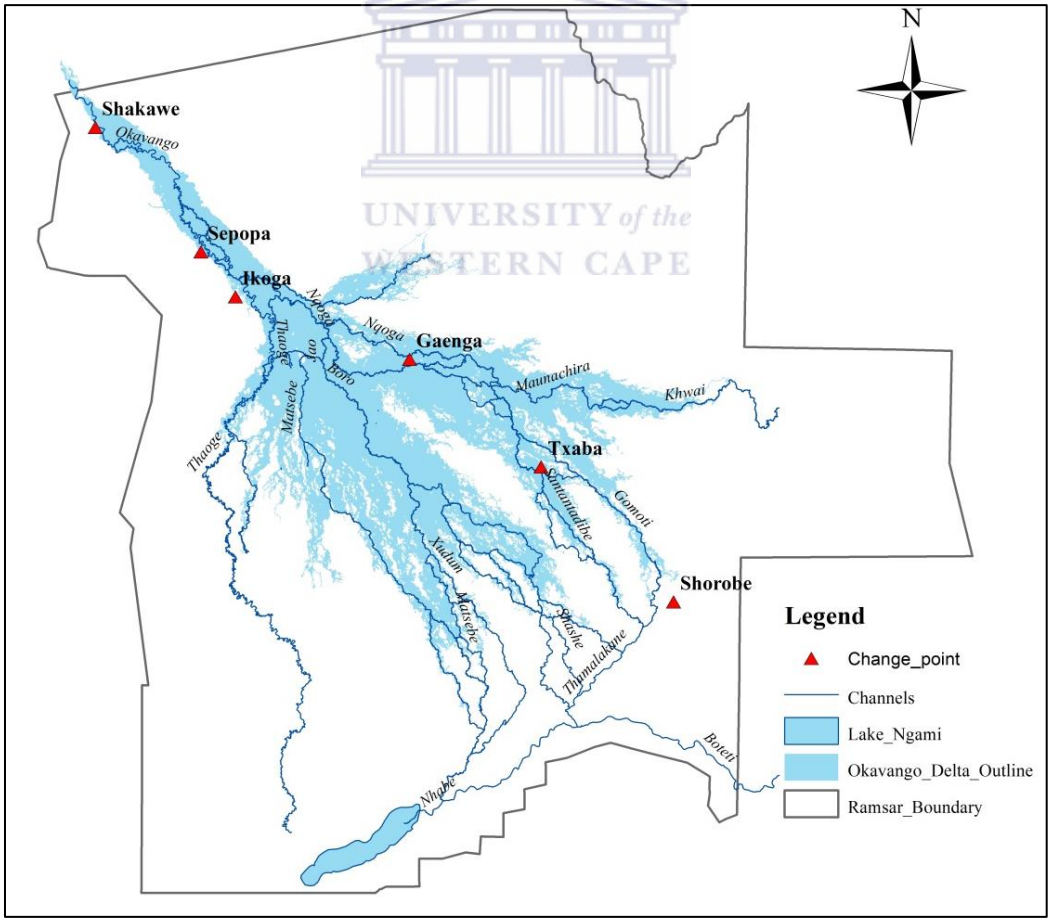


Figure 3.15: Location of stations with statistically significant change point identified by one of the statistical tests

3.4.3.2 Trends in rainfall elements

Six rainfall stations which have long continuous rainfall record, with less gaps compared to other stations were used to conduct trend analysis. The stations have a continuous data series with record length of 20 years and above. According to WMO (2009) long time series give a valid analysis and reasonable characterisation of extreme events such as 20 year return period. The six stations are Shakawe, Seronga, Gumare, Sehitwa, Toteng and Maun. The trends are tested for the period 1960 to 2012, which is 52 years and therefore qualifying for the minimum of 20 years by WMO (2009) to capture any changes or extreme events in any hydrological element. The MK trend test is applied to rainfall time series of individual months of the rainy season and annual series at 5% significance level. The MK trend test statistics are presented in Table 3.3. There are no statistically significant trends at all the stations.

Table 3.3: MK Trend *Z* Statistics and Sen Slope *Q* for the six stations tested for trends in the month of the rainfall season and annual rainfall series

Station	Statistics	October	November	December	January	February	March	Annual
Shakawe	***Q***	-0.124	-0.334	-0.218	0.473	-0.817	-0.032	-2.480
	Z	-0.013	-0.008	-0.003	0.004	-0.003	-0.001	-0.011
Seronga	***Q***	-0.482	0.130	-0.314	0.380	-1.197	0.950	-1.755
	Z	-0.033	0.004	-0.005	0.002	-0.012	0.015	-0.009
Gumare	***Q***	0.009	0.264	0.081	0.749	-0.102	1.000	0.585
	Z	0.008	0.008	0.001	0.008	-0.002	0.018	0.003
Sehitwa	***Q***	0.000	-0.202	-0.408	0.167	0.854	0.006	-1.813
	Z	0.001	-0.005	-0.007	0.003	0.014	0.001	-0.009
Toteng	***Q***	0.000	0.755	1.264	1.800	0.050	0.557	5.430
	Z	-0.024	0.024	0.021	0.026	0.001	0.026	0.029
Maun	***Q***	-0.073	-0.221	0.198	0.085	-0.300	0.237	-1.290
	Z	-0.007	-0.005	0.005	0.001	-0.005	0.005	-0.006

Quantile regression was applied to annual rainfall of four stations for their entire record length, Maun, Shakawe, Gumare, and Sehitwa to test for existence of any trend at different percentiles of the rainfall time series. The quantile regression statistics did not show any significant trend at all the stations except for Shakawe. Shakawe rainfall showed increasing trend around the 10th percentile with the slope coefficient of 3.22 with a *p*-value of 0.03 (Figure 3.16). Generally there are no significant trends in rainfall time series and therefore the general perception about reduction of areas inundated over the years, cannot be attributed to decline in rainfall over the delta.

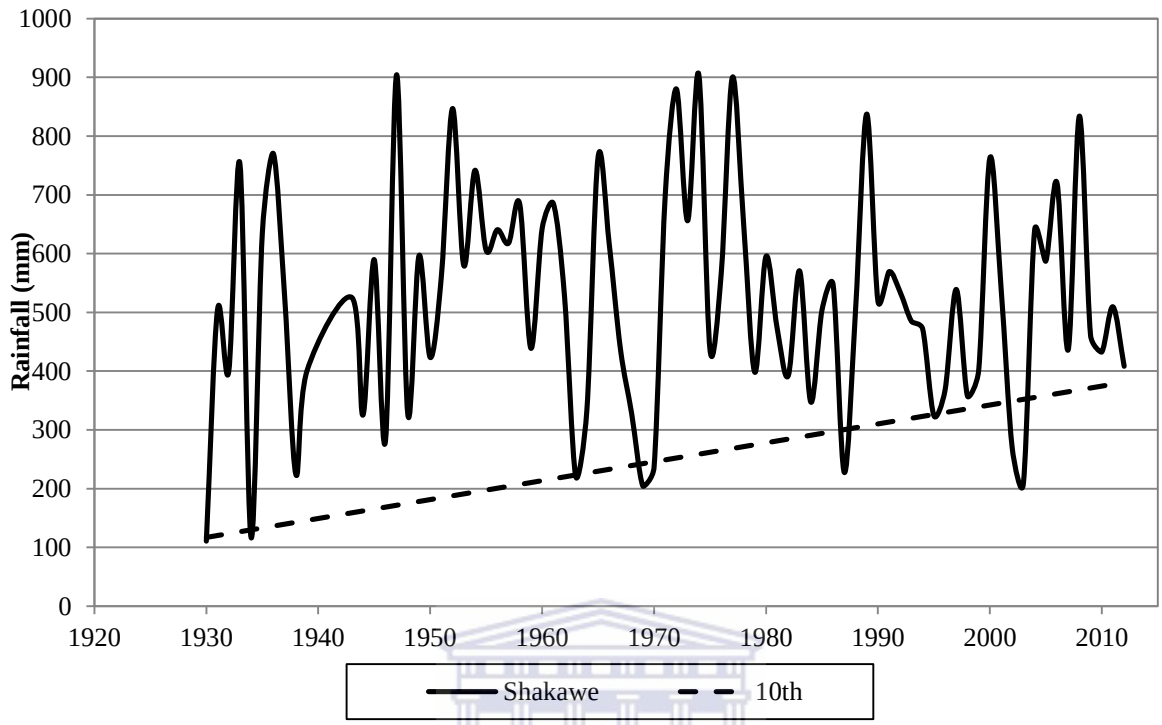


Figure 3.16: An increasing trend detected for the 10th percentile of the annual rainfall at Shakawe

3.4.3.3 Periodicity

The results of applying Fisher's Kappa test and Barlett's Kolmogorov Smirnov test to determine presence of significant cyclic behavior in annual rainfall for selected stations in the Okavango Delta are shown in Table 3.4. Time series of annual rainfall for selected stations with a continuous record length of more than 20 years, Shakawe, Seronga, Gumare, Sehitwa, Toteng and Maun did not show any significant cyclic behavior for both the Fisher's Kappa-test and Barlett's Kolmogorov Smirnov. Although the cumulative depature of rainfall shown in Figure 3.9 illustrates wet and dry periods, there is no significant periodic pattern in rainfall over the Okavango Delta. Therefore, wet and dry periods are random and do not follow any cyclic pattern.

Table 3.4: Results of applying Fisher's Kappa test and Barlett's Kolmogorov Smirnov test to determine presence of significant cyclic behavior in annual rainfall for selected stations in the Okavango Delta

Station	N	Fisher's kappa		Bartlett's Kolmogorov-Smirnov	
		Value	*p*-Value	Value	*p*-Value
Shakawe	69	3.573	0.660	0.130	0.581
Seronga	40	3.002	0.685	0.193	0.434
Gumare	46	4.013	0.304	0.221	0.202
Sehitwa	54	3.307	0.671	0.080	0.994
Toteng	29	3.070	0.476	0.226	0.469
Maun	92	4.163	0.515	0.090	0.839

3.4.4 Regional frequency analysis

Regional Frequency Analysis (RFA) is conducted using annual rainfall for 19 rainfall stations over the entire Okavango Delta.

3.4.4.1 Data screening using L-moments and discordancy measure

L-Moments being, L-CV, L-Skew, L-Kurt and the discordancy measures for all the stations were computed to test if the rainfall stations in the Okavango Delta belong to one homogeneous region. L-Moments ratio diagram are shown in Figure 3.17 and discordancy in Table 3.5. The results suggest that rainfall stations in the Okavango delta are heterogeneous. Two rainfall stations Xakanaxa and Khwai have a discordancy value greater than 3, therefore do not belong to same homogeneous region as other stations. The Xakanaxa and Khwai rainfall stations are on the low eastern fringe of the Okavango Delta, less affected by the ITCZ which is the main rainfall influence over the region.

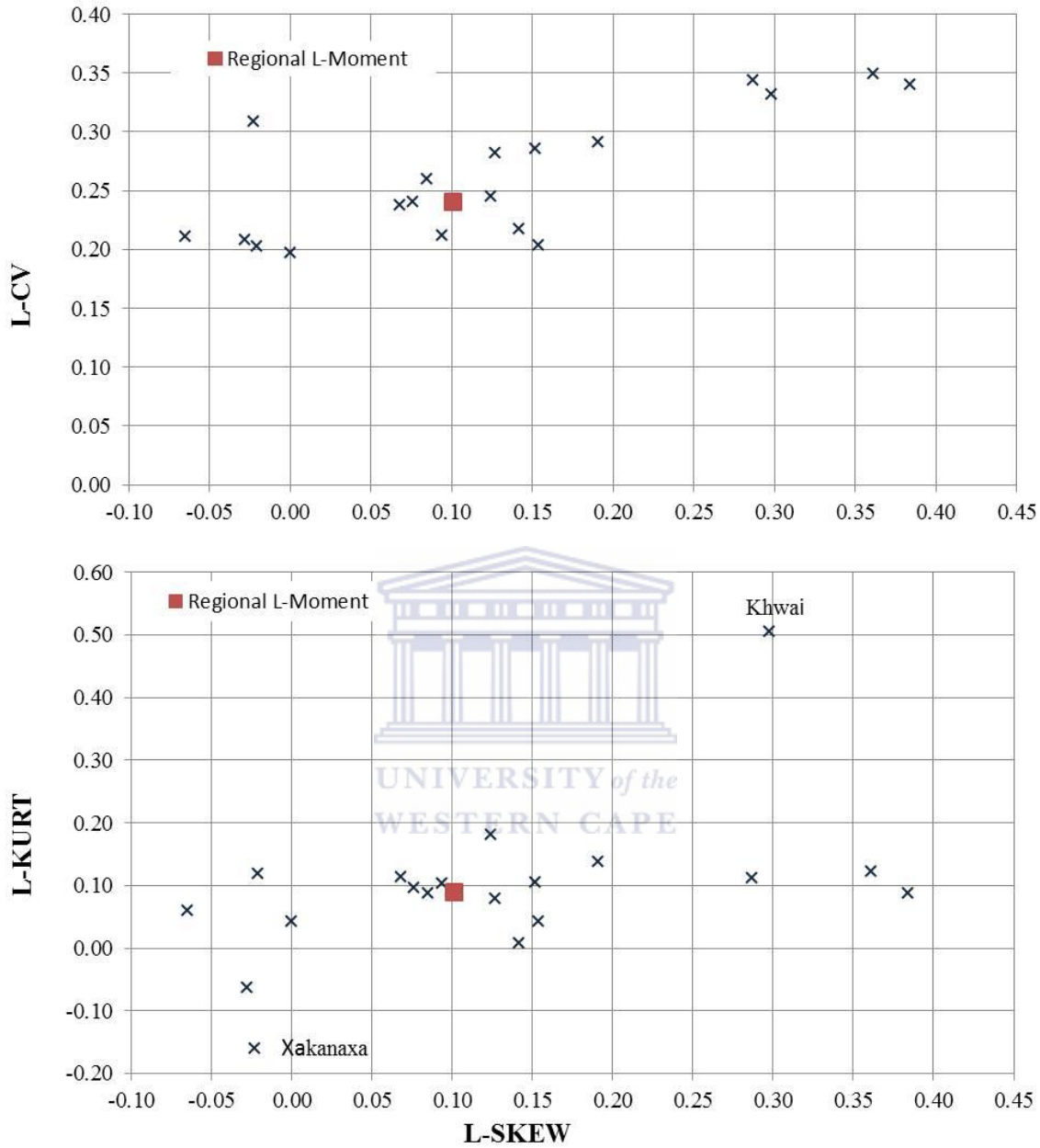


Figure 3.17: L-Moments ratio Diagram of stations in the Okavango Delta

Table 3.5: L-Moments and Discordancy Measure for Stations in the Okavango Delta

Station ID	Station	Record Length	MEAN	L-CV	L-SKEW	L-KURT	*Di*
1	Shakawe	79	591.64	0.203	-0.021	0.118	0.73
2	Seronga	40	521.31	0.211	-0.065	0.059	0.87
3	Ikoga	22	543.35	0.344	0.287	0.111	0.92
4	Sepopa	30	494.50	0.260	0.085	0.087	0.08
5	Etsha6	22	395.90	0.282	0.127	0.079	0.12
6	Gumare	53	490.76	0.212	0.094	0.103	0.49
7	Nokaneng	39	414.62	0.291	0.191	0.137	0.12
8	Tsau	22	410.30	0.240	0.076	0.097	0.08
9	Sehitwa	54	406.55	0.238	0.068	0.114	0.15
10	Toteng	26	354.91	0.197	0.000	0.043	0.50
11	Maun	91	508.42	0.204	0.154	0.043	1.59
12	Matsaudi	25	448.16	0.217	0.142	0.007	1.15
13	Shorobe	31	499.73	0.286	0.152	0.104	0.10
14	Xakanaxa	7	340.28	0.309	-0.023	-0.161	3.78
15	Maqwee	18	452.13	0.245	0.124	0.181	0.28
16	Khwai	7	420.60	0.332	0.298	0.505	4.12
17	Gaenga	7	349.14	0.208	-0.028	-0.063	0.71
18	Txaba	10	310.64	0.340	0.384	0.088	1.85
19	Kwihum	14	400.60	0.349	0.361	0.122	1.36

3.4.4.2 Identification of homogeneous regions

To statistically test the heterogeneity of the 19 stations in the Okavango Delta, the heterogeneity values *H*, were computed using Equation (3.34). The *H* values computed for the Okavango Delta including all the 19 rainfall stations are as follows; $H1$=4.12, $H2$=3.10, $H3$=1.87. Therefore $H1$ and $H2$ suggest that the region is heterogeneous. After removing the discordant stations, Xakanaxa and Khwai, the *H* values were as follows; $H1$=4.74 and $H2$=3.10 still suggesting that the region is heterogeneous, although $H3$=1.68.

Cluster analysis was applied to identify homogeneous regions. Using K-Mean cluster analysis procedure, 3 distinct homogeneous sub-regions are identified with Shakawe being the only station belonging to a unique sub-region with L-CV= 0.203, L-Skew=-0.021 and L-Kurt=0.118. Data screening was run again for the identified sub-regions to confirm that the stations belong to their specified unique sub-regions. The estimated discordancy measure for the station in the specified sub-regions then confirms that they belong to their identified regions (Table 3.6 and Table 3.7).

Table 3.6: L-Moments and Discordancy Measure of Sub-Region 2 Rainfall Stations

StationID	Station	L-CV	L-SKEW	L-KURT	D_i
2	SERONGA	0.211	-0.065	0.059	1.72
3	IKOGA	0.344	0.287	0.111	1.65
4	SEPOPA	0.260	0.085	0.087	0.26
6	GUMARE	0.212	0.094	0.103	0.44
11	MAUN	0.204	0.154	0.043	0.96
12	MATSAUDI	0.217	0.142	0.007	1.05
13	SHOROBE	0.286	0.152	0.104	0.28
15	MAQWEE	0.245	0.124	0.181	1.63

Table 3.7: Discordancy Measure for Sub-Region 3 Rainfall Stations

StationID	Station	L-CV	L-SKEW	L-KURT	D_i
5	ETSHA6	0.282	0.127	0.079	0.050
7	NOKANENG	0.291	0.191	0.137	0.040
8	TSAU	0.240	0.076	0.097	0.170
9	SEHITWA	0.238	0.068	0.114	0.220
10	TOTENG	0.197	0.000	0.043	0.850
14	XAKANAXA	0.309	-0.023	-0.161	2.990
16	KHWAI	0.332	0.298	0.505	2.780
17	GAENGA	0.208	-0.028	-0.063	0.750
18	TXABA	0.340	0.384	0.088	1.720
19	KWIHUM	0.349	0.361	0.122	1.110

The heterogeneity values for the identified regions are also shown in Table 3.9 and the values suggest acceptably of homogeneity in the sub-regions. Therefore using 19 rainfall stations, the whole Okavango Delta within the ODRS main region can be classified into 3 unique sub-regions; sub-region 1, sub-region 2 and sub-region 3 (Figure 3.18). Sub-Region 1 has the highest rainfall amounts compared to the other regions. The regional average rainfall is 592 mm/year. Sub-Region 2 has moderate rainfall amounts whilst sub-region 3 has the lowest rainfall amounts compared to the other sub-regions. The regional average rainfall is 436 mm/year and 351 mm/ year for sub-region 2 and sub-region 3 respectively. Therefore, Sub-Region 1 is highly influenced by rainfall induced by ITCZ movement which is the main rainfall origin of the region,

Sub-Region 2 is less affected by the ITCZ compared to Sub-Region 1 and Sub-Region 3 is likely to be influenced by localised climates as it is in the middle swamp areas of the delta. Sub-Region 3 is a low lying area in the middle of the Gumare and Kunyere faults. This implies sub-region 1 recieves high subsurface water contribution by local rainfall which subsequently inundates floodplains.

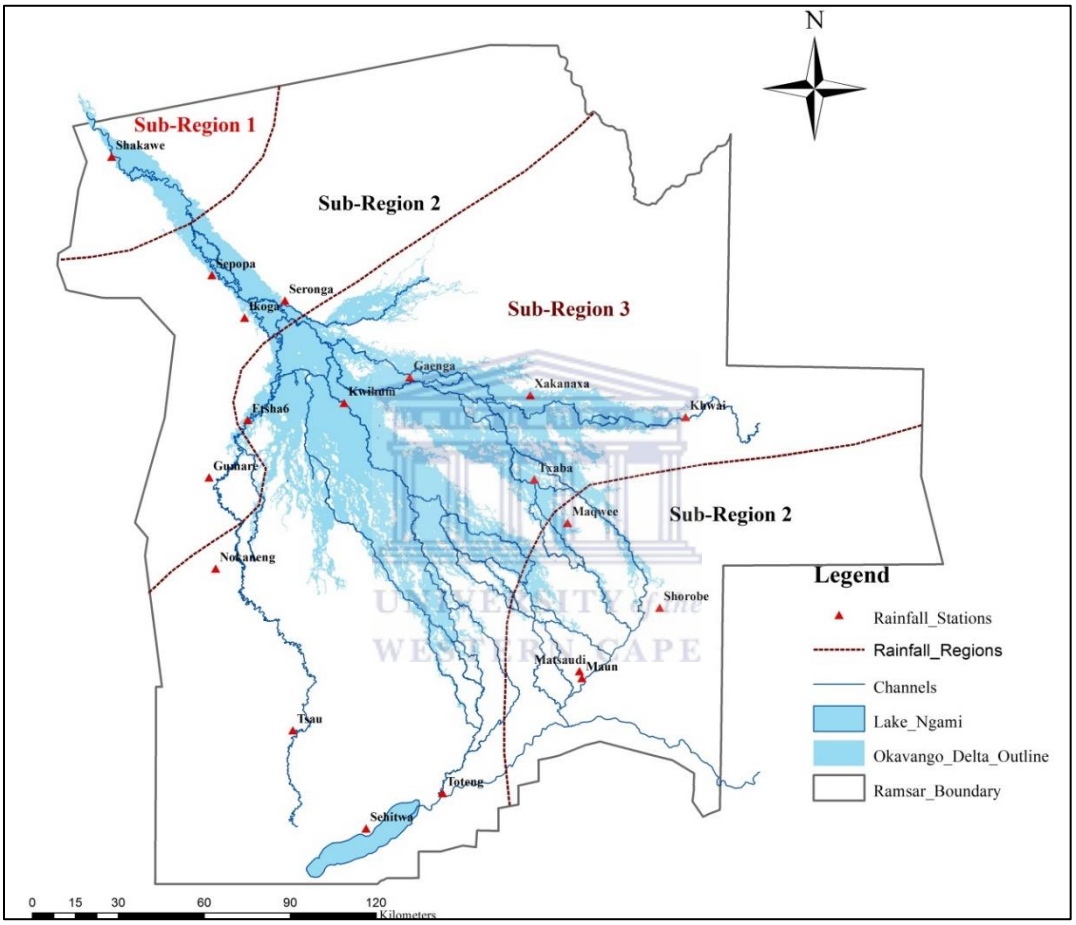


Figure 3.18: A delimitation of the 3 sub-regions of the Okavango Delta identified using the RFA procedure

3.4.4.3 Distribution selection

Frequency analysis was conducted for Shakawe to represent sub-region 1 as it is the only station belonging to a unique sub-region. The annual rainfall for Shakawe is fitted to the 5 probability distributions and the best fit is identified by means of the Kolmogrov-Smirnov statistical test for goodness of fit. The best fit distribution for Shakawe rainfall is the GEV and therefore sub-region 1 is defined by the distribution.

The graphical method of L-Moments ratio diagram for selecting best fit regional probability distribution, Figure 3.19, 3.20 and 3.21 show the L-Skewness vs. L-Kurtosis ratio diagram for the homogeneous sub-regions 1, 2 and 3 respectively. The L-Skewness and L-Kurtosis pairs for the sub-regions are grouped near the Gaucho distribution curve; however the pairs are also centered around the GP, GEV or P3 distributions. The final decision for selection of the sub-regional distribution is based on the goodness of fit statistics. The goodness-of-fit, Z^{dist}-statistics computed using Equation (3.37), are shown in Table 3.8. The Z-Statistics suggests that the Gaucho distribution is the best fit for the two sub-regions. According to Hosking and Wallis (1997) the 4-parameter kappa distribution is flexible and adapts to different distribution models, hence Gaucho which is a special case of the Kappa distribution. Sub-region 2 has GPA also as a fitting distribution and P3, GEV and GNO fits the sub-region 3 (Table 3.8). Although the GEV, GNO and GAUCH fits the sub-region 3, the P3 distribution is used for further analysis as it has a lower Z^{dist}-statistics value compared to other distributions apart from the GAUCHO which is flexible and fits in all sub-regions.

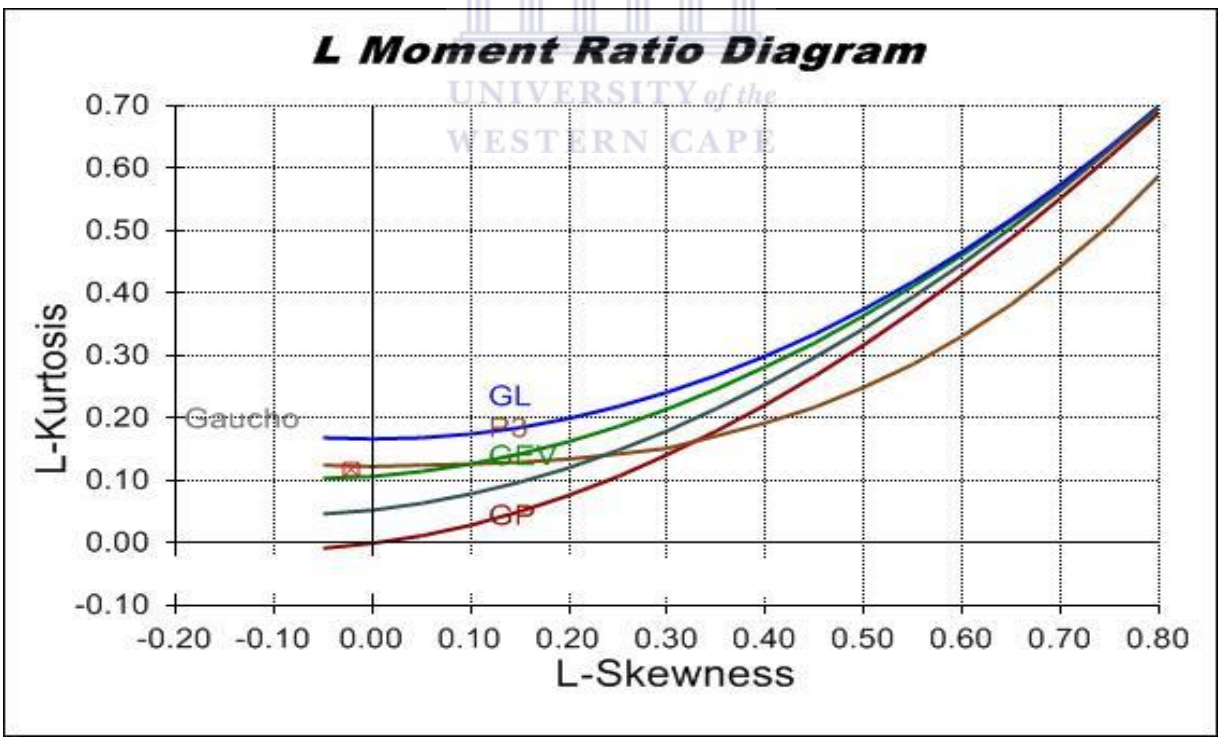


Figure 3.19: L-Moment ratio diagram of L-Skewness Vs. L-Kurtosis for homogenisous sub-region 1 (Red Square showing the regional L-Moment)

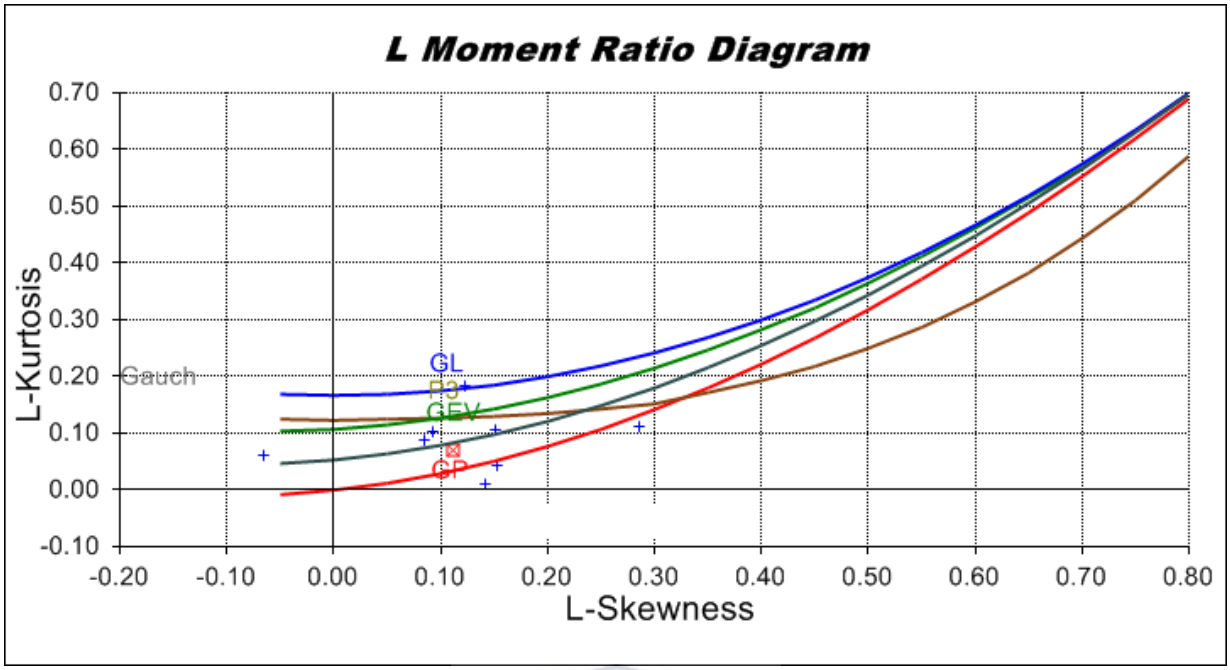


Figure 3.20: L-Moment ratio diagram of L-Skewness Vs. L-Kurtosis for homogenisous sub-region 2 (Red Square showing the regional L-Moment)

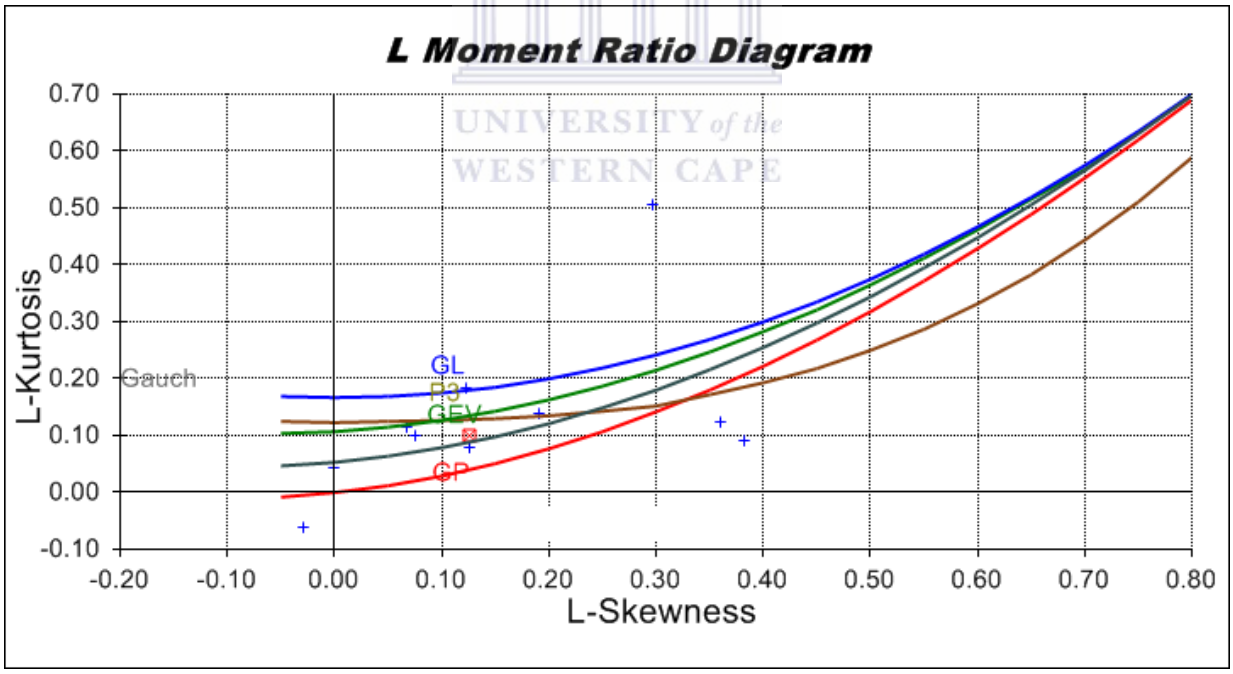


Figure 3.21: L-Moment ratio diagram of L-Skewness Vs. L-Kurtosis for homogenisous sub-region 3(Red Square showing the regional L-Moment)

Table 3.8: Statistics for the Sub-Regions 2 and 3, showing heterogeinity measure, L-Moments and the goodness of fit for the tested distributions

Sub-Region	Stations	$H1$	$H2$	$H3$	L-Cv	L-Skew	L-Kurt	Distribution Z^{dist}-Statistic					
								GEV	GLO	GNO	GPA	P3	GAUCHO
Sub-Region 2	8	3.76	1.47	0.84	0.233	0.113	0.068	3.58	6.19	3.72	-1.62	3.37	0.97
Sub-Region 3	10	0.9	0.72	0.28	0.265	0.126	0.092	1.47	3.19	1.50	-2.07	1.2	-0.27

NOTE: **If at least two of the *H* values are less than 3, this confirms that the stations within the specified sub-regions form a homogeneous sub-region. If the $|Z^{\mathbf{dist}}| \leq 1.64$ then the probability distribution is considered best-fit for the specified sub-region**

3.4.4.4 Estimation of quantiles

The quantiles with specific return periods at specific sites are estimated from regional growth curves. Estimation of quantiles gives an idea of timing of certain rainfall events and their association with inundation of floodplains. The regional growth curves are estimated from the best fit distributions for the identified sub-regions. The inverse form of sub-regional distribution with location (ξ), scale (β) and shape (κ) parameters is given as follows (Shabri, 2002; Nuñez *et al*, 2011; Kaluba, 2011;);

All sub-regions: GAUCHO Distribution; Special Case of 4-kappa distribution with the second shape parameter *h= 0.5*, fitted to all the sub-regions

$$q(F) = \xi + \frac{\beta}{\kappa}\left\{1 - \left(\frac{1-F}{0.5}\right)^{\kappa}\right\} \tag{3.39}$$

GEV fitted to Sub-Region 1;

$$q(F) = exp\left\{-\left[1 - \frac{\kappa}{\beta}(F-\xi)\right]^{\frac{1}{\kappa}}\right\} \tag{3.40}$$

GPA fitted to Sub-Region 2

$$q(F) = \xi + \beta\frac{1-(1-F)^{\kappa}}{\kappa} \tag{3.41}$$

P3 fitted to Sub-Region 3

$$q(F) = \xi + \beta K(F) \tag{3.42}$$

where *K(F)* is the frequency factor given by

$$K(F) = \frac{2}{\kappa}\left[1 + \frac{\kappa}{6} - \frac{\kappa^2}{36}\right]^3 - \frac{2}{\kappa} \tag{3.43}$$

where $q(F)$ is the quantile function or growth curve for the distributions, F is the non-exceedance probability for the desired quantiles of the parameters. Table 3.9 shows the parameters of the selected distributions for the 3 homogeneous sub-regions of the Okavango Delta. The estimates of regional growth curves for the sub-regions are also shown in Figure 3.17.

Table 3.9: Distribution parameters for the 3 homogeneous sub-regions

Region	Distribution	Location	Scale	Shape
Sub-Region 1	GEV	0.881	0.330	0.270
	Gaucho	0.744	0.545	0.557
Sub-Region 2	GPA	0.395	0.965	0.594
	Gaucho	0.672	0.550	0.299
Sub-Region 3	P3	1.00	0.478	0.770
	Gaucho	0.632	0.607	0.270

Indicators of droughts such as 80% or less of average rainfall has a non-exceedance probability of 30% for sub-region 1, and 40% for sub-region 2 and sub-region 3 (Figure 3.22). Therefore sub-region 2 and sub-region 3 are likely to experience frequent droughts compared to sub-region 1.

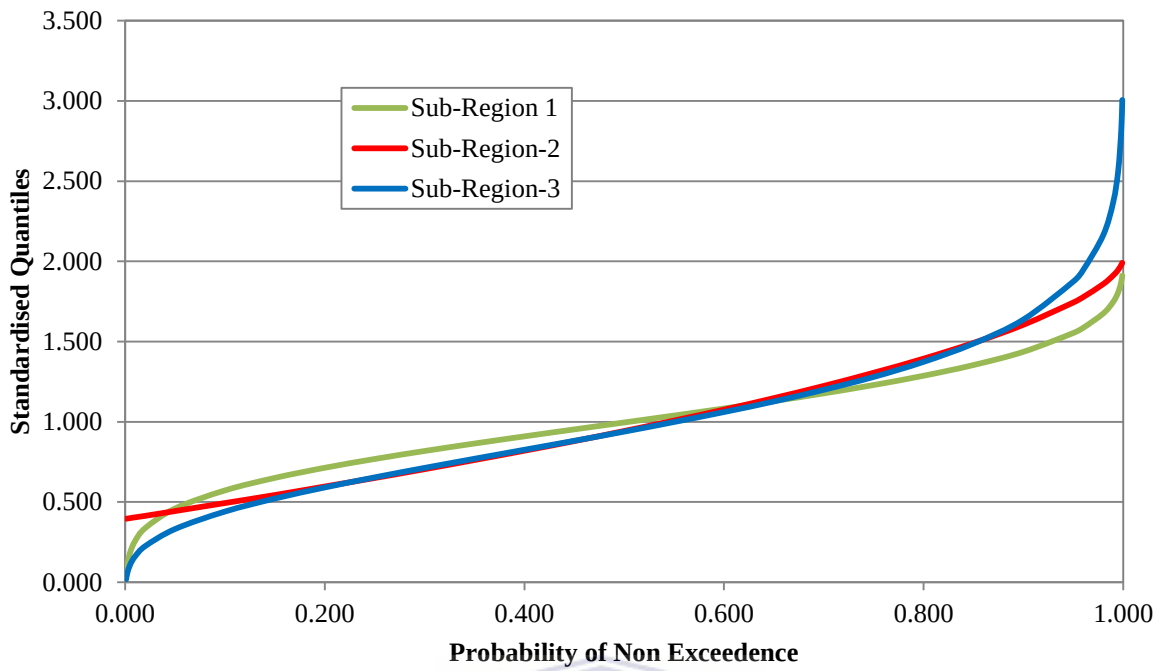


Figure 3.22: Regional growth curve for the 3 homogeneous sub regions, quantiles estimated by the GEV distribution for sub-region 1, GPA distribution for sub-region 2 and P3 distribution for sub-region 3

The return periods, *T(X)*, for the specific quantile is computed;

$$T(X) = \frac{1}{P(X)}\ , \qquad Non - Exceedence\ Probabilty = 1 - P(X) \tag{3.44}$$

where *P(X)* is the probability of exceedance. Using Equation (3.38) and (3.44) the rainfall magnitudes at each specific site in the sub-regions is estimated and the rainfall magnitudes for 10, 20, 30 and 50 years return periods are estimated and shown in Table 3.10. Rainfall magnitudes are likely to remain average or less than average for return periods less than 5 years (Table 3.10). For return periods above 5 years rainfall magnitudes are likely to increase with most increase in sub-region 3 compared to sub-region 2 and sub-region 1. Rainfall magnitudes are likely to increase by more than 40% of average rainfall for return periods of 10 years and above (Table 3.10). Therefore there is a likelihood of increased inundation induced by rainfall in the Okavango Delta every 5 years and above.

Table 3.10: At-Site Rainfall magnitudes for specified return periods

Region	Station	Probability of Exceedence				
		0.50	0.20	0.10	0.05	0.02
		Return Period				
		2	5	10	20	50
Sub-Region 1	Shakawe	522	674	752	814	877
Sub-Region 2	Seronga	435	643	740	805	858
	Ikoga	441	651	750	815	869
	Sepopa	405	599	690	749	799
	Gumare	405	599	689	749	798
	Maun	421	623	717	779	830
	Matsaudi	374	553	637	692	737
	Shorobe	411	608	700	761	811
	Maqwee	377	558	642	698	744
Sub-Region 3	Etsha 6	329	481	574	657	759
	Nokaneng	345	504	601	688	794
	Tsau	341	499	595	681	786
	Sehitwa	338	494	589	675	779
	Toteng	282	412	492	563	650
	Xakanaxa	283	414	493	565	652
	Khwai	282	413	492	563	650
	Gaenga	290	425	506	579	669
	Txaba	258	378	450	515	595
	Khwihum	333	487	581	665	767

3.5 Discussion

Seasonal variation of rainfall is greatly influenced by the migration of the ITCZ (Ratna *et al.*, 2013; Goddard and Graham, 1999). The ITCZ shifts from the upper parts of southren Africa during December, January and February. As a result it affects major parts of the north and the upper eastern parts of the Okavango Delta during December and Januray, then affecting the north and the upper western parts of the delta as it shifts back towards central Africa in February. Therefore, areas around Shakawe, Seronga, Ikoga and Sepopa are likely to have rainfall induced inundation during the months of December, Januray and February whilst Gaenga, Xakanaxa and Khwai are likely to receive rainfall induced inundation in February and areas on the west of the delta, Etsha 6 and Gumare are likely to be more inundated in February. The dry season months show drastic change of spatial pattern from month to month, likely to be induced by localized

weather patterns. The poor correlation of rainfall between stations even at shorter distances is an indication of the dominance of localized and scattered thunderstorms, therefore inducing random localized floodplains inundation. In some studies (Sen and Habib 2001; Ngongondo *et al.*, 2011), the cross correlations are averaged over specific distance to depict a clear correlation decay with distance but this raises the question regarding averaging interrelationship of stations and true representation of rainfall spatial variability. The results of spatial rainfall correlation suggests that neighboring stations do not always receive rainfall within the same period, i.e rainfall received in a station does not imply a possibility of rainfall received in a neighbor station within the same period, such as a month. Therefore rainfall induced inundation is random over space and time.

Due to global warming and climate change, there is a concern that southern Africa is possibly going to experience rainfall decline although there is uncertainty in predictions (Mazvimavi, 2010; Batisani and Yarnal, 2010; Kenabato *et al.*, 2012). Although some studies in Zimbabwe identified a decline in rainfall (Chamaille-Jammes, 2007), Mazvimavi (2010) did not identify any significant trends in rainfall using 40 rainfall stations across Zimbabwe for a period starting from 1892-1940 and ending in 2000. Ngongondo *et al* (2011) found no trends on 42 rainfall stations across Malawi for a period from 1960 to 2006. Similarly, Kampata *et al* (2008) also identified non-significant trend of rainfall using 5 stations across the headstreams of Zambezi river basin in Zambia although one station Mongu showed a regime change around year 1980. The above mentioned findings agree with the results of this study of no significant trends in the selected stations over the Okavango Delta. Other studies in the world revealed significant trends in rainfall. De Luis *et al* (2000) identified significant decreasing trend in annual rainfall with increased concentrations of monthly rainfall in the region of Valencia, Western Mediterranean Basin. Barua *et al* (2012) identified a consistent reduction of rainfall over a period of 50 years in Yarra River Catchment in Australia. Mazvimavi (2010) emphasizes the need to practice caution when testing for change and trends in hydrological time series more especially those with short time series.

Parida and Moalafhi (2008) identified a rainfall regime shift from increasing up to 1981 to a declining rainfall regime using 11 rainfall stations across Botswana. Batisani and Yarnal (2010) made the same conclusion of decreasing rainfall in Botswana using 10 rainfall stations, pointing

out that the conclusion is in agreement with climate change projections for southren Africa. The findings are close to those obtained in this study, where rainfall regime change was detected in 6 rainfall stations; Shorobe in 1973, Gaenga in 1976, Txaba in 1977, from a high to low rainfall regime, Shakawe in 1980 from a low to high rainfall regime, at Sepopa in 1999 from a low to high rainfall regime and at Ikoga in 1999 and 2004 from low to high rainfall regime. A lot of studies have shown that inter-annual variability of summer rainfalls over southern Africa, are a result of ENSO (Nicholson and Entekhabi, 1986; Goddard and Graham 1999; and Nicholson *et al.*, 2001). Therefore the 1976 change at Gaenga and the 1977 change at Txaba might reflect the El Nino episode of 1976 and 1977, the Ikoga and Sepopa change reflecting the 1999 and 2004 La Nina episodes. The floodplain inundation induced by rainfall is therefore likely to follow the ENSO pattern.

Rainfall frequency analysis is an important aspect in predicting how often certain events occur. Although southern Africa is a data scarce region, studies have revealed regional heterogeneity in spatial and temporal rainfall pattern (Ngongondo *et al.*, 2011). Ngongondo *et al* (2011) identified 3 homogeneous regions for extreme rainfall using 23 stations in southern Malawi, following a Generalized Extreme Value (GEV), Generalised Logistic (GLO) and Pearson Type III distributions. Using 11 synoptic stations including Shakawe and Maun in the Okavango Delta, with records from 1961 to 2003, rainfall in Botswana rather showed a homogeneous behavior following the GEV distribution (Parida and Moalafhi 2008). The results of this study showed 3 heterogeneous sub-regions in the Okavango Delta. Therefore compared with results by Parida and Moalafhi (2008) rainfall heterogeneity can be more pronounced at local scales than regional scales. The estimated annual mean rainfall for sub-region 1 is 592 mm/year, 436 mm/year for sub-region 2 and 351 mm/year for sub-region 3. Sub-region 1 is therefore more likely to have more rainfall induced floodplain inundation followed by sub-region 2 then sub-region 3. Rainfall magnitudes increase with increased return periods therefore rainfall induced floodplain inundation is likely to be above normal for rainfall magnitudes with return period above 5 years.

4: CHARACTERISTICS OF OKAVANGO RIVER FLOWS AT MOHEMBO

4.1 Introduction

The main contribution of Okavango Delta water is from the Okavango River flows as a result of rainfall form the highlands of Angola. Therefore, this chapter presents the analysis of flows of the Okavango River at Mohembo (Figure 4.1). This chapter focuses on examining how characteristics of Okavango River flows at Mohembo, such as timing, magnitude and duration vary over time and the implications on floodplain inundation within the Okavango Delta. The general characteristics of the flows at Mohembo are discussed. Change detection, trend analysis, detection of cycilicity and flow frequency analysis are carried out on annual discharge, annual maximum discharge and annual minimum discharge. Change detection is carried out to identify significant change point on the data series and the implication of change on floodplain inundation. There is a general perception by farmers and the general public that reduction in areas inundated in the Okavango Delta is due to decrease in inflows. Therefore, annual time series of flows are tested for any significant trends to establish if inflows into the delta have decreased.There has been a perception that the 1983-2004 period with generally low flows and reduced areas inundated was due to a cyclic behavior of inflows. Therefore an analysis to establish the existence of cyclic behavior is required. Mazvimavi and Wolski (2006) analysed Okavango River flows at Mohembo for change, trends and cyclicity for the 1933-2004 period and at that time low flow period was still persisting. Since the 2009 increase in flows, it is unknown whether the conclusions made by Mazvimavi and Wolski (2006) are still valid. The perception that the frequency of low flows along parts of the Okavango Delta has increased, needs to be tested. Therefore analysis of the frequency of both maximum and minimum flows is necessary. The analysis carried out in this chapter will assist planning by *molapo* farmers and other users of resources within the Okavango Delta.

The major challenge for river flow management is the growing demand of water. Livelihoods, terrestrial and aquatic ecosystems are supported by river flows (Mims and Olden, 2013) and it is therefore important to sustainably manage freshwater. According to Poff *et al* (1997), streamflows shape ecological characteristics of rivers. The specific characteristics of flows such

as magnitude, duration, timing, frequency and rate of change determine the composition, structure and functioning of an ecosystem. Climate change and climate variability, interventions such as construction of dams and large irrigation schemes cause alterations to flow regimes. Although it is important to bring development to communities, maintaining the ecosystem integrity is also important. Developments that modify natural flow regimes result in rivers being unable to support local communities and native species due to the disturbed health of the ecosystem (Poff *et al.*, 1997). River conservation and restoration, is therefore important in order to balance the needs of both human beings and ecosystems.

The management of water resources including flow regimes requires the knowledge of distribution, frequencies and duration of extreme flows. Flow frequency analysis provides information on the number of occurrences specific flows over a specified period; flow duration analysis provides information on the average percentage time during which specific flows may be equalled or exceeded. Flood magnitudes for specified return periods are estimated from flood frequency analysis procedures. Low flow frequency analysis enables estimation of minimum flows needed for maintenance and restoration of the ecosystem. A flow duration curve is important in low flow analysis as the flow exceeded 95% of the time, q_{95}, can be used as an index for water availability in storage design purposes (Dingman, 2002).

One major problem in water resources planning in developing countries is lack of information on water availability. Hydrological models and regionalization of catchment parameters is often used to represent flows in ungauged rivers. This improves understanding of river systems. However the development and configuration of hydrological models is difficult in wetlands, characterized by a complex interplay between the wetland and their catchments and riparian terrestrial ecosystem. Readily developed models are often not necessarily applicable to every hydrological system. Even though the use of information derived from earth observation assists in bridging the data gap of ungauged catchments, satellite derived records are not long enough to capture certain hydrological events and to make conclusive analysis. In this chapter, statistical methods are used to define flow characteristics and assess their implications on Okavango Delta floodplain inundation.

4.2 Materials and methods

4.2.1 Datasets

The Department of Water Affairs (DWA) of Botswana has been measuring river flows at Mohembo since 1933 (Figure 4.1). Monthly measurements were done from 1933 until 1974 after which continuous monitoring was done. Peak flows were derived from the daily discharge data at Mohembo from 1974 to 2014, to make an annual maximum series (AMS). The annual peaks are considered independent of one another as they are selected from data recorded in a hydrological year. A second series of peak flows, Peak Over Threshold/Partial Duration Series (POT/PDS), usually used in extreme flow analysis is filtered from daily discharge as flows above an identified threshold. The threshold was identified using the Mean Excess Plot method (MEP). The time series of minimum flows (AMIN) is filtered from daily flows of 1974 to 2014.

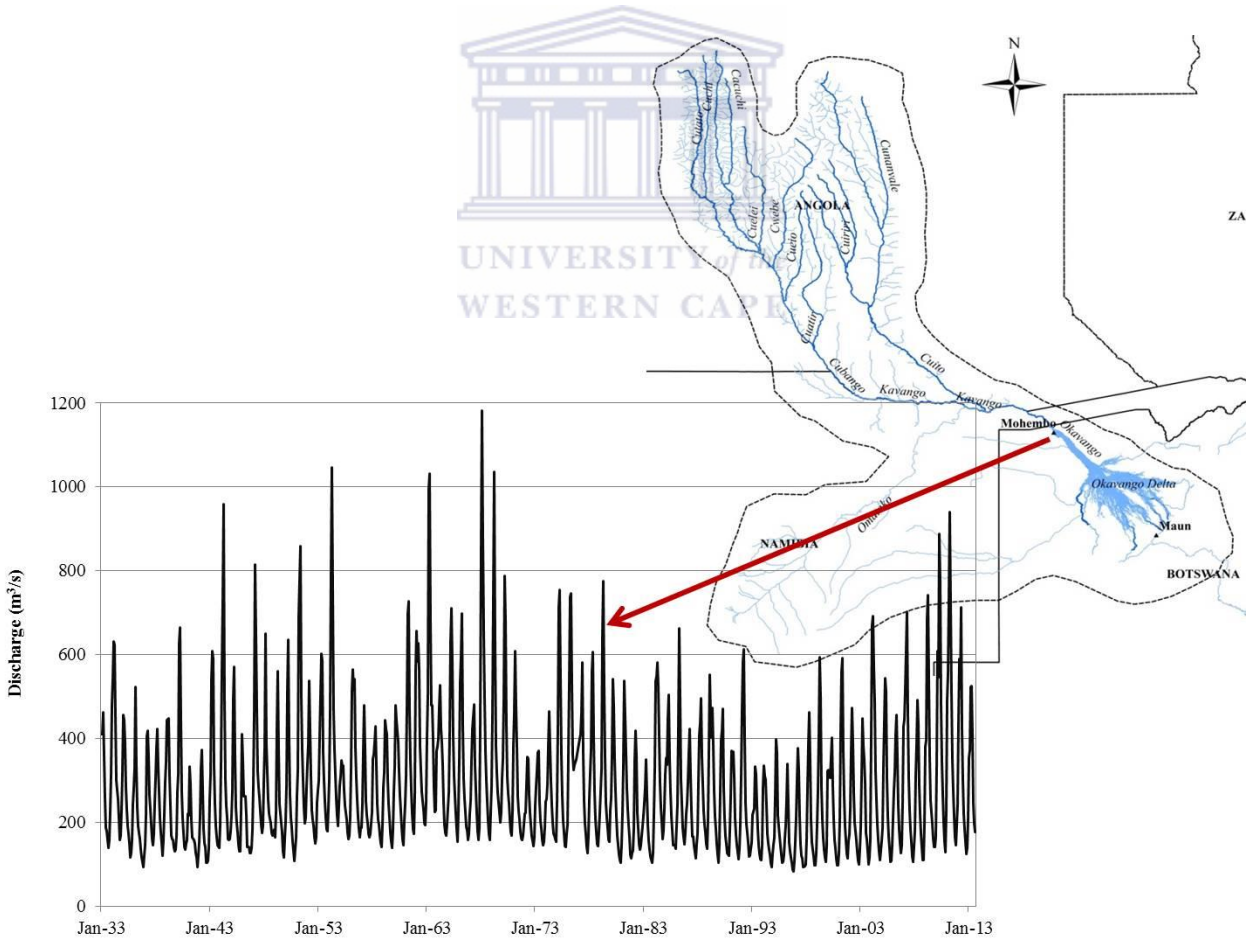


Figure 4.1: Discharge of the Okavango River at Mohembo (1933-2014)

4.2.2 Assessment of change over time

Spectral analysis (Jekins and Priestley, 1957; Fuller, 1996) is undertaken to investigate the presence of a periodic component in the data series. The Pettit test (Pettit (1979) is used for detection of abrupt change (Kang and Yusof, 2012) whilst the Mann-Kendall test is used to identify the existence of trends ((Ngongondo *et al.*, 2011; Barua *et al.*, 2012). It is necessary to ensure that a flow data series is a set of independent data points before examining long term variations of trends or abrupt changes. The data has to be random samples giving no information about the next value that will occur, as an annual maximum or minimum flow in January may be related to an annual maximum or minimum flow in the previous December and creating biasness, therefore autocorrelation test is conducted (Shaw, 1999; Dingman, 2002).

4.2.3 Extreme value analysis

Two commonly used approaches for flood frequency analysis are applied; Annual Maximum Series (AMS) and the Peak Over Threshold or Partial Duration Series (POT/PDS). The methods are primarily used for estimating floods with the POT modelling being a preference as it comprises an extended number of extremes (Rosbjerg and Madsen, 2004). The threshold for filtering the POT series is identified using the Mean Excess Plot procedure. According to Dingman (2002), the threshold for selecting the POT/PDS is typically the value where overbank flow begins. The annual maximum series is analyzed by fitting the General Extreme Value (GEV) distribution. Peak over threshold series was fitted to the Generalised Pareto (GPA) distribution. POT is usually best fit by the Generalised Pareto (GPA) distribution (Rosbjerg and Madsen, 2004; Ngongondo *et al*., 2013). Other studies have shown the Extreme Value/ Gumbel distribution best fit the AMS and, the special case of GPA, the Exponential distribution best fit the POT (Madsen and Rosbjerg, 1993; Mkhandi *et al.*, 2000). The Gumbel (EV1) has been found to be appropriate for annual minimum flows (Shaw, 2002). Therefore the annual minimum flows (AMIN) is fitted to the GEV and the EV1 distributions.

A real valued random variable X with a given probability distribution is found to have a value less than or equal to x. The cumulative distribution function $F(x)$ is the probability that the variate takes the value less than or equal to x and is defined as follows;

Generalised Extreme Value (GEV) distribution

The GEV Cummulative Distribution Function is given by;

$$F(x) = \begin{cases} exp\left(-(1-\kappa z)^{-\frac{1}{\kappa}}\right) \; for \; \kappa \neq 0 \\ exp\big(-exp(-z)\big) \; for \; \kappa = 0 \end{cases}$$

(4.1)

where

$$z = \frac{x-\xi}{\beta}$$

(4.2)

κ is the shape parameter, $\beta$is the scale parameter and ξ is the location parameter estimated using L-Moments

$$\kappa = 7.8590c + 2.9554c^2$$

(4.3)

where

$$c = \frac{2}{3\tau_3} - \frac{ln2}{ln3}, \quad \beta = \frac{\lambda_2 \kappa}{(1-2^{-k})\Gamma(1+\kappa)}$$

(4.4)

Γ is the gamma function

$$\xi = \lambda_1 - \frac{\beta\{1-\Gamma(1+\kappa)\}}{\kappa}$$

(4.5)

The T year return flow, X_T , is then given by;

$$X_T = \xi + \left(\frac{\beta}{\kappa}\right)\left\{1 - \left(-log\left(\frac{T-1}{T}\right)\right)^{\kappa}\right\}$$

(4.6)

<u>Gumbel: Extreme Value Type 1(EV1) Distribution</u>

The special case of GEV distribution is a two parameter Gumbel or Extreme Value Type 1 distribution with $\kappa = 0$. The EV1 cummulative distribution function is given by:

$$F(x) = exp\left[-exp\left(\frac{x-\xi}{\beta}\right)\right] \tag{4.7}$$

where ξ is the location parameter and $\beta$is the scale parameter estimated using the method of moments.

$$\beta = \frac{(6)^{\frac{1}{2}}\sigma}{\pi} \quad and \quad \xi = \mu - (\beta\gamma) \tag{4.8}$$

$$\pi = 3.14159$$

$$\gamma = 0.5772\ (Euler's\ Constant)$$

The *T*-year return flow, X_T, is given by;

$$X_T = \xi + \beta Y_T \tag{4.9}$$

where the Gumbel Reduced Variate,

$$Y_T = -ln\left[-ln\left(1-\frac{1}{T}\right)\right] \tag{4.10}$$

and *T* is the return period in years

<u>Generalised Pareto (GPA) distribution</u>

The GPA Cummulative Distribution Function (CDF) is given by;

$$F(x) = \begin{cases} 1-\left(1+\kappa\frac{(x-\xi)}{\beta}\right)^{-\frac{1}{\kappa}} & for\ \kappa \neq 0 \\ 1-exp\left(-\frac{x-\xi}{\beta}\right) & for\ \kappa = 0 \end{cases} \tag{4.11}$$

The GPA parameter for a given threshold; ξ is the location parameter, κ is the shape parameter, β is the scale parameter and estimated using L-Moments

where

$$\beta = \lambda_1 \left(\frac{1}{\tau_2} - 1\right) \; and \; \kappa = \frac{1}{\tau_2} - 2 \tag{4.12}$$

The T year return flow is given by;

$$X_T = \xi + \frac{\beta}{k}\left[1 - \left(\frac{1}{\lambda T}\right)^{\kappa}\right] \tag{4.13}$$

λ is the expected number of peaks above threshold per year, expressed as the threshold exceedence rate, i.e number of exceedence occurrence n, in t years, assumed to be Poisson distributed (Begueria, 2005) with probability distribution expressed as;

$$p\{n(t) = n\} = exp^{-\lambda t}\frac{(\lambda t)^n}{n!} \quad n = 1, 2, 3 \ldots\ldots where \; \lambda = \frac{n}{t} \tag{4.14}$$

Exponential (EXP) Distribution

The Exponential distribution is a two parameter distribution; a special case of GPA with $\kappa = 0$ (Rosbjerg and Madsen 1993).The EXP cumulative distribution function is given by;

$$F(x) = 1 - \exp\left(-\frac{x - \xi}{\beta}\right) \tag{4.15}$$

The EXP parameter for a given threshold ξ is the location parameter, β is the scale parameter estimated using the maximum likelihood approach. The T year return flow is therefore given by;

$$X_T = \xi + \beta \mathrm{LN}(\lambda T) \tag{4.16}$$

Mean Excess Plot

Threshold selection for filtering the POT series is conducted using the Mean Excess Plot (MEP). If GPA is a valid model for excesses over some threshold u_0, then it is valid for excesses over all thresholds $u > u_0$ (Fawcett, 2013).The expected value of the threshold excesses, being greater than the threshold is (Cole, 2001; Fawcett, 2013);

$$E(X - u|X > u) = \frac{\beta_{u_0} - \kappa u}{1 + \kappa} \tag{4.17}$$

where β_{u_0} and κ are the GPA scale and shape parameters for excesses over the threshold u_0. $E(X - u|X > u)$ is the mean of u, the excesses of threshold. For all $u > u_0$, $E(X - u|X > u)$ is a linear function of u. The MEP is a plot of mean threshold excess against u and the value u_0 is above where there is linearity in the plot (Cole, 2001; Fawcett, 2013).

Goodness-of-fit to Extreme Distributions

The Kolmogorov-Smirnov (KS) test is used for the goodness-of fit test. The KS test is based on the largest vertical distance between the theoretical and empirical CDF and the null (H_0) hypothesis and the alternative hypothesis (H_A) are;

H_o: *The data follows the specified distribution*

H_A: *The data do not follow the specified distribution*

The KS test statistic (D) is defined as (Finkelstein and Schafer, 1971);

$$D = max\left(\left|F(X_i) - \frac{i-1}{n}\right|, \left|\frac{i}{n} - F(X_i)\right|\right), \qquad i = 1, 2, \dots, n \tag{4.18}$$

where F is the theoretical cumulative distribution of the probability distribution being tested, X_i are ordered data points from smallest to largest value and n is the number of data points. The null hypothesis is rejected if D is greater than the critical value at $\alpha = 0.05$ significance level.

4.3 Results

4.3.1 General characteristics of flows

4.3.1.1 Daily flows

The hydrological year is from October to September (Figure 4.2). Within a hydrological year, flows are low from October till mid-December to January when they start rising. The flows continue rising until they reach a maximum in March to May and starting to decline in June. Daily discharge at Mohembo shows two peaks. The first peak takes place around February and there is a second peak which is the maximum peak occurring between March and May. In some instance two second maximum peaks follow each other by 3 to 5 days before the flows recede in a year. The daily flows continue to decrease till they reach minimum flows in September/October. During peak flows around March and April, average daily flows can exceed 628 m^3/s and can be below average daily of 109 m^3/s around October to December.

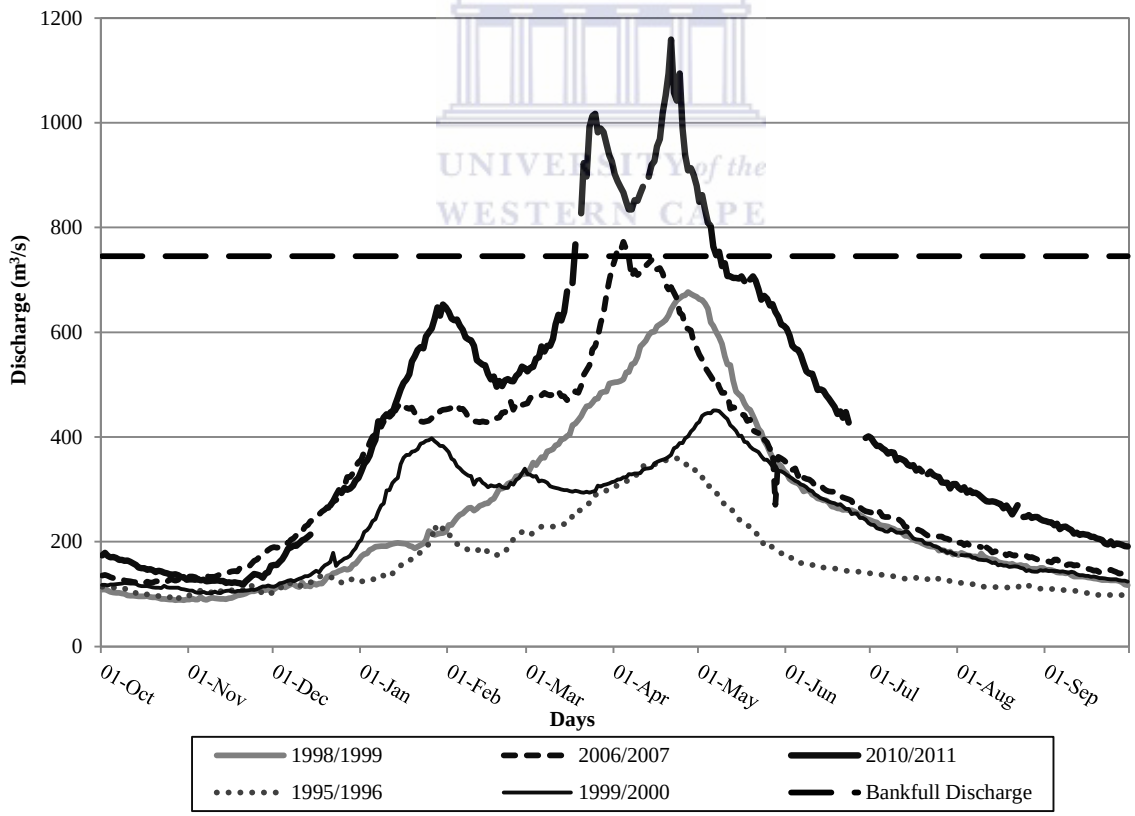


Figure 4.2: Different hydrographs of Okavango River at Mohenbo, for selected years showing different peak; 1995/1996 an 1999/2000 with a peak much lower than bankfull discharge; 1998/199 and 2006/2007 with a moderate peak close to the bankfull discharge; and 2010/2011 with a peak above bankfull discharge

According to the inflow records at Mohembo station, the peak flows entering the Okavango Delta at Mohembo were high in 1969 which was 950 m^3/s. Forty years later, in 2009 a peak flow of 969m^3/s was recorded higher than the 1969 value. The flow peaks were even higher in 2010 and 2011, 1150 m^3/s and 1159 $m^3/$ respectively. Over the period of 1974 to 2014, the observed maximum daily flow is 1159.04 m^3/s, the mean daily flow is 276.74 m^3/s and the observed minimum daily flow in record is 62.56 m^3/s.

4.3.1.2 Monthly and seasonal flows

April is responsible for highest long-term average monthly flows at Mohembo although in some years the highest mean monthly flow is experienced in March or May (Figure 4.2 and Figure 4.3). The lowest long-term mean monthly flows are in November and again in some years lowest are in October or December. With the above being the case, February contains the highest long-term average maximum flow and the lowest long-term average minimum flow is in November. The long-term (1933-2014) mean monthly flow is 292.48 m^3/s, mean monthly maximum is 577.48 m^3/s and mean monthly minimum is 136.60 m^3/s. Monthly flows vary most during the high flow period (February to June) than during the low flow period (July to January). The coefficient of variation is highest in January at 41% and lowest in September at 24%. The monthly maximum and minimum fall outside one-standard deviation of the individual monthly mean (Figure 4.4). The maximum flow deviates considerably from the monthly means during the high flow period from February to June and the deviation is low from July to January.

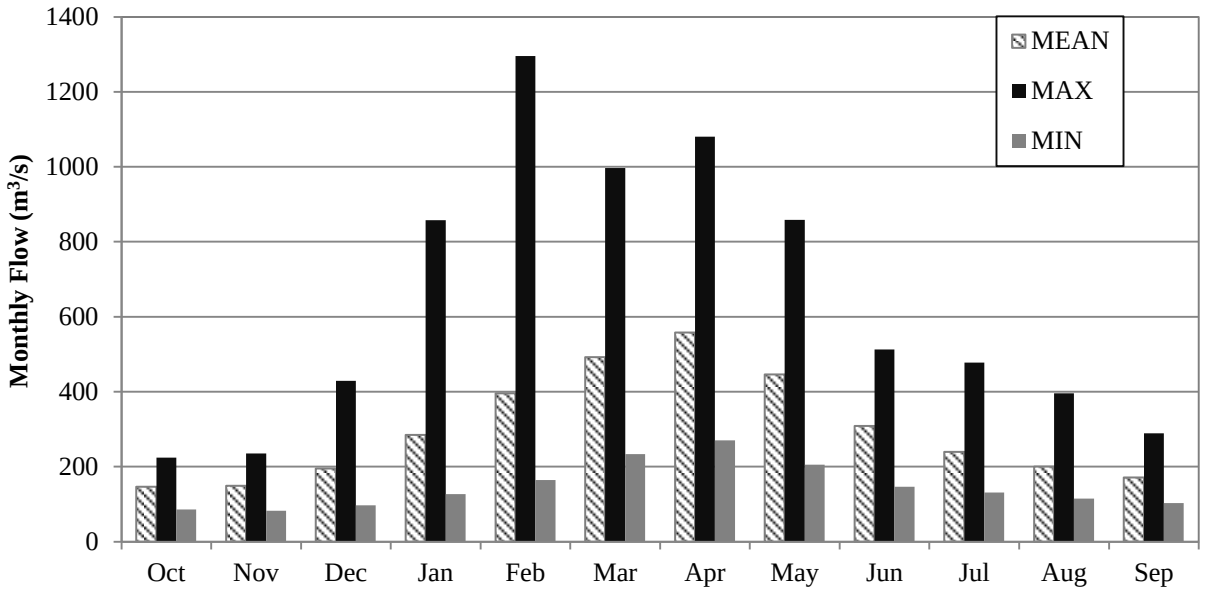


Figure 4.3: Long-term mean, maximum and minimum monthly flows of Mohembo station (1933-2014)

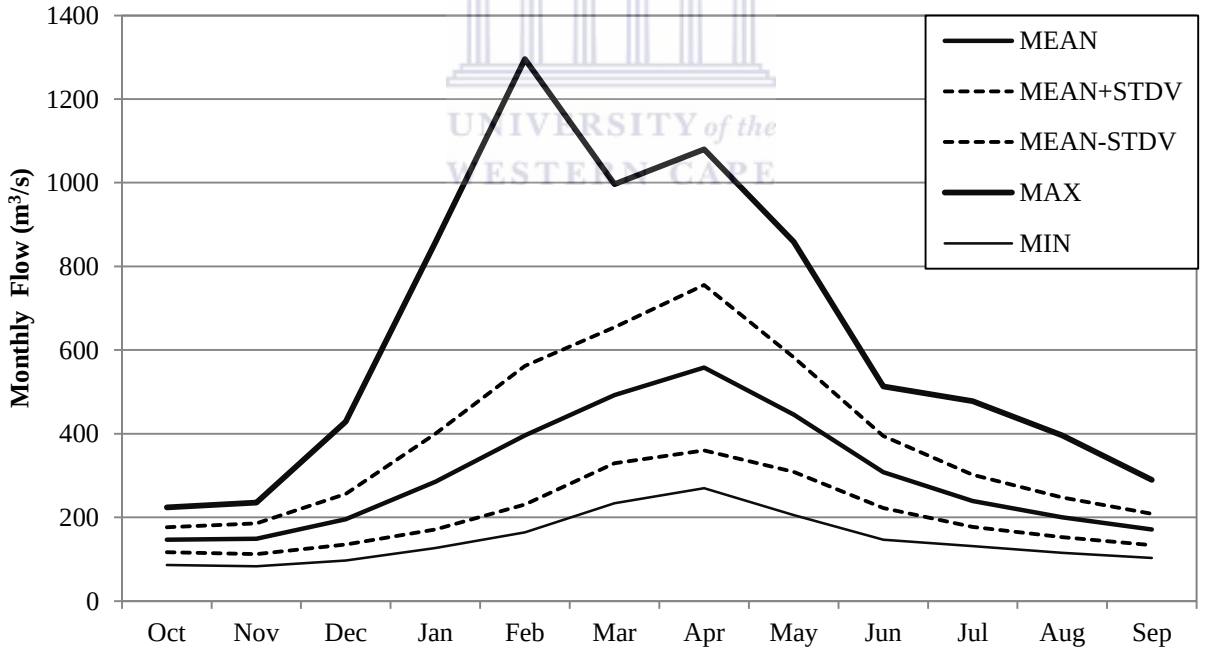


Figure 4.4: Long-term deviation of maximum and minimum monthly flows from the mean flow of Mohembo station (1933-2014)

4.3.1.3 Annual flows

The long-term (1933-2014) mean annual flow at Mohembo is 298 m^3/s with standard deviation of 74 m^3/s and coefficient of variation 25%. Most of the annual flows fall within one standard deviation, i.e 72% of the flows do not deviate significantly from the long term mean, whilst the remaining 28% of the annual mean flows falls outside the one standard deviation, with 11% on the extreme high and 11% on the extreme low (Figure 4.5). The annual flows within one standard deviation fall in the range of 230 m^3/s to 370 m^3/s.

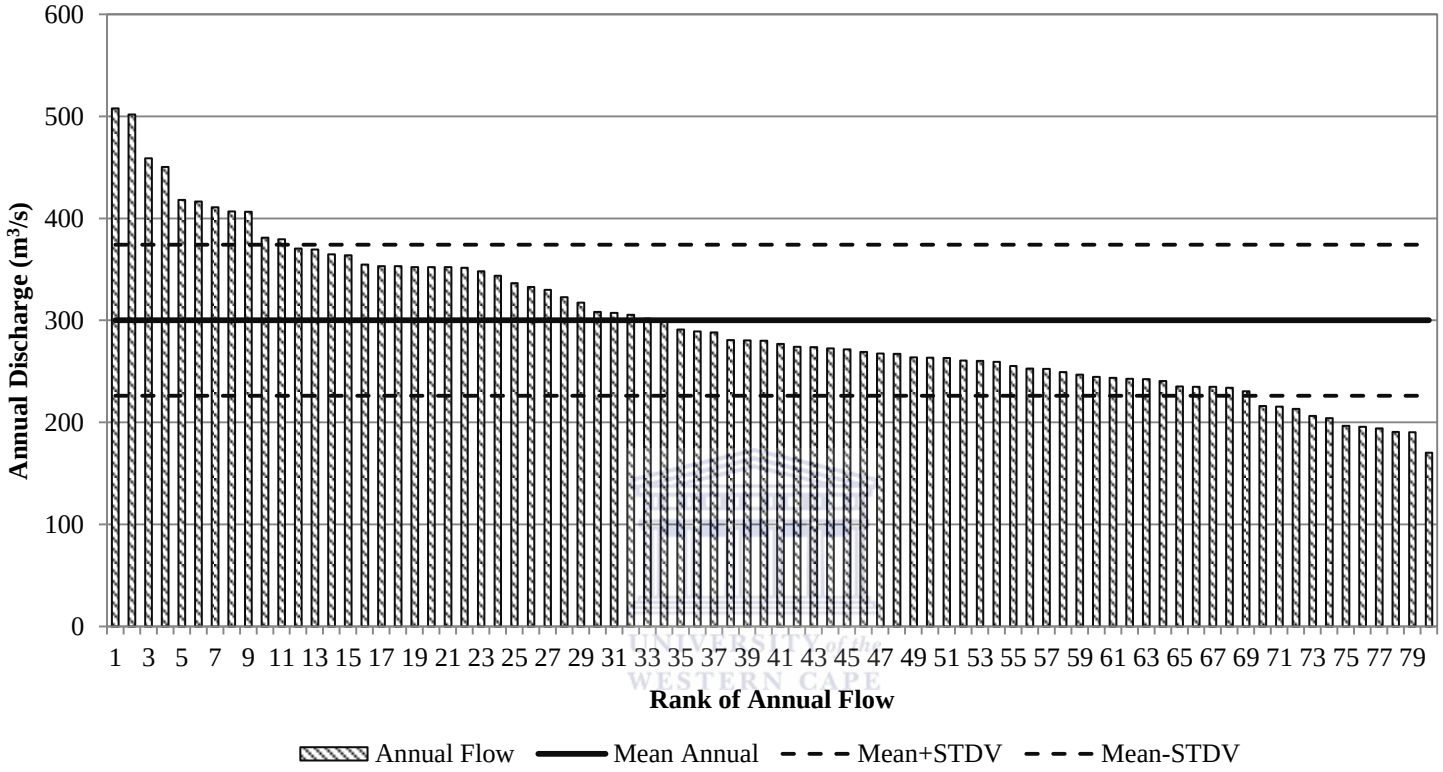


Figure 4.5:Ranked Mean Annual Flow at Mohembo for the Record Period (HY: 1933-2014) showing flows falling inside and outside one standard deviation.

4.3.1.4 Long term variation

Flows at Mohembo vary over time. The data series tested for independence are as follows; annual flow of 1933 to 2014, annual flows of 1974 to 2014, annual maximum series of 1974-2014 and annual minimum Series of 1974 to 2014. All the tested time series have a positive autocorrelation coefficient up to lag 2 except annual flow series of 1974-2014 (Figure 4.6). Thus flows at Mohembo have a positive autocorrelation at lags below 2 years. There is a tendency of years with high or low flows following each other as the serial correlation coefficient is significant at lag 1 for all the data series, at 5% significance level (Figure 4.6).

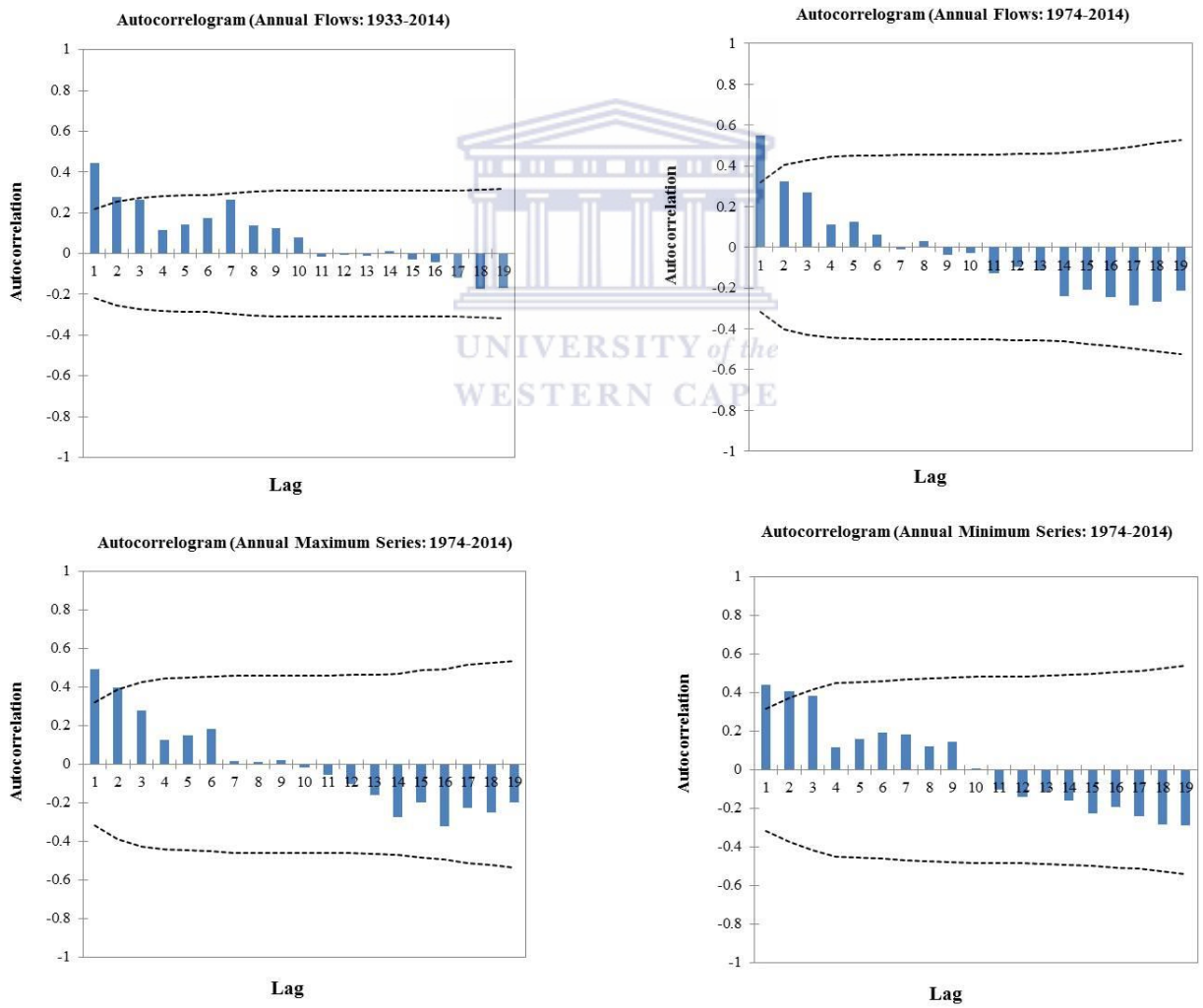


Figure 4.6: Autocorrelation coefficients of the annul flows, annual maximum series and annual minimum series at Mohembo at 5% significance level; Dotted line showing lower and upper bound

Percent deviation of annual flows from the mean is shown in Figure 4.7 below and wet or dry years tend to form groupings of 4 years to 5years. There was an extreme wet period in the 1960's of about 10 consecutive years of above average and an extreme dry period in the late 1990's of another 10 consecutive years below average (Figure 4.7). The cumulative departures of annual flows were estimated (Figure 4.8) to determine the long term variation of annual flows. Cumulative departures form the mean also show a tendency of wet years to follow each other as shown in Figure 4.8. Long term accumulation of flows shows a decrease until 1950's when flows started to persistently increase for about 30 years, until 1980's, a 30 years period of persistent decrease in flow accumulation was observed from 1980's until 2009 when flow accumulation started to indicate increase again (Figure 4.8).

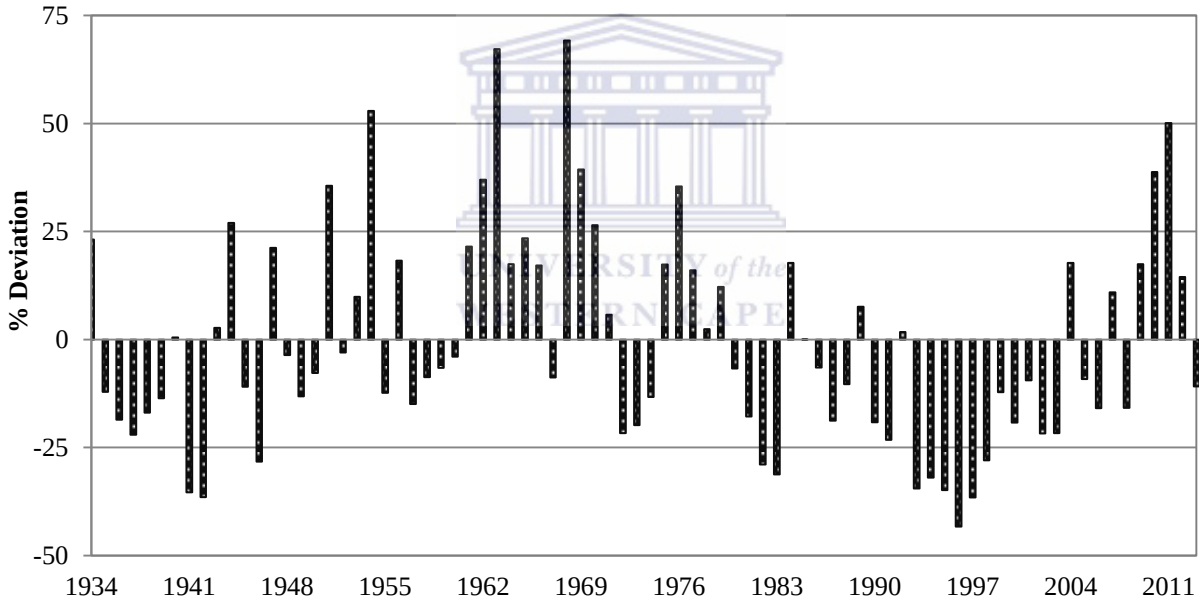


Figure 4.7: Deviation of Annual Flow from Mean Flow for Period of Record, Mohembo (1933-2014)

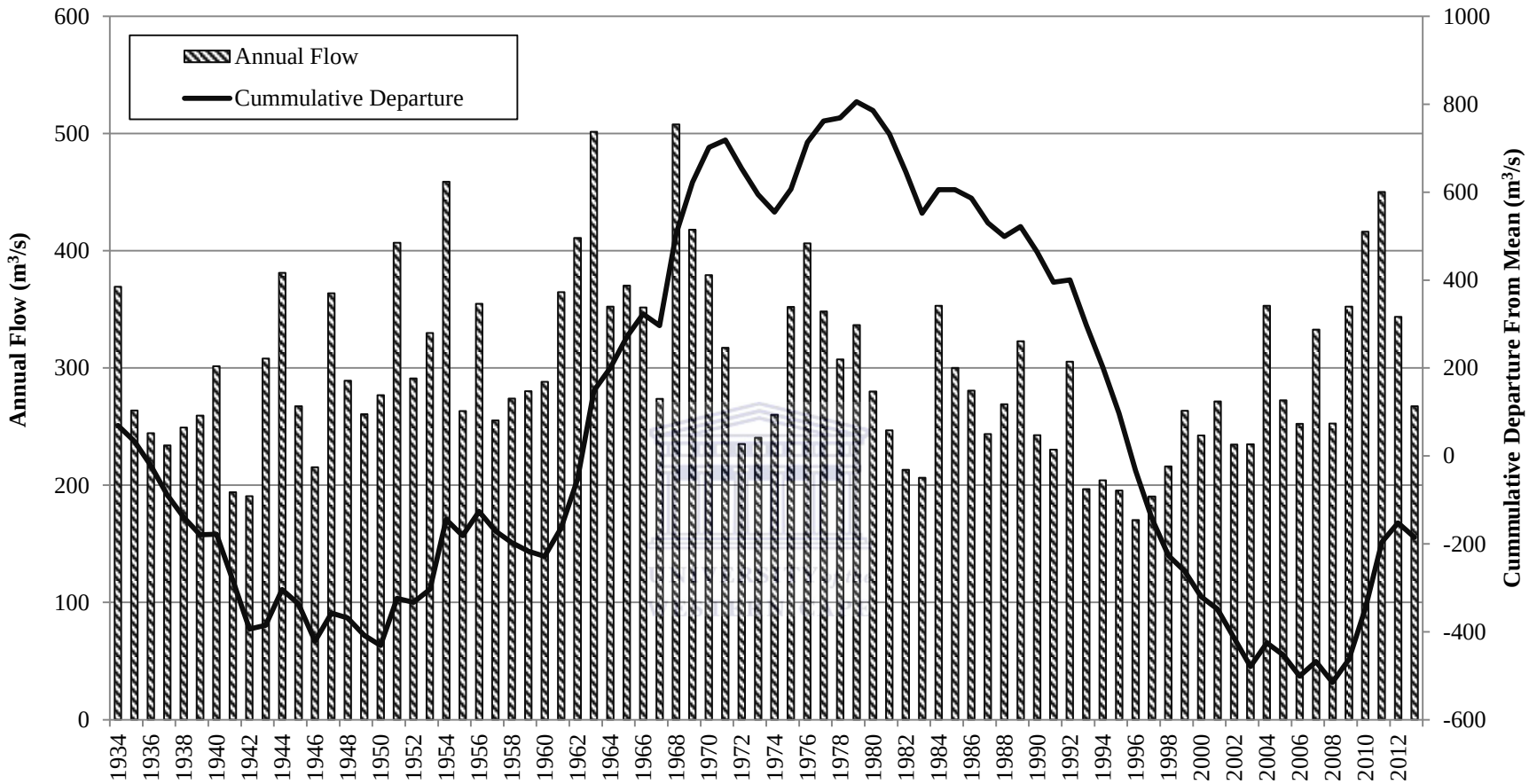


Figure 4.8: Annual Flow and Accumulated Departure Series for Mohembo; An ascending plot indicates periods of persistently above average flows, a descending plot indicates periods of persistently below average flows and a plot indicates flows near the long term mean

4.3.2 Assessment of change over time

4.3.2.1 Abrupt change

A significant change point is identified in 1979 on the annual flow of 1933-2014 and in 1988 for the annual minimum series. Change points are identified for annual flows (1974-2014) and annual maximum series in 2003, although they are not statistically significant therefore concluded as no change points (Table 4.1). Record length can affect the location of change point (Mazvimavi and Wolski, 2006). Using two series of annual flow with different record length; 1933-2014 series and the 1974-2014 series, different change points 1979 and 2003 were identified (Table 4.1). The annual flow series of 1933-2014 and the minimum flow series of 1974-2014 changed in 1979 and 1988 respectively from a high flow regime to a low flow regime (Figure 4.9). Since 1979-1989 there have never been significant land use changes along the Okavango river basin, therefore the change points are not likely due to land use change (Mazvimavi and Wolski, 2006). The change points imply that the areas inundated reduced by the year 1979 and 1988.

Table 4.1: Pettit test results for change detection; significant change is *p*-value < 0.05 and X_k > Critical Value

VARIABLE	*N*	Crtical Value	*p*-VALUE	X_k	Change Point
Annual Flow (1933-2014)	81	393	0.046	550	1979
Annual Flow (1974-2014)	40	167	0.103	155	2003
Annual Maximum Series (1974-2014)	40	167	0.074	161	2003
Annual Minimum Series (1974-2014)	40	167	0.003	220	1988

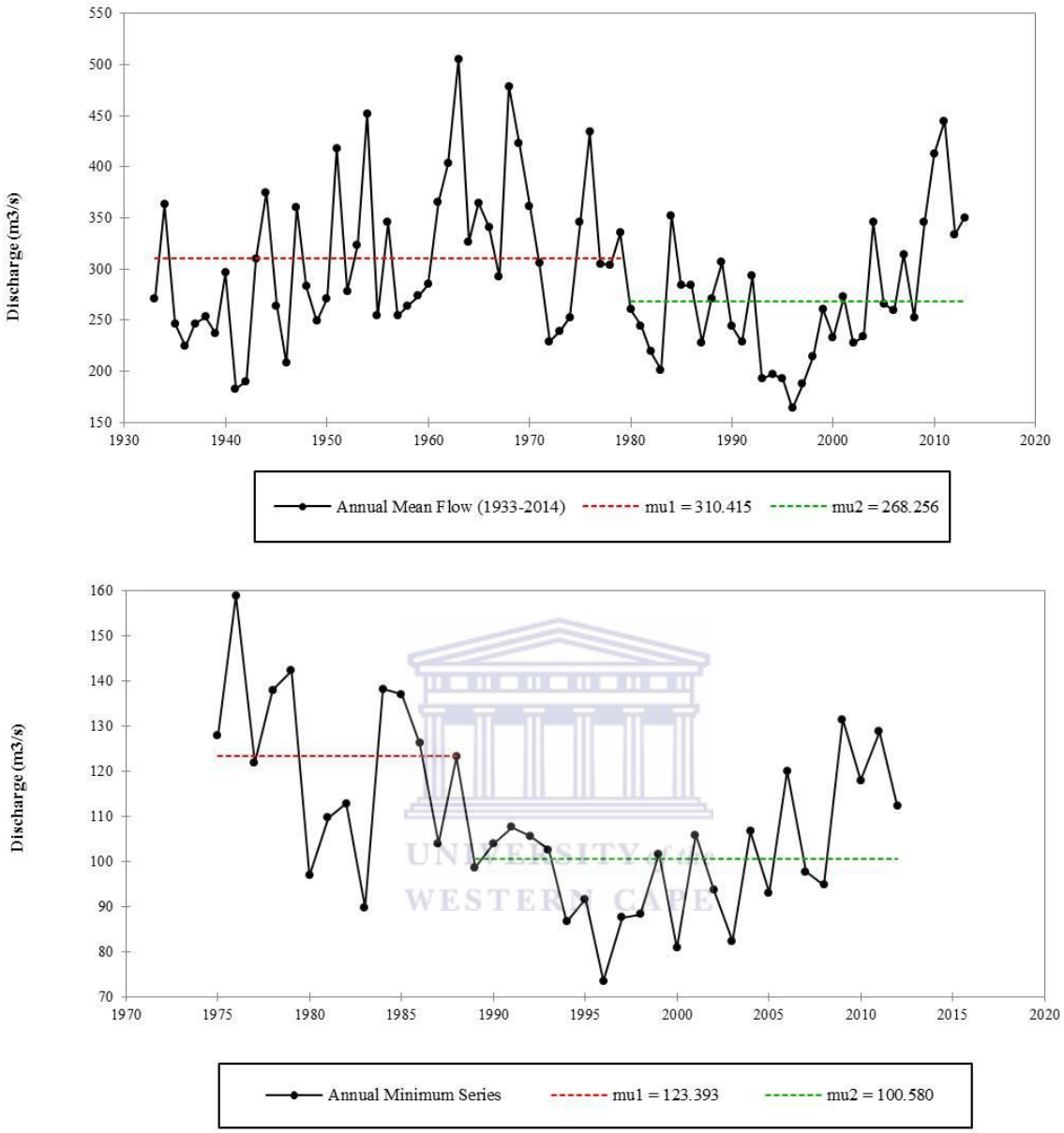


Figure 4.9: Annual flows (1933-2014) and Annual minimum Series showing abrupt change 1979 and 1988 respectively

4.3.2.2 Trend detection

The results of the Mann-Kendal trend test shows no significant trends at the 5% significance level for all the data series except for the annual minimum series which has a significant negative trend (Table 4.2). The results correspond with what was obtained by Mazvimavi and Wolski (2006) of no significant trends for annual flows and annual maximum flows and a significant decreasing trend for annual minimum flows for the period of 1933 to 2000. Two series of annual

flows, 1933-2014 and 1974-2014 shows different trend directions although the trends are not significant (Table 4.2). The annual series of 1933-2014 has a negative slope while the annual series 1974-2014 has a positive slope. Therefore trend direction may change depending on the length and the period of the series tested.

Table 4.2: Trend analysis (Mann-Kendall trend test) at 5% significance level

VARIABLE	N	*p*-VALUE	SLOPE	TREND
Annual Flow (1933-2014)	81	0.639	-0.16	No
Annual Flow (1974-2014)	40	0.96	0.017	No
Annual Maximum Series (1974-2014)	40	0.784	1.283	No
Annual Minimum Series (1974-2014)	40	0.032	-0.724	Yes

Mazvimavi and Wolski (2006) did not identify trends for the 1933-2004 periods. The findings are still valid even after the 2009 increase in flows. The perception by the public of decreasing inflows into the Okavango Delta is therefore not valid. This implies that any reduction in areas inundated cannot be associated with decrease in inflows, as there are no significant trends in either annual flows or annual maximum flows. The decreasing trend of minimum flows implies that magnitudes of minimum flows are decreasing and therefore during low flow season areas inundated in the Okavango Delta are likely to be highly reduced over time.

4.3.2.3 Cyclicity

Using both Fisher's Kappa test and the Bartlett's Kolmogorov-Smirnov test, the times series of annual flow (1974-2014), annual maximum flows (1974-2014) and annual minimum flow (1974-2014) are all identified to be significantly different from a white noise with *p*-values less than 0.05 (Table 4.3). The time series for annul flow (1933-2014) is identified to be significantly

different from a white noise by only the Bartlett's Kolmogorov-Smirnov test (Table 4.3). Therefore significant cycles exist in the tested time series.

Table 4.3:Statistical results for determining presence of significant cyclic behaviour

	Fisher's Kappa		Bartlett's Kolmogorov-Smirnov	
VARIABLE	**Value**	***p*-value**	**Value**	***p*-value**
Annual Flow (1933-2014)	6.063	0.065	0.349	< 0.0001
Annual Flow (1974-2014)	8.411	0.000	0.547	< 0.0001
Annual Maximum Series (1974-2014)	8.585	0.000	0.509	< 0.0001
Annual Minimum Series (1974-2014)	8.750	0.000	0.486	0.000

To identify the top 5 most important cycles for each series, both the periodogram values and the spectral density values were ranked in descending order. Except for the annual mean flow (1933-2014) series the ranked periodogram values and the spectral density values are in agreement in identifying the top 5 most important cycles in each series (Table 4.4). The annual flow series of 1933-2014 has 81 years, 40.5 year and 20.5 as the top 3 most important cycles whilst the annual flow series of 1974-2014 has 38 years, 12.7 years and 19 years as the top 3 most important cycles. The annual maximum series has 38 years, 19 years and 12.7 years as the top 3 most important cycles and the annual minimum series has 38 years, 7.6 years and 2.5 years as the top 3 most important cycles.

The existence of cycles in the Okavango River flows explains the previous periods of persistent low flows and drying of certain floodplains and periods of persistent high flows increasing inundated areas within the floodplains of the Okavango Delta. Due to the cyclic behavior of the inflows into the delta, there will be periods of low flows reducing inundated areas and periods of high flows with increased areas inundated within the delta.

Table 4.4: Rank and duration of 5 most important cycles in the different annual series

Rank	Annual Flow Series (1933-2014)		Annual Flow Series (1974-2014)		Annual Maximum Series (1974-2014)		Annual Minimum Series (1974-2014)	
	Peridiogram Cycle	Spectral Density Cycle	Peridiogram Cycle	Spectral Density Cycle	Peridiogram Cycle	Spectral Density Cycle	Peridiogram Cycle	Spectral Density Cycle
1	81	40.5	38	38	38	38	38	38
2	40.5	81	12.7	12.7	19	19	7.6	7.6
3	20.5	20.5	19	19	12.7	12.7	2.5	2.5
4	11.5	27.5	3.2	3.2	6.3	6.3	12.7	12.7
5	8	7	2.5	2.5	2.9	2.9	2.7	2.7

4.3.3 Flow Frequencies and Probabilities

4.3.3.1 Flow Frequency Analysis

40-year (1974-2014) of daily flow values is used to conduct flow frequency analysis. The probability of exceeding the mean daily flow of 276.74 m^3/s is 39.5%. The overall historical variation of flows can be depicted from an FDC. From the slope of the Mohembo FDC (Figure 4.10) a gradual decrease from high flows to lows can be observed. The flow rate equaled or exceeded 95% of the time, q_{95} is 107 m^3/s and the flow exceeded only 5% of the time q_5 is 607 m^3/s.

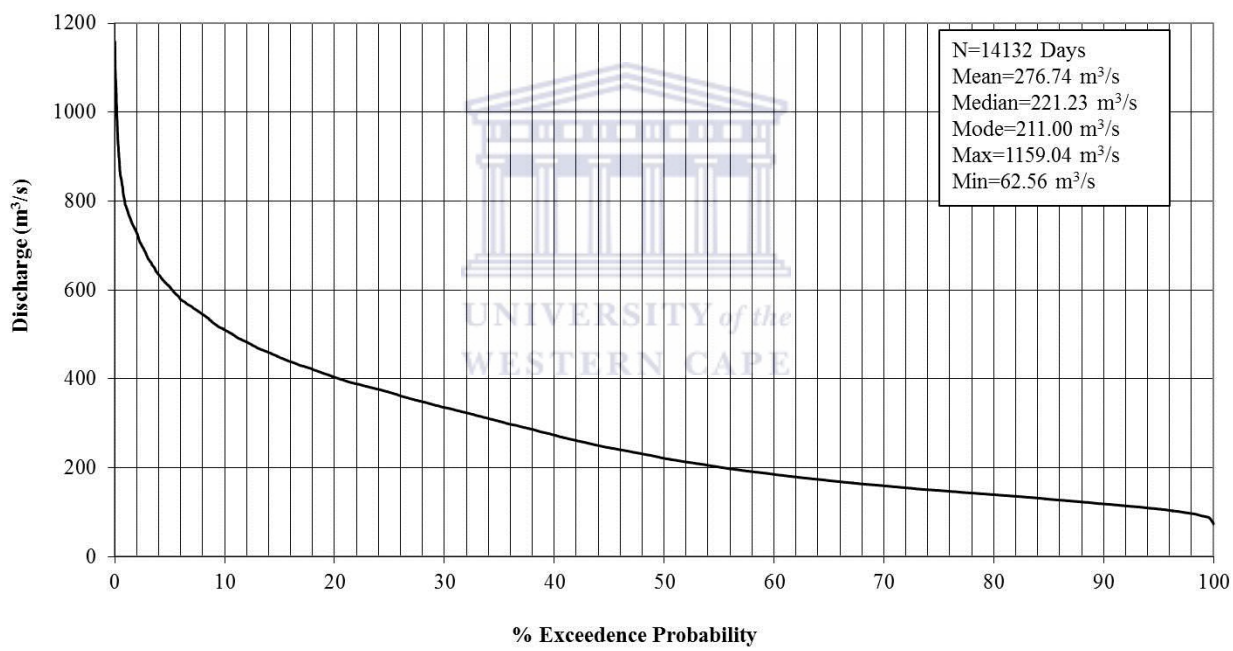


Figure 4.10: Flow Duration Curve for Okavango River at MOHEMBO deduced using the 1974-2014 daily series.

4.3.3.2 Flood Frequency Analysis

4.3.3.2.1 Distribution Fitting

Using the flow data of Mohembo station from 1974 to 2014 to depict the annual maximum flow, 39 data points were obtained to create an annual maximum series (AMS). From the mean excess plot (Figure 4.11), the identified threshold is 700m^3/s, therefore the POT series is filtered for all values above the threshold and 84 data points were filtered to create a POT series.

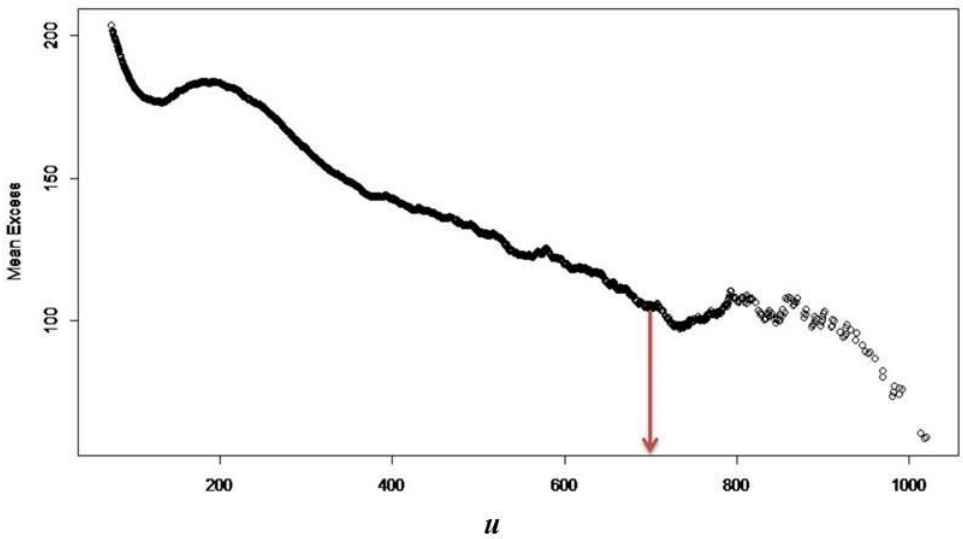


Figure 4.11: A plot of Mean Excess for Okavango River at Mohembo (HY: 1974-2004), Threshold 700m^3/s

The GEV and the EV1 distributions are fitted to the AMS with the GPA and EXP distributions fitted to the POT series. Kolmogorov-Smirnov (KS) is used to test how best the fitted distributions define the time series at significance level $\alpha = 0.05$ and the results are shown in Table 4.5. The *D* statistic values are less than the critical values and therefore accept the null hypothesis that the flows follow the specified distributions.

Table 4.5: Statistical Results of Goodness of Fit for the Distributions Fitted to the Extreme Series

Series	Sample Size	Distribution	Critical Value	*D*
AMS	39	GEV EV1	0.2154	0.0755 0.0876
POT	84	GPA EXP	0.12555	0.0753 0.0744
AMIN	40	GEV EV1	0.2101	0.1091 0.1199

4.3.3.2.2 Flood Prediction

Over a long period, the *T*- year event, X_T has an average chance of exceedance once every *T* years. However, in a period of *n* years the actual probability of exceedance of a *T* year flood is given by (Shaw, 1999);

$$P_n(X_T) = 1 - \left(\frac{T(X_T) - 1}{T(X_T)}\right)^n \tag{4.19}$$

Using Equation (4.6), (4.9), (4.13) and (4.16) estimations of return floods are done for specified return periods. The probability of exceeding the flood magnitudes for specified return periods within a period of 40 years (1974-2004) within the Okavango Delta is estimated using Equation (4.19). Estimated flood magnitudes for specified return periods and exceedance probabilities are shown in Table 4.6.

Table 4.6: Return floods non-exceedance probabilities for specified return periods estimated using Annual Maximum Series (AMS) by GEV and EVI distributions and Peak Over Threshold Series (POT) by GPA and EXP distributions

Probabiity of Exceedance (%)	Return Period (Years)	AMS		POT	
		GEV	EV1	GPA	EXP
		X_T (m^3/s)			
99.99	2	712.87	595.52	850.71	854.06
99.98	5	874.32	771.54	942.56	949.11
98.52	10	977.15	888.07	1011.45	1021.01
87.15	20	1072.84	999.86	1079.82	1092.91
74.23	30	1126.62	1064.17	1119.58	1134.97
63.68	40	1163.99	1109.51	1147.68	1164.81
55.43	50	1192.58	1144.56	1169.42	1187.96
33.10	100	1279.34	1252.99	1236.62	1259.86
18.17	200	1363.34	1361.02	1303.31	1331.76

A flood magnitude which is close to the highest flow on record 1159 m^3/, is 1164 m^3/s estimated using the AMS by the GEV distribution and 1165 m^3/s estimated using the POT by the EXP distributions, with a return period of 40 years. The probability of exceeding a 40 year return flood is 64%. The most recent flood magnitude which induced extreme inundation in the

Okavango Delta is 2009 flood at 969 m^3/s, therefore the estimated return flood just above the 2009 flood is 977 m^3/s estimated using AMS and 949 m^3/s estimated using POT. The estimated flood magnitudes close to the 2009 flood have return period of 10 years with probability of exceedance of 98.52% when using the AMS fitted to the GEV distribution and a return period of 5 years with probability of exceedance of 99.98% using the POT series fitted to the EXP distribution. The probability of experiencing high inundation condition every 5 years or 10 years in a period of 40 years is therefore very high.The AMS fitted to a GEV distribution or the POT fitted to the EXP distribution are best for water resources planning in the Okavango Delta as they both give return floods close to reality.

4.3.3.3 Low Flows Frequency Analysis

4.3.3.3.1 Distribution Fitting

40 data points of annual minimum flows were filtered from Mohembo daily flow data of the period 1974 to 2014 to form an Annual Minimum (AMIN) series. Two distributions; GEV and the EV1 are fitted to the AMIN data series to conduct low flow frequency analysis. Using the statistical approach KS, for goodness of fit test, the annual minimum series fits best to both the GEV and the EV1 (Table 4.5).

4.3.3.3.2 Low Flows Prediction

The estimated minimum flows are all above the lowest flow value, 62.56 m^3/s in record. The lowest estimated minimum flow is 104.48 m^3/s with return period of 2 years and 99.99% probability of exceedance (Table 4.7). Therefore the probability of occurrence of the very low flow in record is a very rare case. The average minimum flow is 109 m^3/s. The estimated lowest flows which are just above the average minimum flow, are 137 m^3/s and 130 m^3/s with return periods of 2 years and 5 years respectively. The probability of exceeding the two lowest estimated minimum flows still remain high; therefore the perception of increased occurrence of minimum flows is not valid. Therefore the reduction in inundated areas within the Okavango Delta is not due to increased frequency of lows flows.

Table 4.7: Low flows predictions and probability of non-exceedence for specified return periods estimated using Annual Minimum Series (AMIN) by GEV and EV1 distributions

Probabiity of Exceedence (%)	Return Period (Years)	AMIN	
		GEV	EVI
		X_T (m3/s)	
99.99	2	137.16	104.48
99.98	5	185.38	130.24
98.52	10	226.09	147.3
87.15	20	268.61	163.66
74.23	30	304.84	173.08
63.68	40	329.16	179.71
55.43	50	349.27	184.84
33.1	100	419.5	200.71
18.17	200	503.38	216.52

4.4 Discussion

Analysis of variations of streamflows has been conducted in several studies. A study by Alemaw and Chaoka (2006) suggested some linear correlation between streamflow and warm ENSO indices in some parts of southern Africa during the 1950-1998 period. Analysing streamflow for 9 stations along the Limpopo catchment in Botswana, Batisani (2011) did not find any association of streamflow variation with either climate change or ENSO episodes. The streamflows rather showed a random behavior with minimal significant trends that could be associated with antrophogenic activities (Batisani, 2011). Significant change points are identified in 1979 on annual flows and in 1988 on minimum flows from a high flow regime to low flow regime of the Okavango River flows at Mohembo. The change points cannot be associated with human intervention, major land use changes or abstraction since the Okavango River Basin as a whole has never had any land use changes before 1989. Mazvimavi and Wolski (2006) also identified the significant change points on Mohembo flows for annual flows, annual maximum flows and annual minimum flows during the 1979-1989 period. Southern Africa is a region of high hydrological variability, experiencing extreme floods and droughts (Ngongondo *et al*., 2013) and climate change is expected to increase the challenges associated with water availability (Batisani ,2011; Love *et al.*, 2010). The Okavango river flows do not show any significant trends, therefore there are not yet detectable changes due to climate change. However there is a decreasing trend in annual minimum flows and this can be explained by the persistent low flow period in the Okavango River flows before the 2009 high flow event.

Before the year 2004, an apparent decline of inflows into the Okavango Delta was experienced of which Mazvimavi and Wolski (2006) associated it with an existing cyclic component of inflows into the delta rather than trends and sudden changes in flows. The Okavango River inflows at Mohembo have three important cycles of close to 10, 20 and 40 years. The results are close to what was obtained by Mazvimavi and Wolski (2006) of 17.5 and 7.8 years cycles in the Okavango river flows. The identified cycles correspond with the return period of a flood event above 969 m^3/s and above 1159 m^3/s, which suggests that maximum inundation in the Okavango Delta can be observed every 10 or 40 years. The chance of exceeding the one day maximum of over a 969 m^3/s within a period of 40 years is 98.52% with reccurence interval of 10 years and the chance of exceeding the one day maximum of over a 1159 m^3/s within a period of 40 years, is 64 % with reccurence interval of 40 years. The flow value of 969 m^3/s is the maximum reached in 2009 and 1159 m^3/s is the maximum in record. These two maxima caused major flooding in the Okavango Delta. The frequency of low flows does not indicate any increase, therefore the perception of associating decrease in inundation to increased low flows is not valid. Increase and decrease in inundation can be associated with the cyclic behavior of the Okavango River flows.

It is important to identify the best distribution model for a specific data series to conduct frequency analysis, but a lot of studies concentrates on regional flood frequency analysis to identify homogeneous regions and their best fitting distribution (Makhandi *et al.*, 2000; Kjeldsen *et al.*, 2002; Saf, 2008; Ahmad *et al.*, 2011 and Zaman *et al.*, 2012) rather than frequency analysis for individual gauging stations due to the problem of ungauged catchments. Makhandi *et al* (2000) identified 41 homogeneous regions of annual maximum flows from 407 stations in 11 countries in southren Africa, fitting to the Pearson Type 3, Lognormal 3-parameter, General Pareto and General Extreme Value are suitable for flood frequency analysis distributions. Ngongondo *et al* (2013) conducted a flood frequency analysis for the Machiya station in the Upper Kafue catchment and investigated the impacts of climate change on the estimated floods. The results of this study are in line with the previous findings as the Annual Maximum Series fitted to the GEV and EV1 distributions whilst the Peak Over Threshold series fitted to the GPA and EXP distributions.

5: FLOW PARTITIONING AND DISTRIBUTION WITHIN THE OKAVANGO DELTA

5.1 Introduction

In this chapter an analysis and interpretation of historical hydrometric record of discharge and water levels at various points along the main distributary channels of the Okavango delta is carried out. The chapter addresses the objective of examining the distribution and partitioning of flows within the Okavango Delta and the implications to floodplain inundation. Floodplain inundation at different parts of the delta is experienced differently over time depending on the magnitude of Okavango River inflows and a complex interplay of hydrological processes taking place within the delta. Previous studies have revealed that partitioning of flows gradually change over time therefore influencing inundation of different floodplains. Kurugundla (2005) revealed that due to accumulation of vegetation blockages, flows shift to different channels and as a result changing direction of inundation. Wolski and Mudson (2006) suggested a gradual shift of inundation over a long period of time from Thaoge River towards the Xudum River. An analysis and interpretation of hydrometric record is done to assess evidence of change of partitioning and distribution of flows along the three main distributary channels of the Okavango Delta. Through interpretation of long term hydrological records within the delta, timing and extent of inundation along the channels will be identified.

Deltaic accretion results in anabranching rivers or formation of multiple channels (Nanson *et al*., 1996). These channels are separated by accumulated vegetation debris or semi-permanent alluvial islands formed from floodplain abrasion (Nanson *et al*., 1996). Anabranching of rivers occurs in flood dominated flow regimes with erosion resistant river banks, or within systems characterized by blockages which constrict channels and therefore triggering avulsion (Nanson *et al.*, 1996). Deltas are formed by a network of rivers constantly changing their channel course by lateral migration and avulsion (Kleinhans *et al*., 2011). Avulsion results in the formation of bifurcations. Bifurcations are unstable as they spontaneously break symmetry, enlarging one channel and shrinking the other, therefore the idea of long lived bifurcations seems paradox (Kleinhams e*t al*., 2011). According to Kleinhams *et al* (2011), the unstable nature of bifurcations is mainly due to sediment deposition in one channel being less than its transport

capacity, easily eroded, and sediment deposition in the other channel being more than its transport capacity and making it narrow. The same observation was done by Wolski *et al* (2006) as the Okavango river sediments are deposited within channels due to low velocities and vegetated banks resulting in a series of feedbacks. The sediments build up over time, change the channel morphology and slope. Kurugundla (2005) identified a series of blockages in the Okavango delta, which results in cessation of channels, accumulation of flows forming reservoirs, and formation of new channels by channel flow spill-overs or just branching. Nanson *et al* (1996) categorized anabranching rivers into cohesive sediment rivers, sand-dominated rivers, gravel-dominated rivers and mixed-load laterally active meandering rivers. Kurugundla *et al* (2009) explained the multiple channel formation as a result of ponding or reservoir formation of lagoons due to low flow velocities along a low gradient causing overflows into the neighbouring floodplains; ponding or reservoir formation as a result of blockages causing meanders or cut off into different flow directions. Overflows onto floodplains or overflows into a different channels to lose or gain flows.

5.2 Flood pulse concept

The annual flood pulsing and propagation through inundation of the channel-floodplain systems provides a dynamic ecosystem services at different parts of the Okavango Delta. Flood pulsing is an important hydrological and ecological variable in defining inundation of a channel-floodplain system which are habitats for a variety of biota (Wolski and Murray-Hudson, 2006). The flood pulse concept focuses on understanding channel-floodplain dynamics as it considers the channel and their fringing floodplains as one dynamic system linked by the interaction of hydrological and ecological processes (Tockner *et al*., 2000). Flood propagation and inundation of channel-floodplains dynamics play an important role in ecosystem maintenance and services more especially in low gradient deltaic systems. Variations in any river system's storage and conveyance capacity, temporal and spatial variation in flood magnitudes are a result of channel-floodplain interaction (Wolski *et al*., 2005). In most cases, large pristine, channel-floodplain systems are habitats to vast biota with high productivity mainly controlled and supported by a flood pulse (Junk *et al.*, 1989; Tockener and Standford, 2002). A typical biota adapts to the geomorphology and hydrology of a specific channel-floodplain system sustained by a flood pulse

(Junk *et al*., 1989). A flood pulse hydrologically affects biota of a specific channel-floodplain system, by means of floodplain inundation dynamics, causing biota to adapt and respond by displaying a defined reaction to the flooding dynamics creating characteristic community structures (Junk *et al.*, 1989). Regular flood pulsing is considered an important factor in developing biological cycles of recruitment of animal and plant species and overall productivity (Tockner *et al.*, 2000; Junk *et al.*, 1989; Bayley, 1989).

Due to the industrialization and modern farming, a considerable number of river-floodplain ecosystems have lost their natural functioning as a result of modified flooding patterns (Bayley 1995). About 90% of natural flood plains in Europe and North America are cultivated and therefore considered extinct whilst in the developing world natural floodplains are disappearing at a fast rate due to hydrological changes (Tockner and Standford, 2002). Hydrological alterations and agricultural expansions caused major ecological transformations of the floodplain area of Mississipi Alluvial Valley, the confluence of Mississipi and Ohio rivers (Jenkins *et al*., 2010). Although the Okavango delta is not subject to major human interventions, a major shift occurred in the 18th century where the western distributary, the Thaoge River, gradually dried up and no longer draining into Lake Ngami and this was associated with an increase of floodwaters towards the eastern distributaries, Mainachira, Mboroga and Santantadibe (Wolski and Murray-Hudson, 2006). Lake Ngami dried since 1989 only to receive considerable amounts of flows in 2004 even though other distributaries did not receive extensive flooding that year (Wolski and Murray-Hudson, 2006).

Urbanization, land use change, damming and mining waste have damaged stream corridors and wetlands requiring high demand of watershed and river restoration (Simmenstad *et al*., 2006). It is challenging to try to restore and rebuild an ecosystem due to lost traces of histroric ecosystem functions and disturbed or removed regular hydrologic pulsing, but Simmenstad *et al* (2006) suggest that one of the fundamental concepts of restoration include indigenous knowledge, historical template of the ecosystem and the understanding of how the ecosystem changed over time. Flood pulsing re-establishment has become a recognized concept in wetlands restoration (Middleton, 2002). Wetland restoration activities have been done on the outflow section, such as rehabilitation of Mopipi Dam and Boteti River by removal of bunds to restore natural river flow

channels, and the removal of bunds along the Nhabe River towards Lake Ngami. Channel clearing has also been taken into consideration by DWA, to remove the vegetation blockages as they potentially change the natural hydrological and geomorphological dynamics in the delta, therefore affecting the ecosystem functioning. In view of the above, an analysis of hydrometric records is therefore conducted to assess the behavior of inflows and their effects on inundation within the Okavango Delta. A 40 year hydrometric record is interpreted to depict physical characteristics that describe the inundation patterns at different parts within the Okavango Delta.

5.3 Materials and methods

5.3.1 Long term hydrometric record

The exchanges of water between the main channel and floodplain are complex and not easy to predict even with hydrological models (Moalafhi *et al*., 2014). Historical records of discharges and water levels at various stations along major distributaries of the Okavango Delta (Figure 5.1) are used to determine the partitioning of flows. Observed time series data of the Okavango River at Mohembo and other stations within the Okavango Delta were obtained from the Department of Water affairs (DWA) of Botswana. DWA conducts hydrometeorological measurements at 51 stations in the delta and discharges are estimated at 22 of the stations. Water levels are read from staff gauges and discharge measurements are done based on the current meter method. Data series for these stations generally range from 1970 to 2012. The discharge and water level measurements are done on monthly basis except at Mohembo and Maun Bridge stations where daily measurements are made. Long gaps are present in the datasets due to problems such as lack of accessibility to some stations especially during high flow periods. Elimination of erroneous data values is done by visual inspection

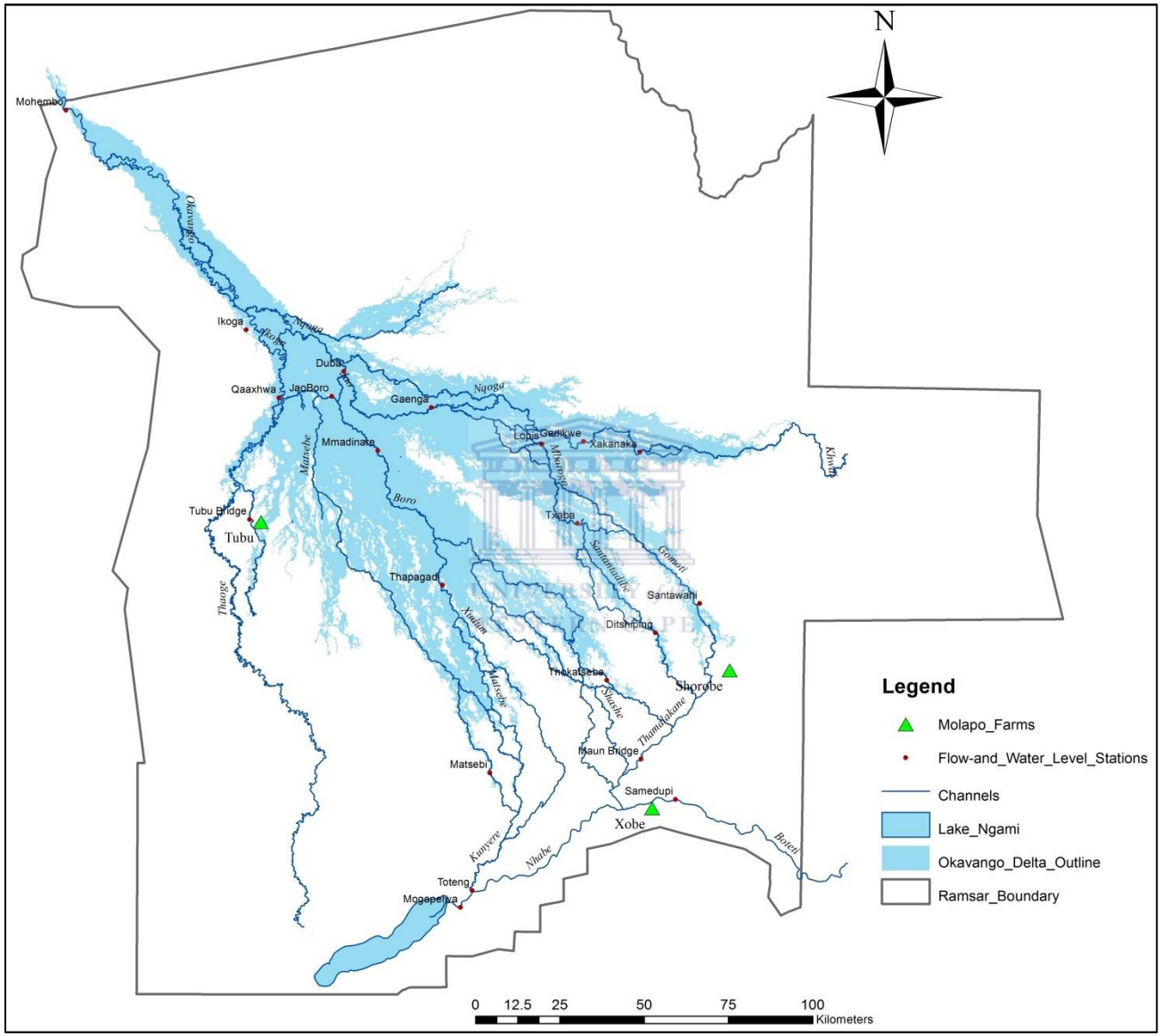


Figure 5.1: Okavango Delta discharge and water level stations used in this study along the three main distributaries, showing location of three areas used for *molapo* cultivation

5.3.2 Double mass curve analysis

The double-mass curve analysis procedure is used to identify the occurrences of inconsistencies of outflows against Okavango River flows at Mohembo as the pattern. Okavango River flows generally determine the flows within the Okavango Delta; therefore the outflows are clearly associated with Mohembo flow magnitudes. A double-mass curve analysis is a common technique used to detect inconsistency in hydrological data. The inconsistency is identified by comparing data for a single station with that of a general system pattern (Searcy and Hardson, 1966). The double-mass curve is a plot of cumulative hydrological data at a specific station against the average of cumulative hydrological data for the same period collected at several gauges in the same region and it is a straight line if the relationship between the variables has a fixed ratio. (Searcy and Hardson, 1966; Dingman, 2002). The breaks in the slope of a double-mass curve can occur due to the changes in data collection method, physical changes that may affect the relationship, and climatic shifts (Searcy and Hardson, 1966; Dingman, 2002).

5.3.3 Water balance and linear reservior model

A linear reservoir model is used to model the outflows from the Okavango Delta at Maun Bridge on Thamalakane River, through Samedupi station along Boteti River and at Rakops along Boteti River entering Mkgadikgadi pans. The flows are modeled on a monthly time interval. Water balance is calculated for three sections;

1. from Mohembo on Okavango River to Maun Bridge on the Thamalakane River
2. from Maun Bridge on Thamalakane River to Samedupi on the Boteti River,
3. from Samedupi to Rakops on the Boteti River.

On the first section Okavango River flows at Mohembo and rain falling onto the water surface are the only contributing factors to water into the resevoir for triggering outflows at Maun Bridge. The Okavango Delta is considered as a single reservoir between Mohembo and Maun Bridge before triggering outflows along Thamalakane and Boteti Rivers. For the second and the third sections, outflows from the Okavango Delta and rain falling onto the water surface of the Thamalakane-Boteti river are the only contributing factors to flows in the channel. The main

hydrological processes in the three reservoirs are storage and transmission of outflows from the delta, groundwater recharge, evapotranspiration, and channel precipitation. The start and end of the reservoirs coincide with location of flow measuring stations with data used for model calibration. In each reservoir the water balance is calculated following the same procedure as Dincer *et al* (1987). The water balance is therefore given by;

$$V_{t+1} = V_t + Inflow - Outflow - Losses \tag{5.1}$$

where losses are given by;

$$Losses = Area * (ET - P) \tag{5.2}$$

where *ET* is evapotranspiration and *P* is precipitation.

The storage and flow of water in each of these reservoirs is therefore estimated as follows;

$$V_{t+1} = V_t + I_t - X_t + A_t(P_t - ET_t) - gV_t \tag{5.3}$$

where V_t is volume of water stored in a reservoir at the beginning of month *t*, I_t is the inflow into the reservoir during the time *t* to *t+1*, *g* is parameter for estimating recharge to groundwater A_t is the average reservoir area from the beginning to end of month *t*, given by;

$$A_t = bV_t^n \tag{5.4}$$

b and *n* are parameters. X_t is outflow from the cell during the period *t* to *t+1*, given by;

$$X_t = \begin{cases} k(V_t - V_{min}); & if\ V_t > V_{min} \\ 0; & if\ V_t \leq V_{min} \end{cases} \tag{5.5}$$

The contribution of rain falling (P_t) directly onto the channel is estimated using rainfall for Shakawe and Maun, and the surface area (A_t) of each reservoir estimated from the surface area – storage volume relationship (Equation 5.4). Evaporation from the reservoirs (ET_t) is estimated from mean monthly evaporation rate measured at Shakawe and Maun. Outflow (X_t) from each reservoir is a function of the storage volume above a minimum threshold volume (V_{min}) (Equation 5.5). k and V_{min} are calibrated parameters. Thus if the volume of water in each reservoir is less than V_{min}, no outflow occurs. Recharge to groundwater (gV_t) is modelled as a loss which is a function of the volume of water stored in each reservoir.

Two fitness criteria are chosen.

1. The measure of the deviation between simulated and observed data, the root mean square error, RMSE

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_{s,i} - X_{o,i}\right)^2} \tag{5.6}$$

Where $Q_{o,i}$ is the observed discharge, $Q_{s,i}$ is the model output, i represents the different time steps at which the system is observed and N is the total number of time steps. The closer the RMSE is to zero the better the model is (Dre´court, 2004).

2. The measure of the ability to simulate the variation in the discharge hydrographs for a particular river gauging station, R^2.

$$R^2 = \frac{\sum_i (X_{o,i} - \overline{X_o})^2 - \sum_i (X_{s,i} - X_{o,i})^2}{\sum_i (X_{o,i} - \overline{X_o})^2} = 1 - \frac{\sum_i (X_{s,i} - X_{o,i})^2}{\sum_i (X_{o,i} - \overline{X_o})^2} \tag{5.7}$$

Where;

$X_{o,i}$ is the observed for discharge for time step *i*, $X_{s,i}$ is the simulated discharge for time step *i* and $\overline{X_o}$ is the average discharge for the test period. The maximum value of R^2 is 1 and this expresses a perfect model fit (Henriksen *et al*., 2003; Ondracek, 2005).

5.4 Results

5.4.1 Channel flow directions and flow distribution

The annual flood pulse which enters Botswana at Mohembo, flows through the main Okavango River until Ikoga where this forms a large reservoir before splitting into four distributary channels which convey the flows on to extensive perennial flood plains, defined as the classic 'bird's foot'(McCarthy *et al.,* 1986) (Figure 5.1 and 5.2). The Selinda spillway on Magweqana channel is the first to branch from the Okavango Delta connecting to the Chobe River system towards the north eastern direction joining the Zambezi River. During extremely high flow years, flows through the Magweqana reach the Chobe River system. In 2009, the flows through Selinda managed to connect to the Kwando/Linyanti River. No flow measurements are carried out along the Selinda channel and therefore the analysis presented in this chapter is restricted to the three main distributaries. After the panhandle, the reservoir splits into the Thaoge River system on the western part, the Jao-Boro River system from the middle and the Nqoga-Maunachira river system on the eastern side. Flows eventually leave the delta through Boteti River and reach the Makgadikgadi system during years with high flows (Figure 5.2).

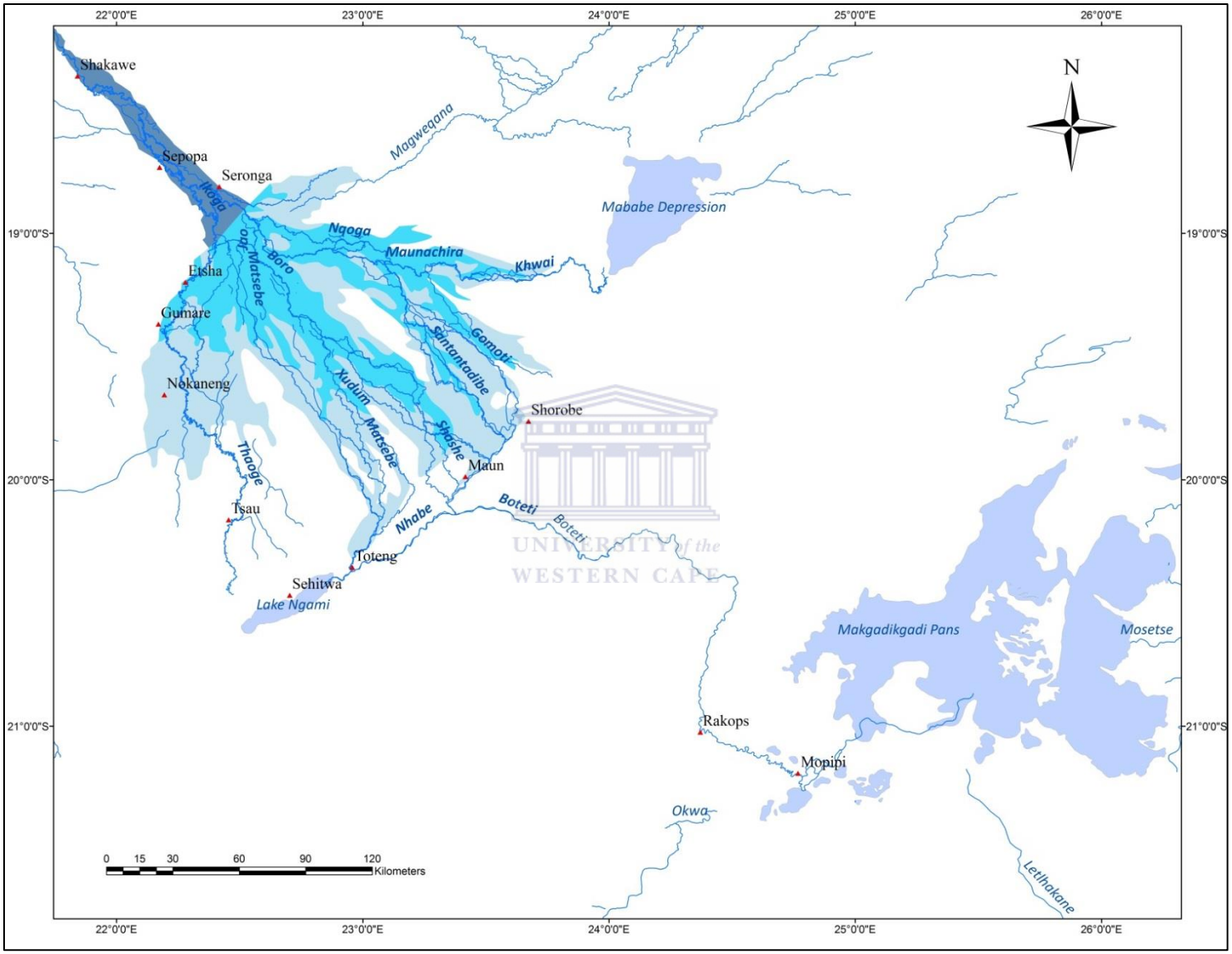


Figure 5.2: Okavango Delta main distributaries and showing the connection with the Mkagadikagadi pans

Due to swampy conditions of the Okavango wetland, there are interconnections of channels making it difficult to make a clear distinction between some channels. The following flow directions are presented to distigush the channels comprising the main distributary systems.

5.4.1.1 Thaoge System: Okavango→Crescent channel→Thaoge River

The Crescent Channel on the western side, branches off from the main Okavango River at Ikoga and terminates in the Thaoge River. Upstream of The Thaoge River, is a series of lagoons and a series of small floodplain channels before emerging into a well-defined channel further downstream. A small channel branches from the main Thaoge River towards Tubu villlage, further terminating in a series of small floodplain channels and lagoons (Figure 5.1 and 5.2). The Thaoge River system is responsible for inundating the western floodplains including *molapo* floodplains at Tubu.

5.4.1.2 Jao-Boro System: Okavango→Jao/Boro/Xudum Rivers

The Jao-Boro River system emerges from the middle of the burfication and subsequently splits to form Boro and Xudum rivers. The Jao River splits into Boro River and Matsebe River on the west. The Jao River feeds the Boro River which then splits into the Xudum and the Thamalakane Rivers (Figure 5.2). The Jao and Boro Rivers flow through lagoons and floodplains and then into a more or less confined channel discharging into the Thamalakane River. The Thamalakane River feeds the Boteti River which is the main outlet from the Okavango Delta. The Thamalakne River also drains into Nhabe River which joins the Kunyere River, terminating into Lake Ngami The Kunyere River is fed by both Matsebe River and Xudum River (Figure 5.1 and 5.2). The Jao-Boro River system is responsible for inundating the *molapo* floodplains along Thamalakane and at Xobe along the Boteti Rivers.

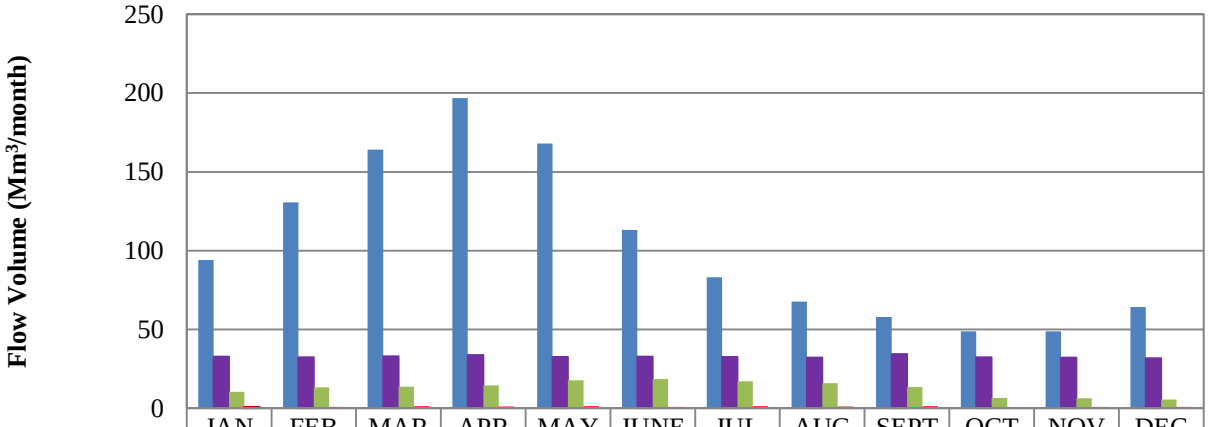
5.4.1.3 Ngoqa-Maunachira System: Okavango→Nqoga→Maunachira/Mboroga→ Gomoti/Santantadibe River

The Nqoga-Maunachira River system flows towards the east and splits into Mboroga and Maunachira Rivers. The Ngqoga River splits into a large number of channels that form a complex system of flood plains. The Maunachira River eventually becomes Khwai River which has wide permanent flood plains in its middle reaches and discharges into poorly defined

floodplains. The Mboroga River splits into Santantadibe and Gomoti Rivers, both flowing into the Thamalakane River (Figure 5.1 and 5.2). The Ngoqa-Maunachira River system inundates the Shorobe *molapo* floodplains along the Gomoti River.

5.4.2 Flow partitioning

The most upstream stations along the three main distributaries of the Okavango Delta are; Qaaxhwa along the Thaoge River system, Jao/Boro along the Jao-Boro River system and at Duba along the Nqoga-Maunachira River system. The Duba station receives the highest flow volumes, followed by Jao/Boro station then the Qaaxhwa station (Figure 5.3). There is no significant difference between monthly flows at Duba station whilst Jao/Boro and Qaaxhwa stations show an increase in monthly flow volumes from March until June and July when the volumes start decreasing again until February. Using the flow records for the period when the three stations had continuous records, 2004-2007, 32% of average annual flow volume at Mohembo is received at Duba station whilst 12% reaches Jao/Boro station and 1% reaches Qaaxhwa station. The three stations are almost the same distance from Mohembo station which is approximately 115 km. These three locations are permanently inundated.

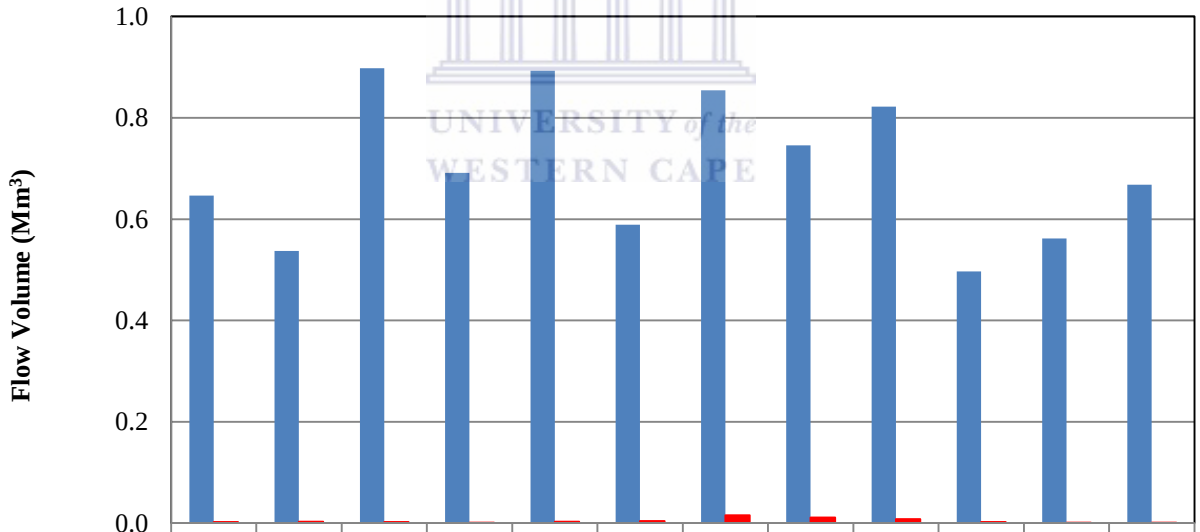


	JAN	FEB	MAR	APR	MAY	JUNE	JUL	AUG	SEPT	OCT	NOV	DEC
Mohembo	94.109	130.624	164.089	196.834	167.984	113.155	83.108	67.696	57.931	48.768	48.796	64.313
Duba	32.718	32.305	32.971	33.687	32.573	32.761	32.493	32.177	34.399	32.312	32.097	31.782
Jao/Boro	10.487	13.216	13.570	14.566	17.655	18.547	17.125	15.986	13.465	6.549	6.338	5.538
Qaaxhwa	0.902	0.829	1.252	0.996	1.245	0.848	1.191	1.040	1.184	0.692	0.809	0.931

Figure 5.3: Flow volumes at the most upstream stations along the main distributatry channels; Qaaxhwa along Thaoge System, Jao/Bo along Jao-Boro System and Duba along Nqoga-Maunachira System

5.4.2.1 Partitioning along the Thaoge distributary

Flows along the Thaoge River inundate the floodplain on the eastern side towards Tubu village. Flow measurements were done at Tubu Bridge along the main floodplain channel passing through Tubu village until the 1990's when this river dried up. DWA did not revive the station even after the 2009 flood which managed to reach Tubu floodplains. The percentage of flows that spill from the main Thaoge River and received at Tubu Bridge is relatively small. The highest percentage of flow volumes received at Tubu Bridge station is reached in July which is 0.8% of flow volumes of Qaaxhwa station whilst the lowest percentage of 0.1 % is received in the month of November (Figure 5.4). Qaaxhwa station is 50 km upstream of Tubu village. Peak flows do not reach Tubu floodplains every year and these floodplains are classified as being occasionally flooded areas of the Okavango Delta. Overall, Tubu Bridge receives 0.004% of Mohembo flows.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Qaaxhwa	0.647	0.537	0.898	0.692	0.893	0.589	0.854	0.746	0.822	0.497	0.562	0.668
Tubu Bridge	0.002	0.003	0.002	0.001	0.003	0.004	0.015	0.011	0.008	0.002	0.001	0.001

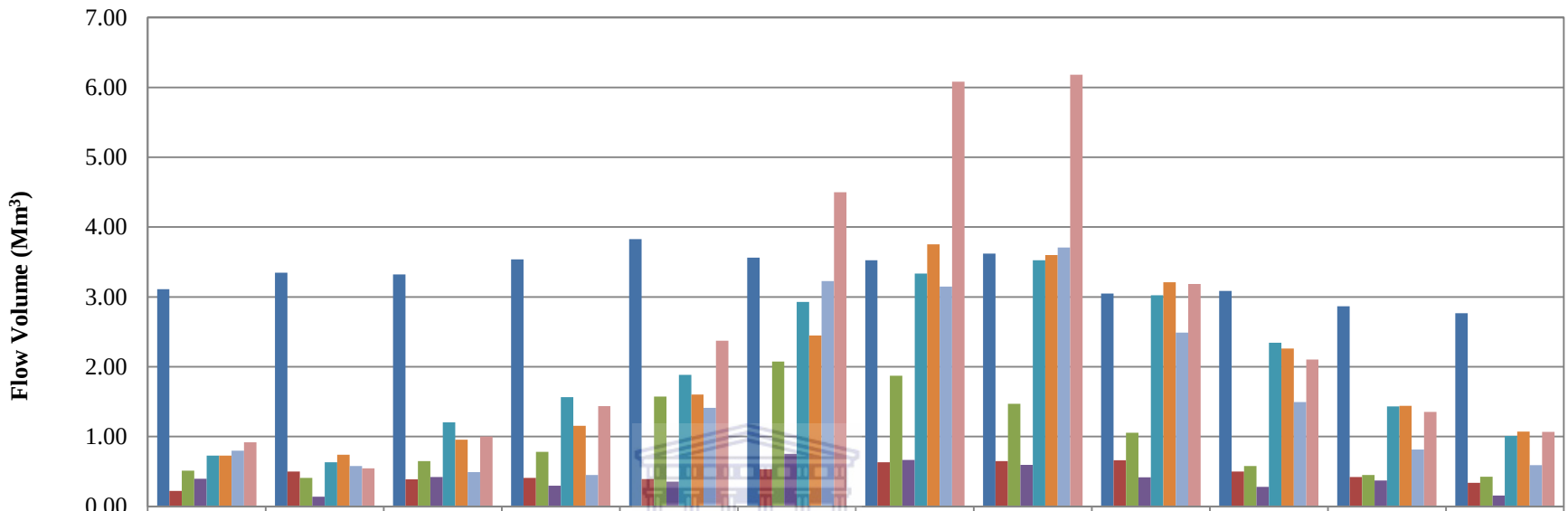
Figure 5.4: Monthly Flow Volumes at Qaaxhwa most upstream of Thaoge System and Tubu Bridge along the floodplain channels at Tubu capturing spillovers from the main Thaoge River

5.4.2.2 Partitioning along the Jao-Boro distributary

From Jao/Boro station, 8 flow gauging stations monitor flows (Figure 5.1);

- Madinare station along the main Boro River
- Matsebe station along Matsebe River,
- Thapagadi station which is along the Xudum River
- Thokatsebe station along the Boro River,
- Toteng station on the Kunyere River
- Maun Bridge station along Thamalakane River,
- Mogapelwa station along Nhabe River
- Samedupi along Boteti River

Along the Jao-Boro River system, Jao/Boro station receives the highest flow volumes followed by Madinare station which receives large volumes from October to May. Mogapelwa station starts having larger volumes than the other stations from June to August followed by Maun Bridge, Toteng and Samedupi. Thokatsebe and Matsebe receive the lowest flow volumes throughout the months. The Okavango River annual flood peak reaches Madinare station around April and May, just a month after the peak at Mohembo station. The flood peak reaches the downstream station of the Jao-Boro distributary around June to August (Figure 5.5) also one month after the Madinare peak flow. Based on long term averages from 1970 to 2012, the percentage of Mohembo flows reaching the different stations along the Jao-Boro River system is shown in Table 5.1. Although Maun Bridge, Toteng, Mogapelwa and Samedupi are downstream, they receive more flow volumes than of Thapagadi, Matsebe and Thokatsebe which are on the upstream parts along Jao-Boro system. This is due to additional flows which come from the Nqoga-Maunachira system through the Gomoti and Sanatantadibe River, adding to Thamalakane River, through Nhabe to Mogapelwa and through Boteti to Samedupi. However; during low flow years, these downstream stations receives lower flows than the upstream stations.



	JAN	FEB	MARCH	APR	MAY	JUNE	JUL	AUG	SEPT	OCT	NOV	DEC
Madinare	3.111	3.347	3.321	3.539	3.826	3.564	3.526	3.621	3.048	3.085	2.868	2.767
Thokatsebe	0.224	0.503	0.390	0.408	0.393	0.535	0.631	0.648	0.662	0.499	0.422	0.341
Thapagadi	0.512	0.409	0.650	0.783	1.573	2.073	1.871	1.472	1.054	0.581	0.449	0.427
Matsebe	0.40	0.14	0.42	0.30	0.35	0.75	0.67	0.60	0.42	0.28	0.37	0.16
MaunBridge	0.728	0.633	1.203	1.566	1.886	2.929	3.336	3.525	3.023	2.343	1.433	1.011
Samedupi	0.728	0.741	0.955	1.157	1.604	2.449	3.752	3.601	3.211	2.263	1.442	1.074
Toteng	0.80	0.58	0.49	0.45	1.41	3.23	3.15	3.71	2.49	1.49	0.82	0.59
Mogapelwa	0.92	0.55	1.00	1.44	2.37	4.50	6.08	6.18	3.18	2.10	1.36	1.07

Figure 5.5: Average monthly flow volumes at different station along the Jao-Boro system

Table 5.1: The average annual percentage of Mohembo flows reaching the stations along the Jao-Boro River system

Station	Annual Volume (Mm^3)	Percentage of Mohembo Flows
Madinare	39.62	3.20
Thokatsebe	5.66	0.46
Thapagadi	11.85	0.96
Matsebe	4.85	0.39
MaunBridge	23.62	1.91
Samedupi	22.98	1.86
Toteng	19.21	1.55
Mogapelwa	30.75	2.49

The Madinare, Thapagadi and Thokatsebe receive flows every year. Thapagadi and Thokatsebe receive flows only during the high flow season only. Generally Matsebe, Maun Bridge, Toteng, Mogapelwa and Samedupi stations did not receive flows in some years within the period of 1993-2003 (Table 5.2). Therefore the stations are on the occasionally flooded floodplains of the Okavango Delta. Matsebe and Maun Bridge received some flows within some years in the period of 1993-2003, however, there was strong seasonality.

Table 5.2: Periods during which Okavango River flows did not rich stations along the Jao-Boro System

Station	**Dry Period**
Matsebe	1993/1994-1997/1998
Maun Bridge	1996/1997
Toteng	1993/1994-2002/2003
Mogapelwa	1993/1994-2002/2003
Samedupi	1993/1994-2002/2003

5.4.2.2.1 Floodplain inudation along Jao-Boro River system

There was a general decline in both water levels and discharge from 1990 to 2001 at all stations along the Jao-Boro distributory (Figure 5.6 and Figure 5.7). Little or no water reached the downstream stations around the period of 1990 to 2003. This corresponds with the general decline in flows at Mohembo through the period of 1979 to 2003 which is further explained by

the drought in southern Africa during the same period. The water level variations correspond well with the discharge variations in all the stations along the distributary except for some discrepancy at Thapagadi and Toteng. Both Thapagadi and Toteng are along the Xudum secondary distributary of Jao-Boro system. Wolski and Murray-Hudson (2006) explained an increased inundation on the Xudum River due to the 1997 shift of flows from the Thaoge River which resulted in decrease inundation in the western margin and increasing inundation along Xudum River. There is a negative correlation between monthly water levels and local rainfall at all the stations along the Jao-Boro distributory. The decline in flows and water levels of 1990-2001 implies decline in inundation.

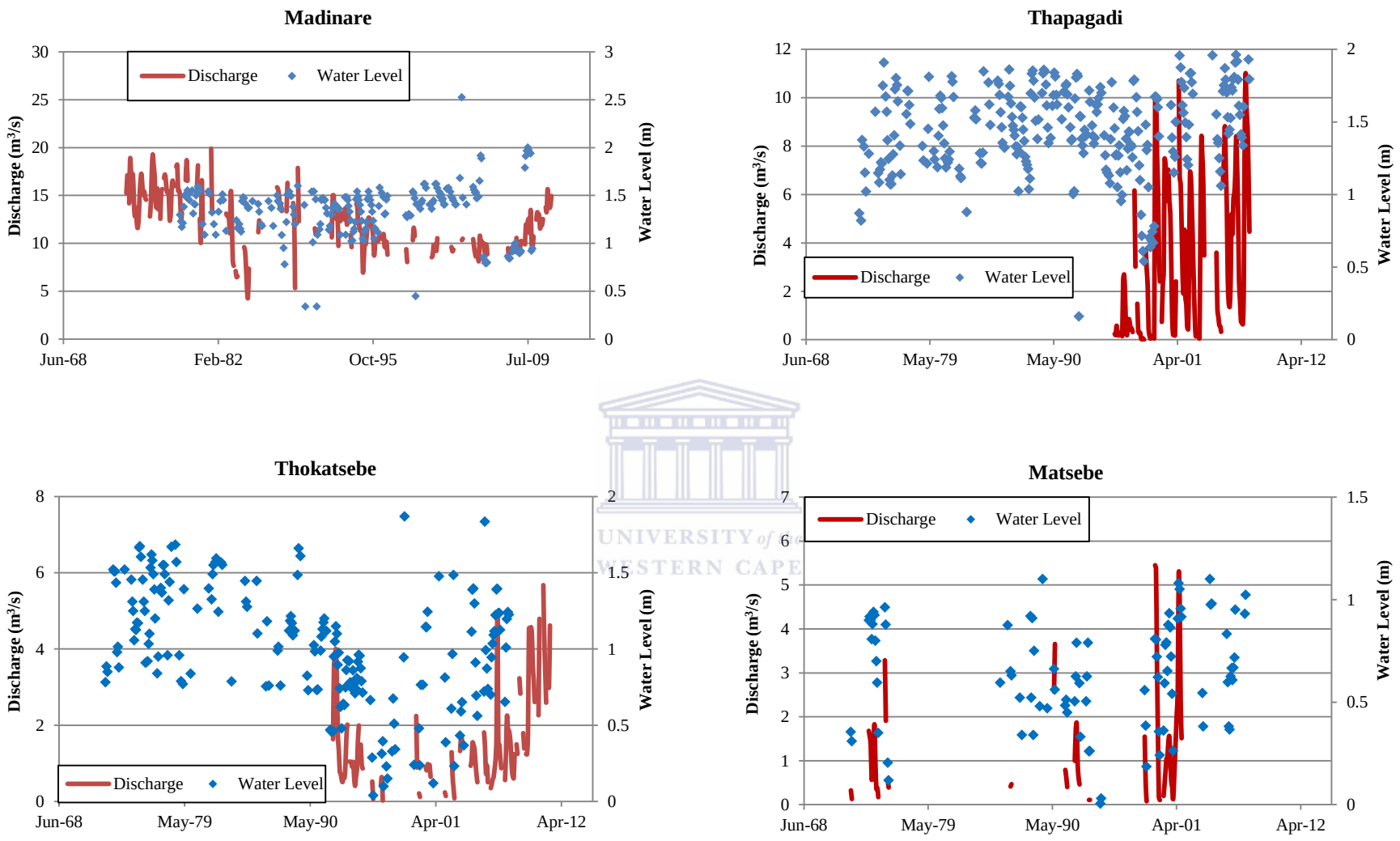


Figure 5.6: Variation of Water levels with flows at the upstream stations of the Jao-Boro system

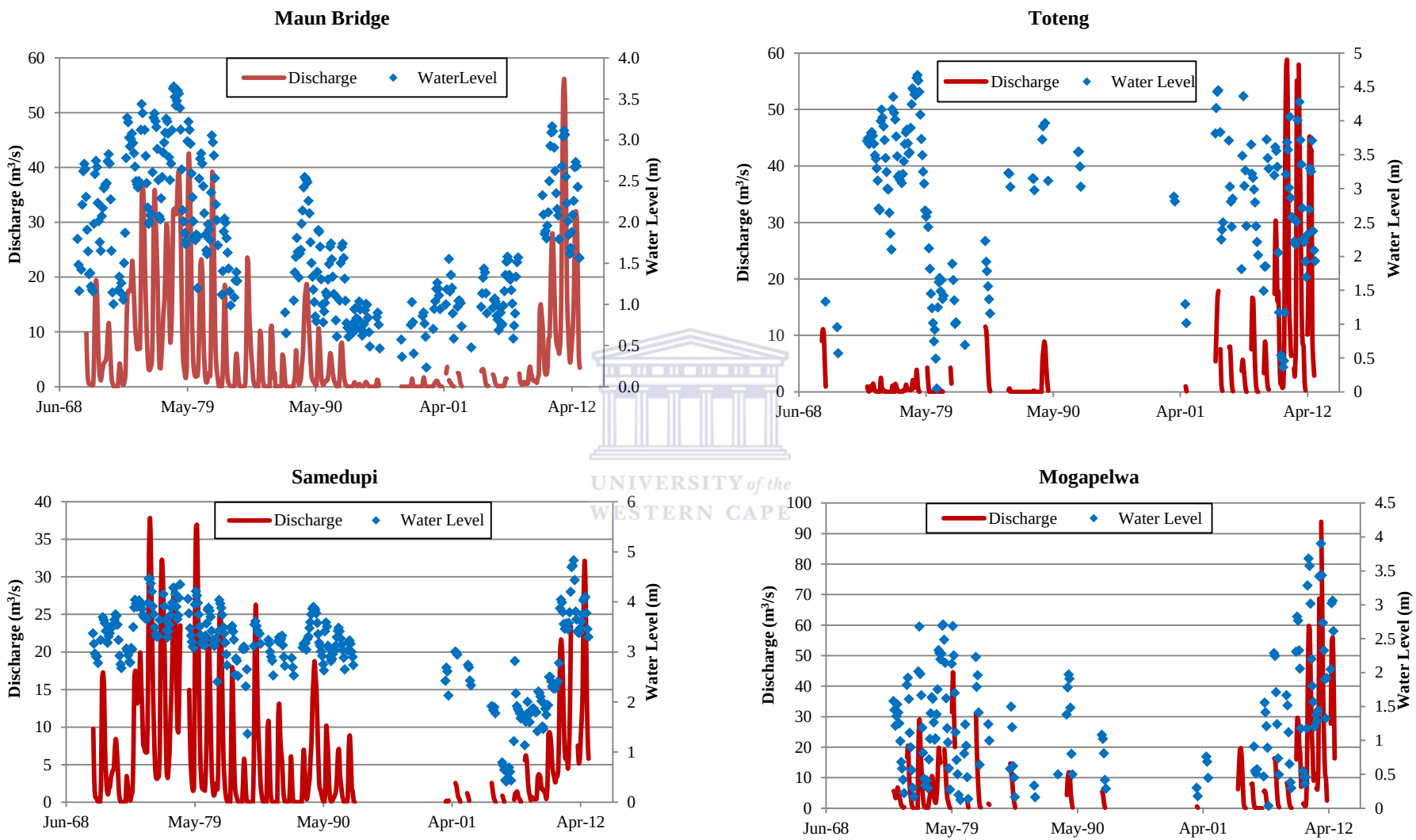
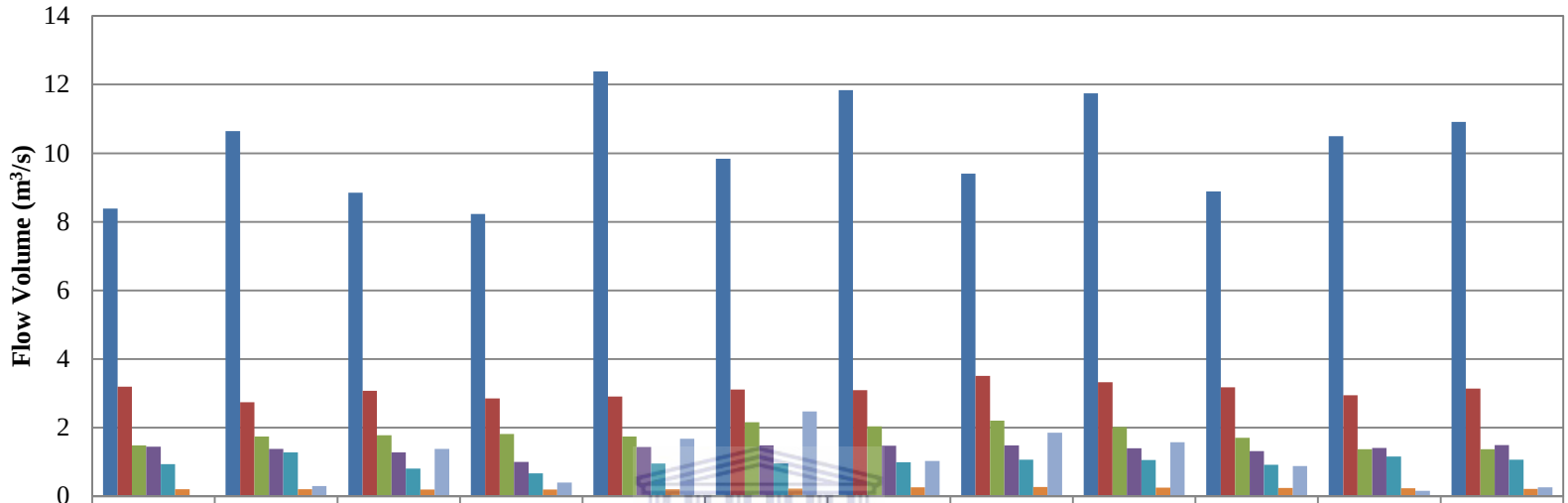


Figure 5.7: Water Level variations with flows at the downstream stations of the Jao-Boro system

5.4.2.3 Partitioning along the Nqoga Maunachira distributary

From the most upstream station, Duba, along the Ngoqa-Maunachira system, 7 flow gauging stations were used to explain the flood pulse as it propagates downstream. After the Gaenga station on the Ngoqa River, flow measurements are done at Gadikwe on Maunachira River and Lopis on Mboroga River. Flow measurements are taken at Xakanaxa on the Khwai River. Along the Santantadibe River there is Txaba station and Ditshiping with Santawani station on Gomoti River. Larger flow volumes go towards the Maunachira River direction as observed at Gadikwe station than the Mboroga River observed at Lopis station. From Lopis station larger flow volumes reach Santawani on Gomoti River than the Ditshiping station on the Santanatdibe River (Figure 5.8 and 5.9). Based on long term averages from 1970 to 2012, the percentage of Mohembo flows reaching the stations along the Ngoqa-Maunachira River is shown in Figure 5.9. The distributary generally receives more flows than the other two distributaries throughout the year (Figure 5.8).



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
Gaenga	8.381	10.640	8.846	8.227	12.382	9.836	11.838	9.406	11.748	8.888	10.493	10.916
Gadikwe	3.190	2.738	3.073	2.853	2.905	3.110	3.088	3.508	3.319	3.177	2.946	3.137
Lopis	1.482	1.739	1.775	1.812	1.741	2.153	2.038	2.207	2.013	1.701	1.365	1.369
Txaba	1.442	1.374	1.274	0.997	1.433	1.484	1.475	1.479	1.401	1.311	1.406	1.487
Xakanaxa	0.938	1.281	0.806	0.670	0.955	0.956	0.991	1.065	1.053	0.919	1.157	1.060
Ditshiping	0.199	0.204	0.195	0.197	0.205	0.221	0.263	0.269	0.249	0.240	0.227	0.214
Santawana		0.296	1.382	0.399	1.672	2.472	1.031	1.847	1.576	0.883	0.160	0.263

Figure 5.8: Monthly flow volumes for the stations along the Ngoqa-Maunachira system

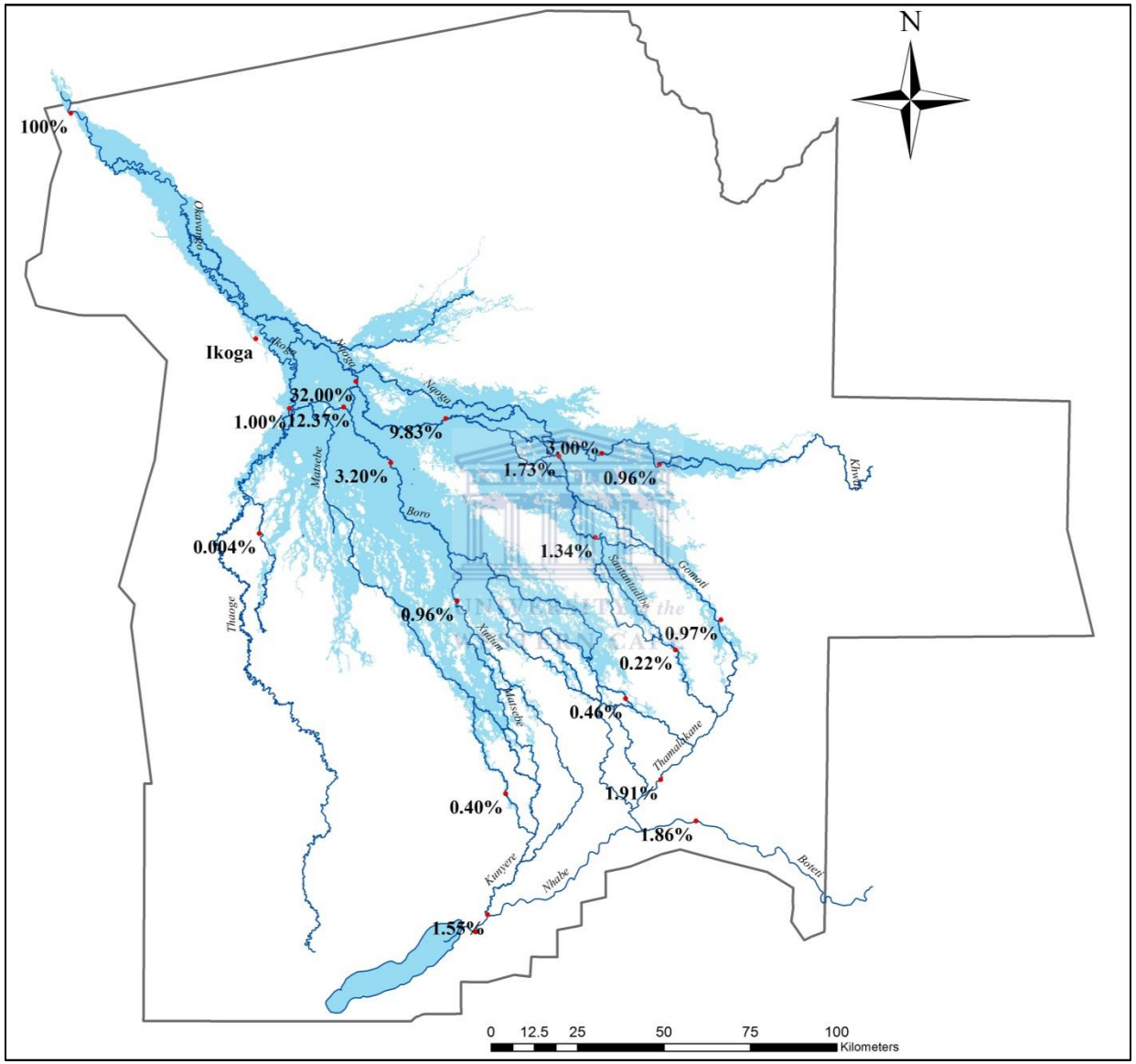


Figure 5.9: Percentage of Mohembo flows reaching different stations along the distributaries of the Okavango Delta

5.4.2.3.1 Floodplain inundation along Ngoqa-Maunachira River system

There is inconsistency in the variation of water levels along with discharge on the Ngoqa-Maunachira distributary more especially on the upstream stations (Figure 5.10). A general decline in discharge from the 1990's onwards was observed at the stations along the Ngoqa-Maunachira distributary (Figure 5.10). However some stations show an increase in water levels from the 1990's onwards. Despite the general decline in channel flows at all stations along the system from 1990's, Xakanaxa station rather shows a different pattern of flow increasing during the period. The correlation between water levels and rainfall is also poor at the stations along the Ngoqa-Maunachira system; therefore this cannot explain the discrepancy between discharge and water levels. The inconsistency of flow pattern with water level variation patterns can be explained by the flow measuring methods which do not include floodplain flows due to blockages in the upstream of the distributary. Wolski and Hudson (2006) explained inconsistency between discharge variation with water level variations along the Ngoqa-Maunachira distributary as a result of many processes including; a) channel aggradation processes due to deposition of sediments within channels causing reduction in channel bed slope, therefore resulting in the rise of water levels and reduction of discharge; b) spilling of water from different channels which causes rise of water levels; c) change of channels conveyance caused by aquatic vegetation which result in flow resistance. It is therefore difficult to attribute inundation variation to either water level variation or discharge variation at different points along the Ngoqa-Maunachaira River systems.

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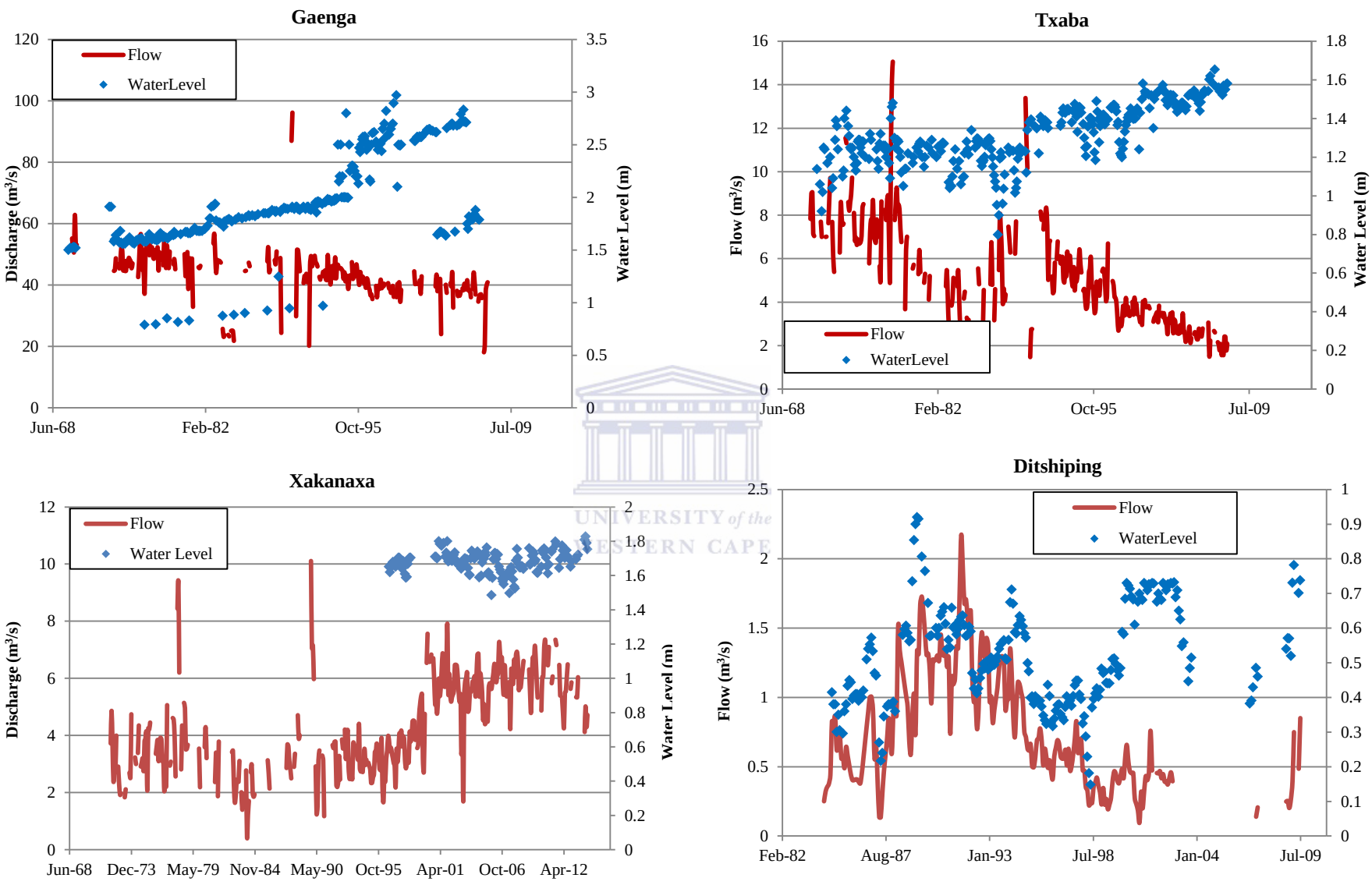

Figure 5.10: Discharge and Water level variations along the Nqoga-Maunachira distributary

5.4.3 Change over time of flow partitioning

Annual discharge for selected stations along the main distributaries of the Okavango Delta, were tested for trends using the Mann-Kendall trend test at 5% significance level. The *p*-values and the slope coefficients (*Q*) are shown in Table 5.3. A decreasing trend is observed at Qaaxhwa station along the Thaoge River. There is a decreasing trend at Madinare station along Jao River, however an increasing trend is observed at Thapagadi and Thokatsebe stations downstream of Madinare along Xudum and Boro Rivers respectively. The results imply that inundation has been decreasing along the Thaoge River, and increasing along Xudum River. This confirms long term reduction of flows towards the Thagoge River, shifting towards Xudum as indicated by Wolski and Hudson (2006). Although the Thokatsebe which is upstream of Maun Bridge has an increasing trend, Maun Bridge and Samedupi downstream shows a decreasing trend. The decreasing trend of flows at Maun Bridge and Samedupi is possible due to the persistent long low flow period of 1990-2008 (Figure 5.11). Therefore this implies that areas inundated have been reducing over time around Thamalakane and Boteti River.

Table 5.3: Mann-Kendall statistics of significant trends at 5% significance level in discharge of selected stations along the distributaries of the Okavango Delta

Station	Period	Channel	p-Value	Q
Madinare	1972-2012	Jao	< 0.0001	-0.164
Thapagadi	1995-2007	Xudum	0.001	0.421
Thokatsebe	1990-2012	Boro	0.007	0.063
Maun Bridge	1970-2012	Thamalakane	0.002	-0.139
Samedupi	1970-2012	Boteti	0.004	-0.145
Qaaxhwa	1988-2008	Thaoge	< 0.0001	-0.238
Gaenga	1969-2007	Ngoqa	< 0.0001	-0.334
Xakanaxa	1972-2014	Maunachira	< 0.0001	0.077
Txaba	1970-2007	Santantadibe	< 0.0001	-0.154
Ditshiping	1984-2009	Santantadibe	0.004	-0.034

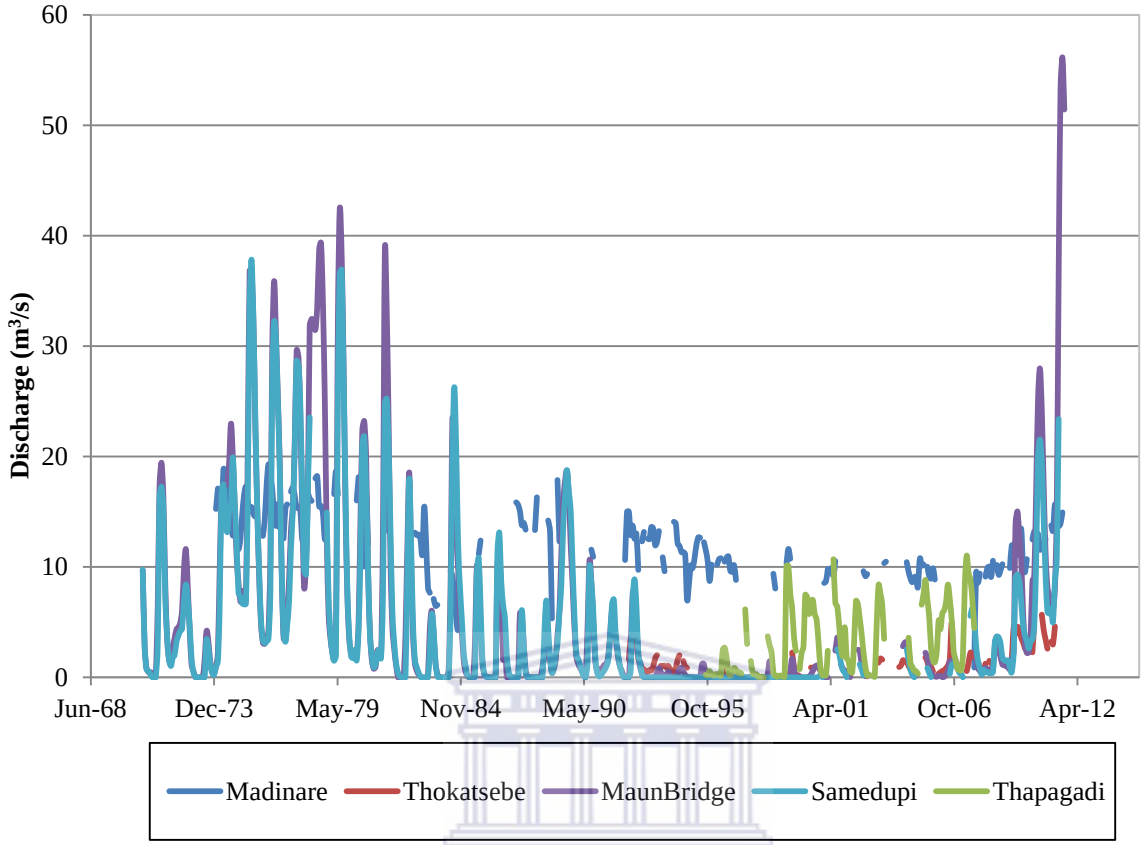

Figure 5.11: Comparison of monthly flow variation along the Jao-Boro River system; showing high flows during 1970-1980 period and low flows during 1990- 2008 period which significantly affected downstream parts at Maun Bridge and Samedupi.

The Gaenga station on Ngoqa River has a decreasing trend and Xakanaxa station along the Maunachira River has an increasing trend, whilst Txaba along Santantadide also downstream of Gaenga rather shows a decreasing trend (Table 5.3). Ditshiping downstream of Txaba along Santantadibe is also showing a decreasing trend. Although Txaba and Xakanaxa stations are almost the same distance downstream of Gaenga station, they show different trend directions. Therefore, inundation along the Ngoqa-Maunachira shifts from one channel to the other (Figure 5.12), depending on the dominance of either, channel aggradation processes, channel-floodplain interaction processes or the changes in channel conveyance due to aquatic vegetation.

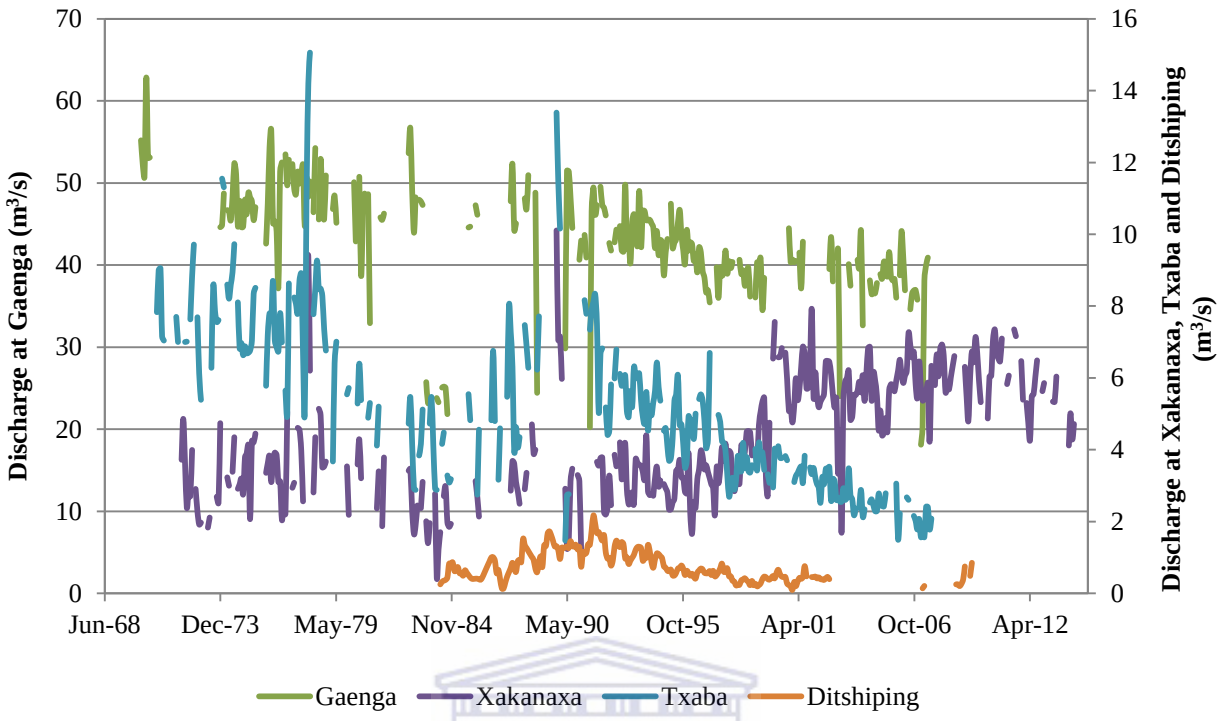

Figure 5.12: Comparison of monthly flow variation along the Ngoqa-Maunachira River system; showing variations at different stations.

5.4.4 Outflows

5.4.4.1 General characteristics of outflows

Peak flows from the Okavango Delta reach the downstream stations; i.e Maun Bridge, Samedupi, Toteng, Mogapelwa and Rakops, during the May to June period and peak flows occur usually in August (Figure 5.13). In a year the lowest flows occur in January and February at the downstream stations. The average daily flow at Maun Bridge station is 6 m^3/s and 5 m^3/s at Samedupi station. The average daily flow is also 5 m^3/s at Rakops about 200 km downstream of Samedupi. The average daily flow at Toteng is 2.5 m^3/s and 11 m^3/s at Mogapelwa. It takes 4-5 months for the peak flow at Mohembo to reach the outflow stations (Figure 5.13). As a result highest inundation at the downstream of the Okavango Delta is reached in the months of July August and September.

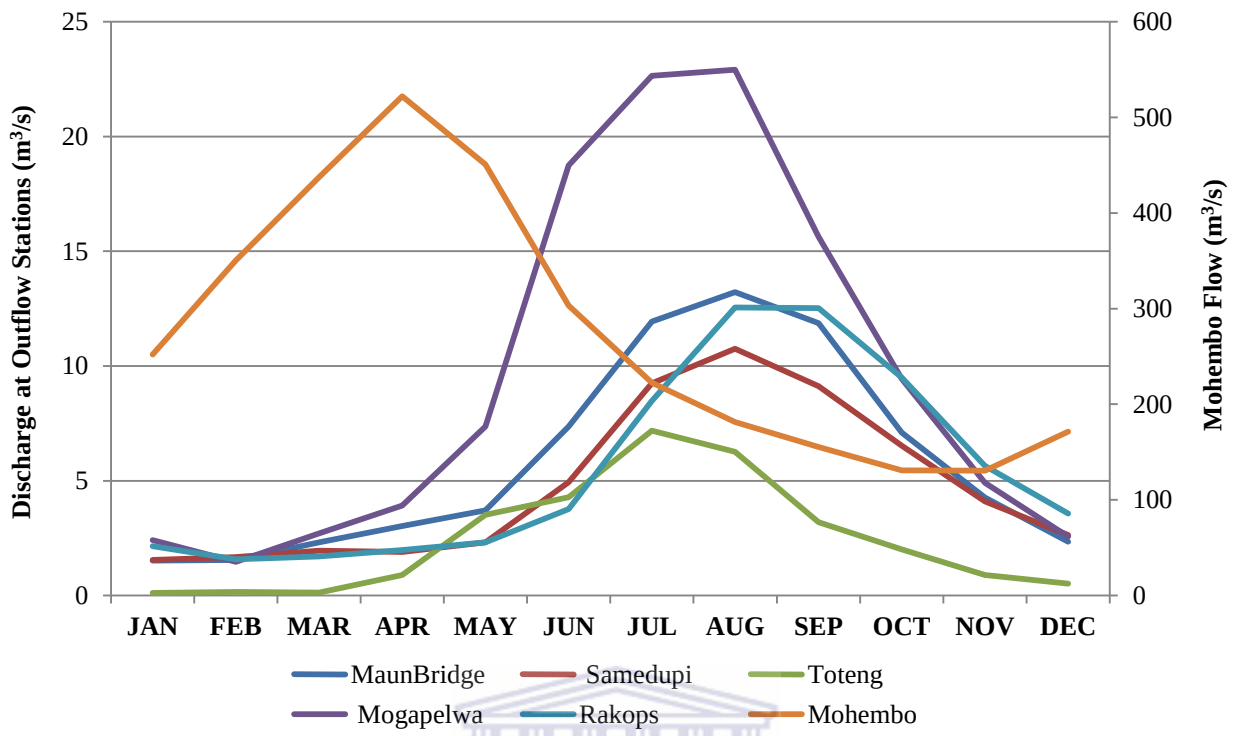

Figure 5.13: Average Monthly inflows at Mohembo on the Okavango River and outflows at Maun Bridge along Thamalakane River, Samedupi and Rakops along Boteti river, Mogapelwa along Nhabe River and Kunyere River at Toteng

River flow measurements made on Thamalakane River at Maun, and Boteti River at Samedupi and Rakops and Mogapelwa on Nhabe show that the 1972-1980 period was characterized by very high flows (Figure 5.14 and 5.15). However; Toteng received very low flows until 2008 when flows started increasing (Figure 5.15). Very low flows occurred from 1990 to 2008, and the whole section of the Boteti River from Chanoga to its distal end including Rakops was dry during this period

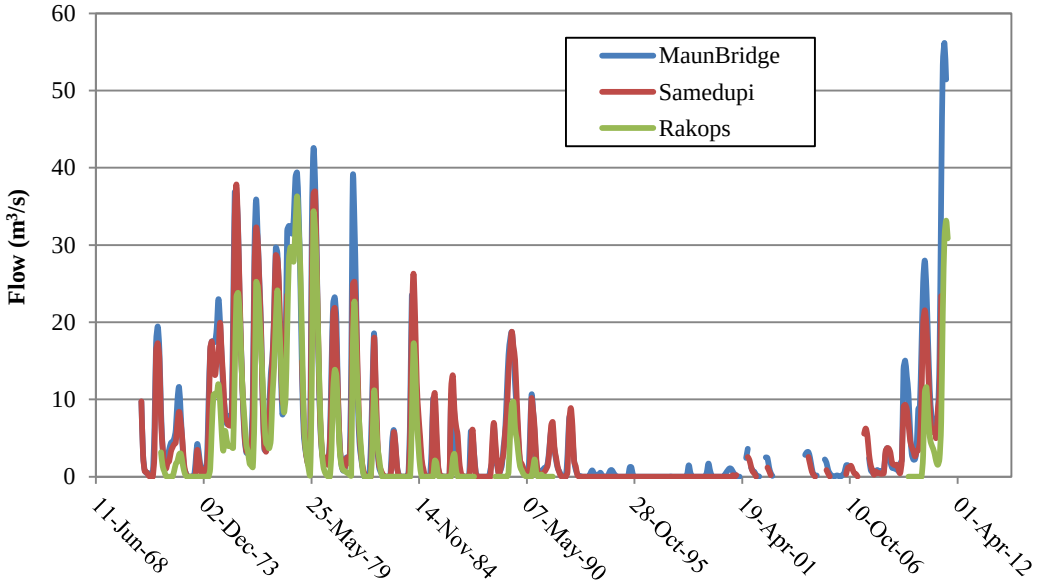

Figure 5.14: Monthly flow variation of Thamalakne at Maun Bridge with outflow through Boteti river at Samedupi and Rakops for 1970-2012 period

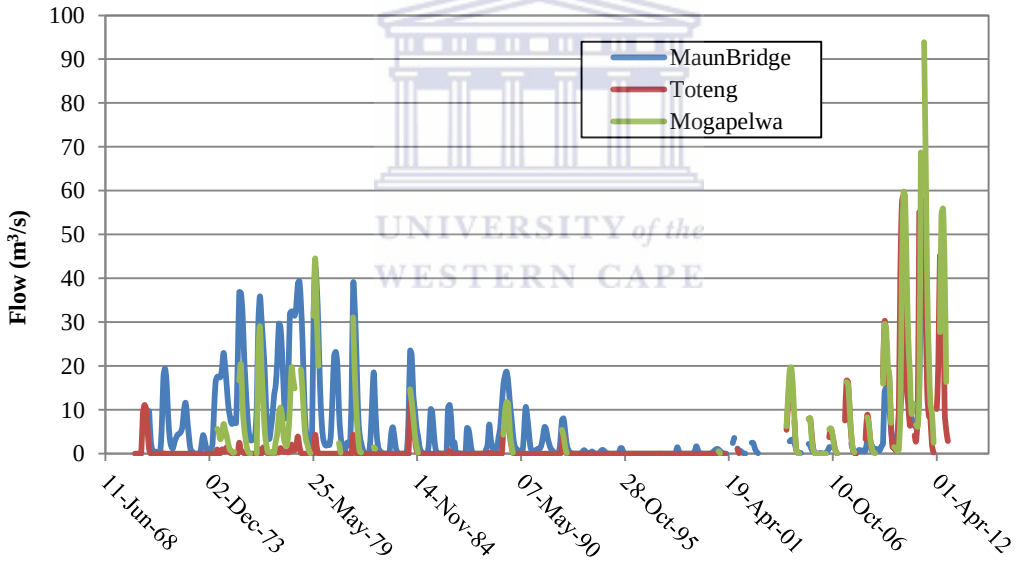

Figure 5.15: Monthly flow variation of Thamalakne at Maun Bridge with outflow to Lake Ngami at Mogapelwa and Totengfor 1970-2012 period

Flow duration curves constructed using monthly flow data for the period 1970-2012 show that zero flows are exceeded at both Maun Bridge and Samedupi during 79% of the months, and 43% of the months at Rakops (Figure 5.16). The zero flows are exceeded during 42% of the months at both Mogapelwa and Toteng (Figure 5.16). This implies that for most of the time during the 1970-2012 period, most of the floodplains along Thamalakane River and upstream Boteti River were inundated whilst inundation was less downstream of Boteti River.

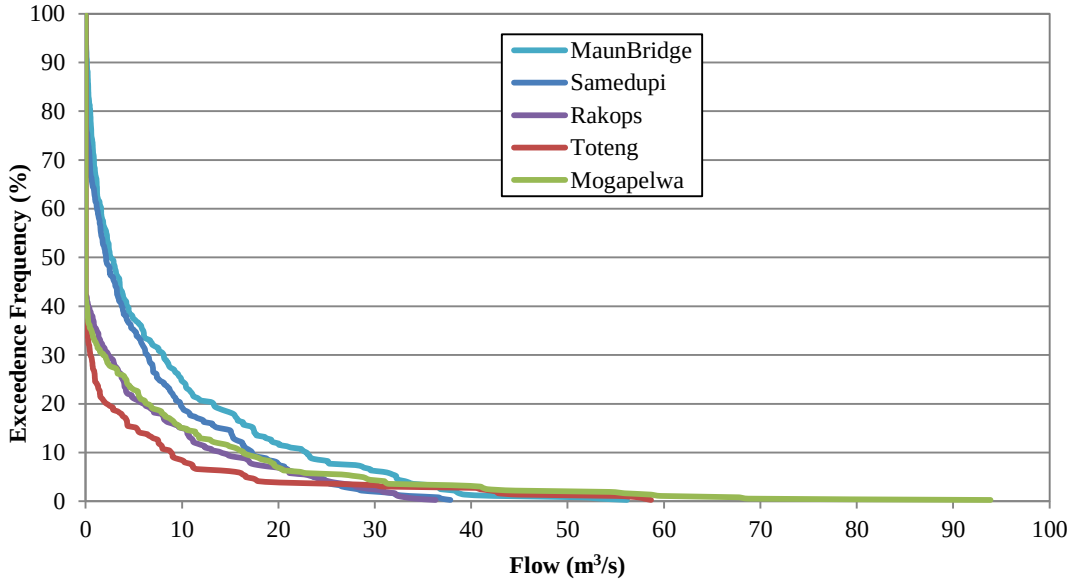

Figure 5.16: Flow Duration curves for the outflow stations, Maun Bridge along Thamalakane River through Samedupi and Rakops along Boteti River, Mogapelwa on Nhabe River and Toteng on Kunyere River outflows to Lake Ngami

5.4.4.2 Flow regimes on outflow channels

Identification of inconsistency between discharges at downstream stations with Mohembo flows was done using the double mass curve analysis. From the double-mass curve, change of slope was identified from the plot of annual cumulative flow at Maun Bridge against annual cumulative flow at Mohembo to depict different flow periods (Figure 5.17). The classification of the flow regimes was done depending on the flow values at each station in comparison to the stations average value (Table 5.4). A high flow regime is when the stations were dominated by annual flow values above average for the flow period, low flow regime is when all stations were dominated by flow values below the average within the period, and the dry period is when there were no flows (Table 5.4).

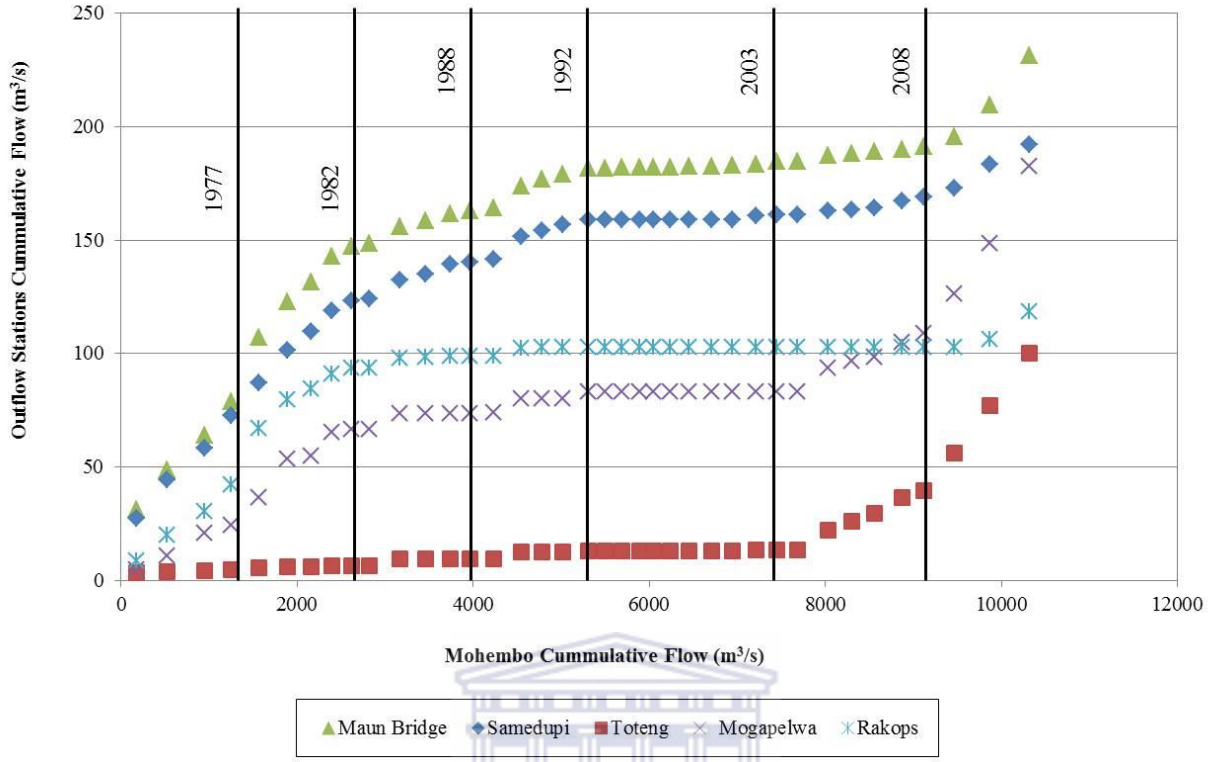

Figure 5.17: Double mass curve of Mohembo cumulative flows against the downstream stations of the Okavango Delta showing the change of slope therefore marking beginning and end of different flow periods

Boteti River has in the past experienced periods without flow, e.g. 1929-1939 (Shaw, 1984) however the 1993 – 2008 period has been the longest since 1900 when flows never reached Rakops (Table 5.4). The Nhabe and Kunyere Rivers were also dry for the 1993-2003 period therefore no flows reached Lake Ngami. Only in 2004 flows reached this lake. High flows causing maximum inundation, reaching Lake Ngami and Boteti River at Rakops are triggered when annual flow at Mohembo reaches values more than 400 m^3/s, as observed in 1974-1977 and 2009-present periods. Subsequently the system remains wet for another 4-5 years even if the annual flows at Mohembo drop below 400 m^3/s.

Table 5.4: Periods with and without flows at the outflow stations from the Okavango Delta, with annual flow range at Mohembo

Period	Number of Years	Condition of the Thamalakane River at Maun Bridge	Condition of the Boteti River at Samedupi	Condition of the Boteti River at Rakops	Condition of the Nhabe River at Mogapelwa	Condition of the Kunyere River at Toteng	Annual Flow Range at Mohembo (m^3/s)
1970-1973	4	Low Flows	Low Flows	Low Flows	Low Flows	Low Flows	229-361
1974-1977	4	High Flows	High Flows	High Flows	High Flows	High Flows	173-434
1978-1982	5	High Flows	High Flows	High Flows	High Flows	High Flows	220-335
1983-1988	6	Low Flows	Low Flows	Low Flows and DRY	Low Flows and DRY	Low Flows and DRY	201-351
1989-1992	4	Low Flows	Low Flows	Low Flows and DRY	Low Flows and DRY	Low Flows and DRY	228-305
1993-2003	11	Low Flows and DRY	DRY	DRY	DRY	DRY	163-260
2004-2008	5	Low Flows	Low Flows	Low Flows	Low Flows	DRY	252-347
2009- Present	6	High Flows	High Flows	High Flows	High Flows	High Flows	344-447

5.4.4.3 Triggering outflows

Waters of the Okavango Delta are lost within the delta through evapotranspiration or groundwater recharge and the remaining is drained towards the Zambezi River and the Makgadikgadi pans which are the end-sinks of the endorheic drainage system (Shaw, 1984). The amount and distance reached by the outflows along the channel towards Zambezi River i.e The Selinda Spillway on Magweqana River and the channel towards Makgadikgadi pans i.e Boteti River is highly dependent on Okavango River at Mohembo inflows, precipitation and hydrological conditions in the swamp (Shaw, 1984), therefore triggering flows at different reaches. Since major outflow from the Okavango Delta is through the Thamalakne and Boteti rivers, it is therefore taken into consideration in this study. The outflows through Thamalakane and Boteti River play a major role in water supply of Maun and areas along Boteti River as there is groundwater scarcity, usually of saline nature along those areas (Gieske, 1996).

Parameter Optimisation

The linear resevior model was set up for three reseviors. Reservoir-1 is between Mohembo and Maun Bride stations, Reservoir-2 is between Maun Bridge and Samedupi stations and Reservoir-3 is between Samedupi and Rakops stations. The model was run at monthly and annual intervals. The values of *b*; the area-volume constant, *n* ; the area-volume exponent, g; the groundwater outflow parameter , *k*; the reservoir constant and V_{min} ; the minimum volume were optimised by means of trial and error based on findings from previous studies and, modeling by Dincer *et al* (1987) and Gieske (1996) to obtain the best model fit. The comparisons of simulated and observed flows are shown in Figure 18 to Figure 23. The graphs of simulated and observed compare well except for Maun station. There are some discrepencies of overestimation of flows during the low flow years. The discrepancy of simulating flows at Maun station can be explained by the Okavango Delta being the reservior between Mohembo station and Maun Station. The Okavango Delta is characterized by a complex interplay of hydrological processes and therefore difficult to optimize the minimum flow volume required for flows to be triggered at Maun station.

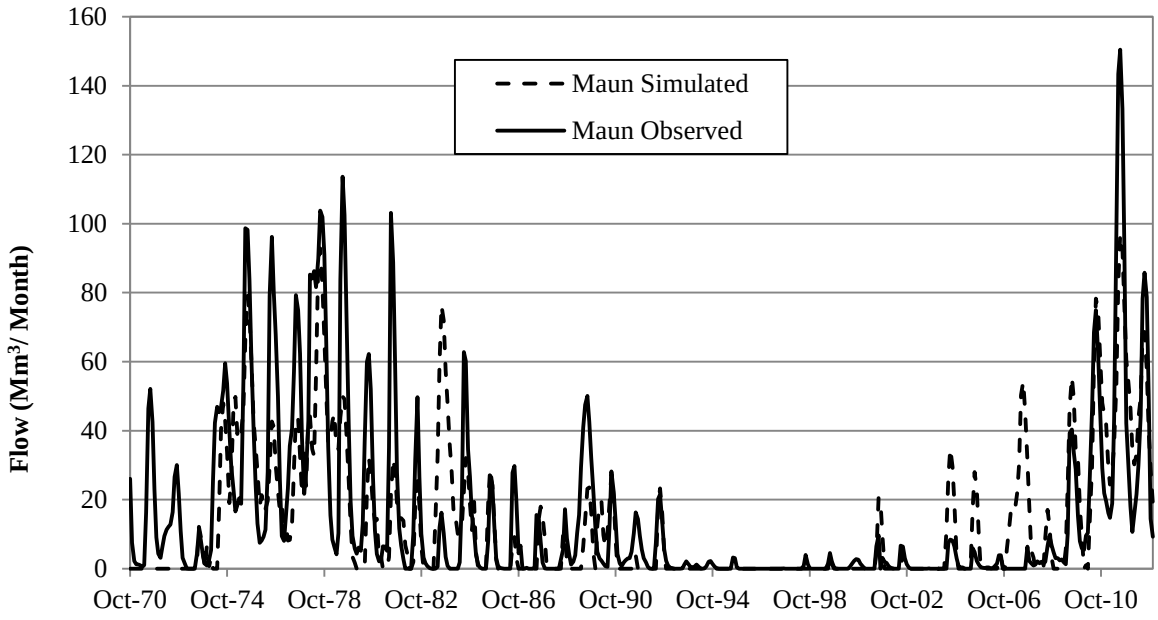

Figure 5.18: A comparison of simulated and observed monthly outflows for the modeled Maun Bridge outflow for reservoir-1.

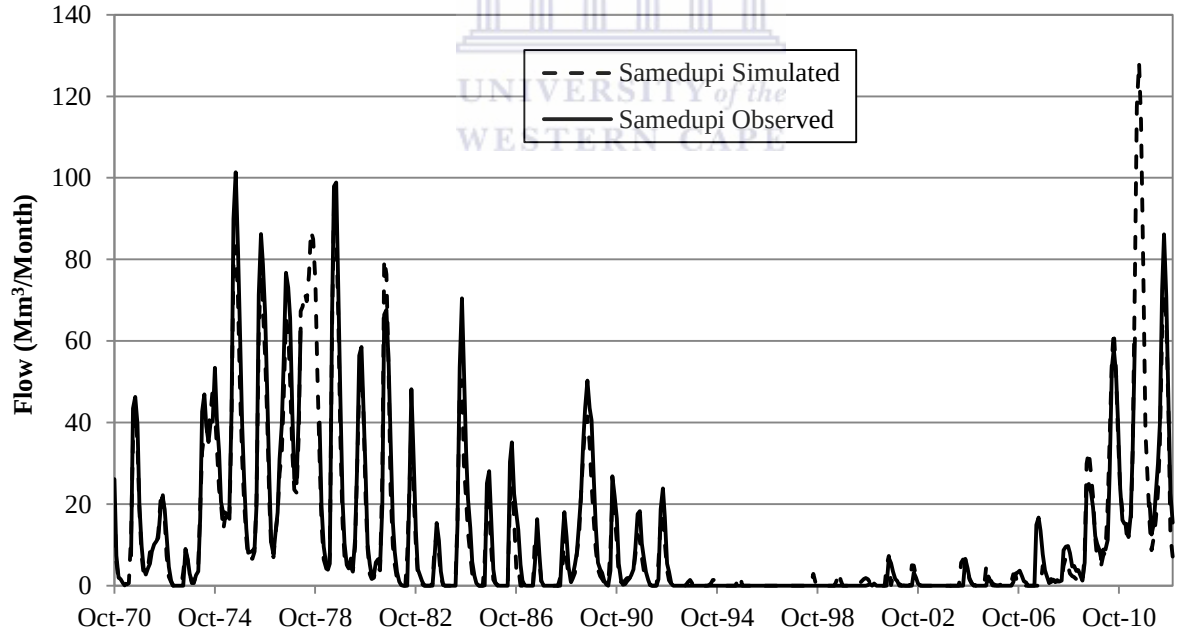

Figure 5.19: A comparison of simulated and observed monthly outflows for the modeled Samedupi outflow for reservoir-2.

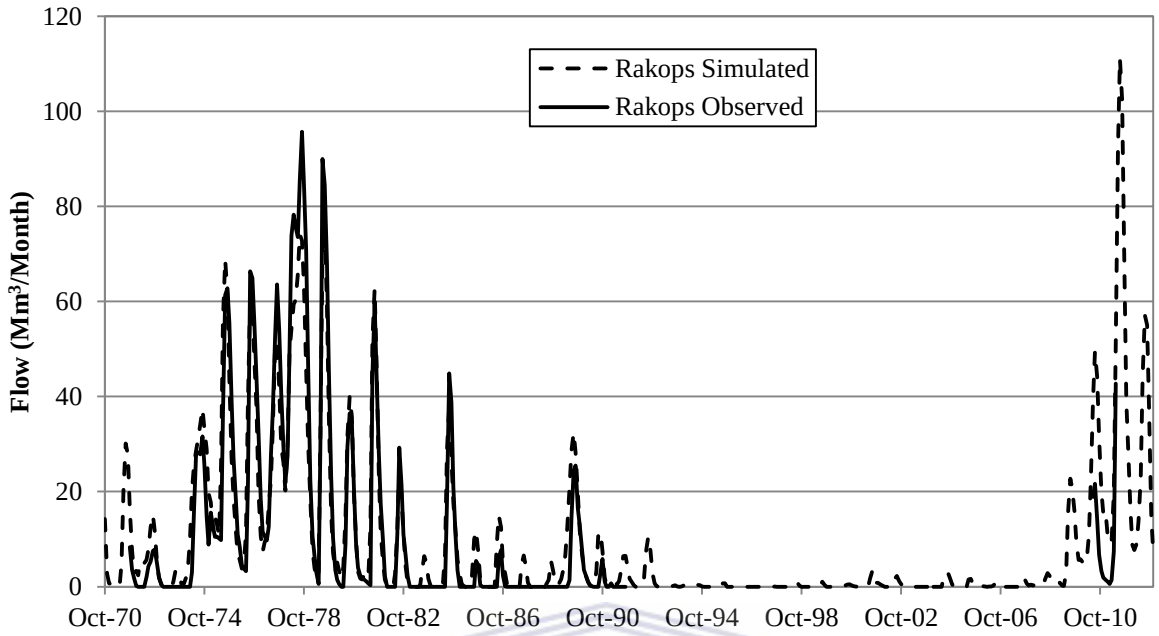

Figure 5.20: A comparison of simulated and observed monthly outflows for the modeled Rakops outflow for reservoir-3.

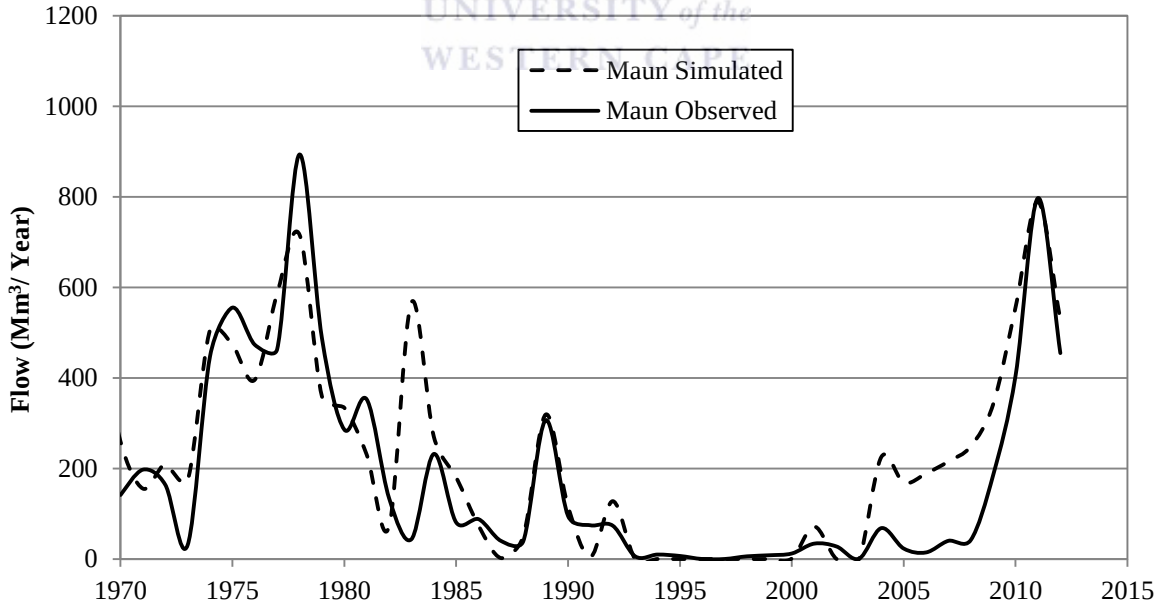

Figure 5.21: Comparison of annual simulated and observed outflows at Maun Bridge for Reservoir-1

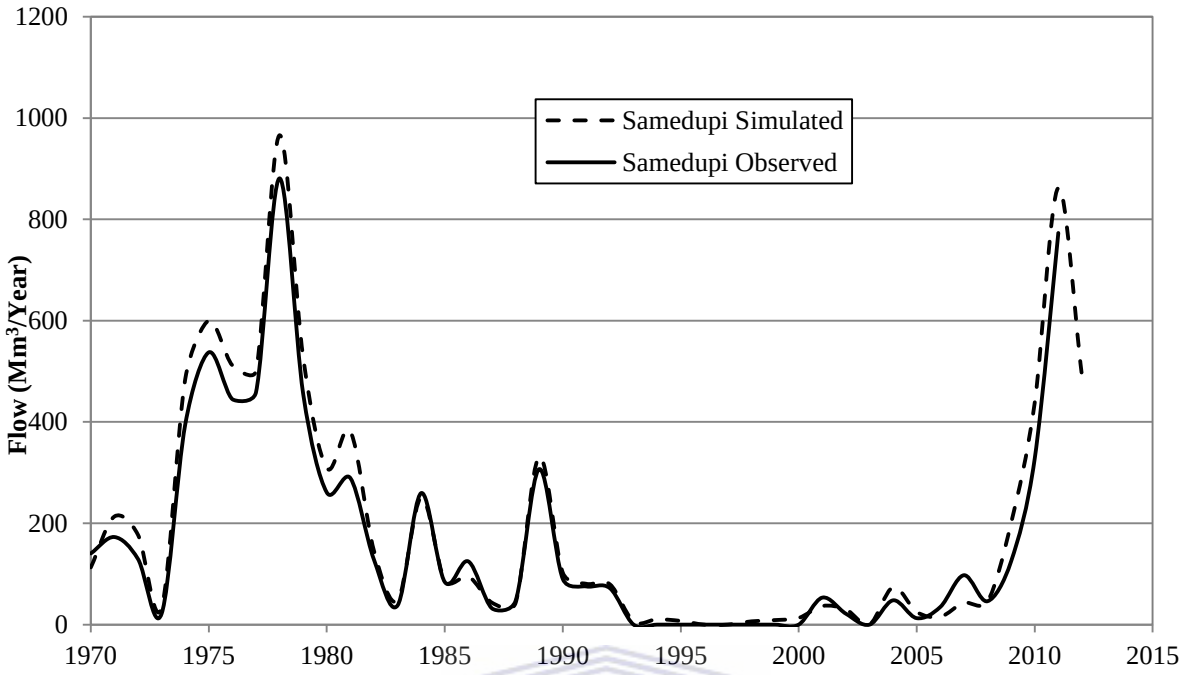

Figure 5.22: Comparison of annual simulated and observed outflows at Samedupi for Reservoir-2

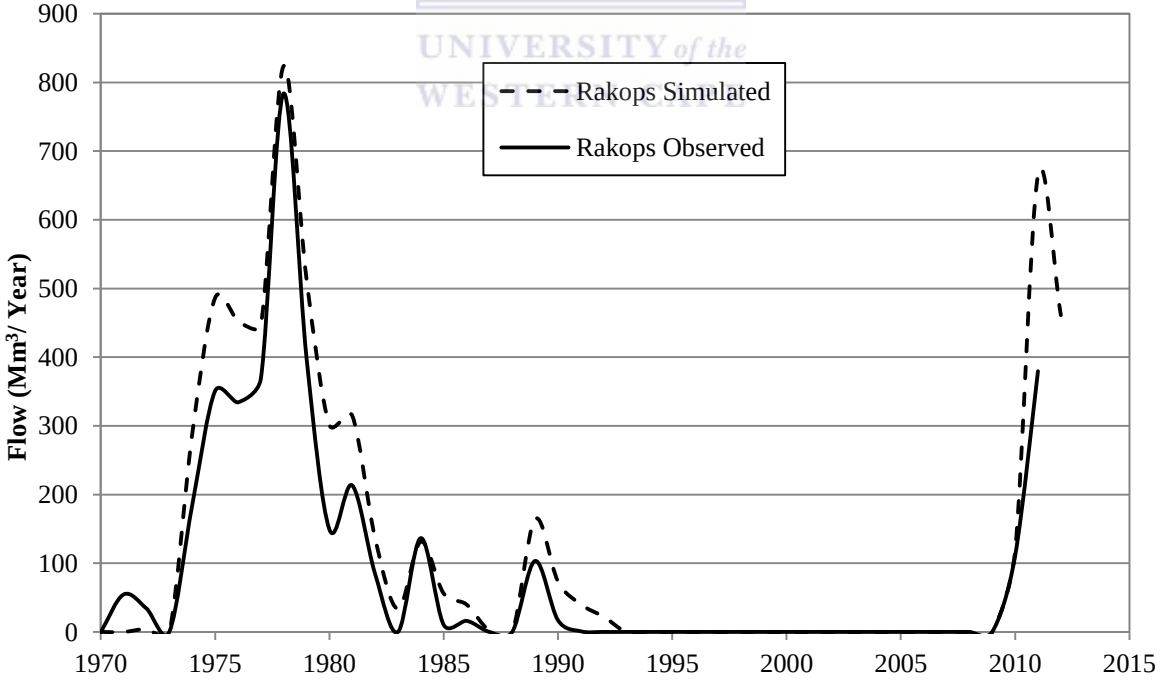

Figure 5.23: Comparison of annual simulated and observed outflows at Rakops for reservoir-3

Table 5.5: Optimised model parameter values at the three resiviours; Reservoir-1: Between Mohembo and Maun Bridge Stations, Reservoir-2: Between Maun Bridge and Samedupi Stations and Reservoir-3: Between Samedupi and Rakops stations.

Parameter	Symbol	Value	
		Monthly	Annual
Reservoir Constant -1	k_1	0.019	0.09
Reservoir Constant -2	k_2	0.779	1.12
Reservoir Constant -3	k_3	0.263	1.12
Area-Volume Constant -1	b_1	35	29
Area-Volume Constant -2	b_2	8.2	8.2
Area-Volume Constant -3	b_3	7.5	7.5
Area-Volume Exponent -1	n_1	0.59	0.57
Area-Volume Exponent -2	n_2	0.72	0.72
Area-Volume Exponent -3	n_3	0.6	0.6
Minimum Volume -1	V_{min-1}	4000	7800
Minimum Volume -2	V_{min-2}	0	0
Minimum Volume -3	V_{min-3}	30	400
Groundwater Outflow Parameter -1	g_1	0.021	0.0015
Groundwater Outflow Parameter -2	g_2	0.035	0.035
Groundwater Outflow Parameter -3	g_3	0.035	0.035
Maun Bridge Simulation	*RMSE*	0.78	18.6
Sanedupi Simulation	*RMSE*	0.64	6.7
Rakops Simulation	*RMSE*	0.47	12.9
Maun Bridge Hydrograph	R^2	0.57	0.74
Sanedupi Hydrograph	R^2	0.72	0.96
Rakops Hydrograph	R^2	0.88	0.89

Table 5.5 shows optimized parameters of the water balance equation at the three reservoirs. The RMSE values are higher for annual than the monthly simulations. This is likely to be due to the complexity of optimizing the minimum volume of water within Okavango Delta to be able to trigger flows at the downstream. There is a complex interplay of processes within the Okavango Delta which varies within a year (i.e; high flow season and low flow season) and therefore makes it difficult to estimate a single annual data point. The model performed well in simulating the hydrographs at the outflow stations with R^2 values much closer to 1.

Thresholds

The optimised storage volumes required to trigger outflows at each outlet station from the reservoirs are shown in Table 5.5. The results of the model show that minimum storage, i.e $V_{min,}$ needed within the Okavango Delta reservoir, between Mohembo and Maun Bridge to have outflows at Maun Bridge along Thamalakane River is 7,800 Mm^3 in a year and 4,000 Mm^3 in a month. Between Maun Bridge and Samedupi station, the minimum reservours storage is zero for both monthly and annualy. This is likely due to the short distance of about 20 km between the two stations. The two stations also receive almost the same average monthly and annual flows. To receive flows at Rakops station the minimum storage required to be exceeded is 30 Mm^3 in a month and 400 Mm^3 annually. The obtained thresholds correspond with months and years when flows were observed at the outlet stations. Table 5.6 and 5.7 shows selected months and years when the simulated storage was just above the threshold and resulted in flows observed at the outlet stations.

Table 5.6: Simulated minimum storage for selected months which triggered monthly flows at the specified stations

Year	Month	Simulated Storage (Mm^3)	Observed Maun Flow (Mm^3/month)
1973	July	4100	4.33
1982	July	4101	10.06
2009	May	4297	1.28

Year	Month	Simulated Storage (Mm^3)	Observed Rakops Flow (Mm^3/month)
1981	December	36.1	9.8
1984	December	34.1	3.5
2010	July	68	18.9

Table 5.7: Simulated minimum storage for selected years which triggered annual flows at the specified stations

Year	Simulated Storage (Mm^3)	Observed Rakops Flow (Mm^3/Year)
1972	405.0	34.0
1991	433.0	0.9
2010	472.0	110.5

Year	Simulated Storage (Mm^3)	Observed Maun Flow (Mm^3/Year)
1991	7853	74.51
1992	9092	73.51
2000	7812	12.24
2001	8526	33.98
2004	10079	68.23

5.5 Discussion

Various studies have been conducted in an attempt to understand partitioning of flows amongst the distributary channels of the Okavango Delta; Thaoge system, Jao-Boro system and Ngoqa-Maunachira system. Wolski *et al* (2005) used a 30 year hydrometric record from 1970 to 2000 for analysis and interpretation of flooding dynamics in the Okavango Delta. Wolski *et al* (2005) found out that water level and discharges at any given point in the delta is a product of complex interplay between incoming flood wave and local rainfall. Channel-Floodplain interaction is responsible for short and long term flood dynamics in the Okavango Delta (Wolski *et al*., 2005). The other main factor deriving the flooding dynamics in the delta is sediment transport and deposition which plays a major role in channel morphology (Wolski *et al*., 2005). This is more evident on the Nqoga Maunachira system where there is no consistency in the variations of water levels along side discharge at different points. Kurugundla *et al* (2009) explained the discrepancy as a result of blockages which cause ponding especially on the upstream of Ngoqa-Maunachira system, resulting in delay and reduced velocity of channel flow. Discharge trends also vary considerably along the different reaches of the same distributary channels of the Okavango Delta therefore inundation also varies. There are indications of shifts in direction of flows between channels, therefore increasing inundation along certain channel causing a reduction along the other. This is evident along Ngoqa-Maunachira river system where there is an increase in flow at Xakanaxa along Maunachira River from 2001 with a decrease at Txaba along Santantadibe River at the same time. A similar event happened over a long period of shifting of inundation from the Thaoge River towards the Xudum River (Wolski and Murray-Hudosn, 2006).

Kurugundla *et al* (2009 revealed that due to its elevation, the Thaoge system receives less flows compared to the other two systems. 32% of Okavango River flows at Mohembo reach Duba station along the Ngoqa-Maunachira distributary, whilst 12 % reach Jao/Boro station along the Jao-Boro distributary and 1% reach Qaaxhwa station along Thaoge River. Thaoge River experiences permanently inundated floodplains only up to Qaaxhwa station. The Jao-Boro system is perennial only up to the Madinare stations, from when it becomes seasonal to occasionally flooded as moving further downstream. Kurugundla *et al* (2009) revealed that most

of the Ngoqa-Maunachira system is perennial. This is confirmed by evidence of perennial flows at downstream stations such as Txaba and Xakanaxa.

About 2% of Okavango River flows at Mohembo leaves the Okavango Delta throung Boteti River. The outflow characteristics from the Okavango Delta give an idea of inundation extent over long time. 1983-2003 was a very long low flow period. When low flows persist the downstream channels; Nhabe River at Mogapelwa and Kunyer River feeding Lake Ngami, Thamalake River at Maun Bridge, Boteti River at Samedupi and Rakops started drying out and flows no longer reached certain floodplains. During the period of 1983-2003, the downstream channels were gradually becoming dry in most floodplains due to the persistence of low flows of that period. The identified flow periods on the downstream part of the Okavango Delta together with the cyclicity of the Okavango River inflows at Mohembo can give a clue about future inundation conditions of the delta.

6: CASE STUDY: RESPONSE OF SUB-SURFACE WATER TO INUNDATION

6.1 Introduction

In this chapter the, findings of field monitoring of soil moisture and groundwater table fluctuations are presented. The chapter presents the sub-surface water fluctuation in response to inundation induced by either rainfall or channel flows on the floodplains at three *molapo* farming areas within the Okavango Delta. The three *molapo* farming areas are Tubu, Shorobe and Xobe. The conceptualization of causes and processes associated with inundation of floodplains in the Okavango Delta is presented in Figure 6.1. The infiltration of water originating from local rainfall or river flows is highly influenced by the antecedent soil water content. Through percolation water is lost from soil moisture storage to groundwater storage. Water can either be removed from groundwater storage through capillary rise back into soil moisture storage, discharge into the channels or through subsurface flow into riparian vegetation. Water is lost from channels, soil and groundwater through evapotranspiration. Field monitoring of soil moisture and groundwater table was done for a period of one year along transects on *molapo* fields of Shorobe, Tubu and Xobe

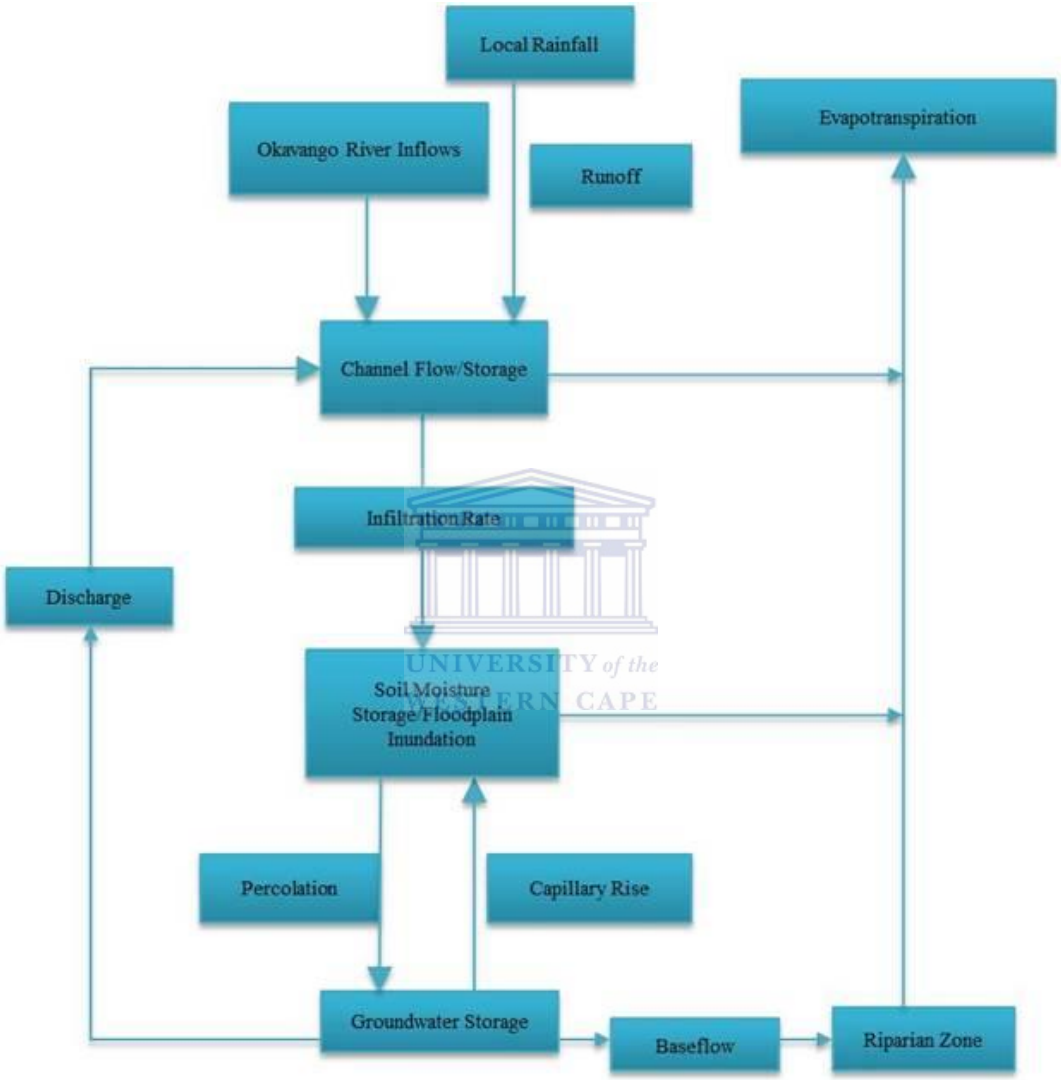

Figure 6.1: A schematic representation of interaction of hydrological processes that take place in the Okavango Delta channel-floodplain system.

Soil water status is a key variable in the spatial hydrological dynamics (Farrar *et al.*, 1994; Grayson *et al.*, 1997; Zehe *et al.*, 2010). The hydrophilic and hydrophobic soil status is strongly controlled by the antecedent soil moisture conditions (Zehe *et al*., 2010). The inundation variation can be identified by subsurface water content changes. Subsurface water occurs beneath the ground in the form of soil moisture in the vandose zone, soil moisture in the pheatric zone or a groundwater resevior (Linsley *et al*., 1975). According to Grayson *et al* (1997) soil moisture creates a link between water balances and surface energy through evapotranspiration and therefore determining the amount of water available for plants. Varying inundation frequency and duration explains the growth and survival of different floodplain vegetation species (Miller and Zedler, 2002). Different riparian plant species survive under different hydroperiods (Miller and Zedler, 2002). According to Farrar *et al* (1994) soil moisture is an important aspect in the distribution of vegetation. Horton and Clark (2000) also showed a strong relationship between the growth, survival and regeneration of riparian vegetation, with the groundwater table fluctuation.

6.2 Description of flood recession cultivation sites

Flood recession (*molapo*) cultivation is practiced on the fringes of the delta by communities in Shorobe, Tubu and Xobe (Figure 6.2). Shorobe communities cultivate along the floodplains of Gomoti and Santantadibe Rivers which sometimes receive water through backflows from the Thamalakne River. *Molapo* is practiced on the floodplains of Thaoge River at Tubu and for Boteti River at Xobe. River flows reach the three areas at different times of the year. Due to the inter-annual variations of the inflows, cultivation is not possible during some years. Every year, *molapo* cultivation is highly dependent on the onset of the rainy season and soil moisture conditions retained after recceeding floods. Farmers sow crop seeds at the onset of the rainy season (October-November) and immediately after the receding of water levels along floodplains (November –December). This is to utilize soil moisture derived from flooding for germination and early crop growth, then later stages of crop growth are supported by rains (December to March). Molapo farmers mainly cultivate maize; the Kgalagadi Early Pearl (KEP). KEP takes about 125-130 days (4 months) to reach maturity and therefore harvesting takes place around February-March before the arrival of upstream inflows and the dry season.

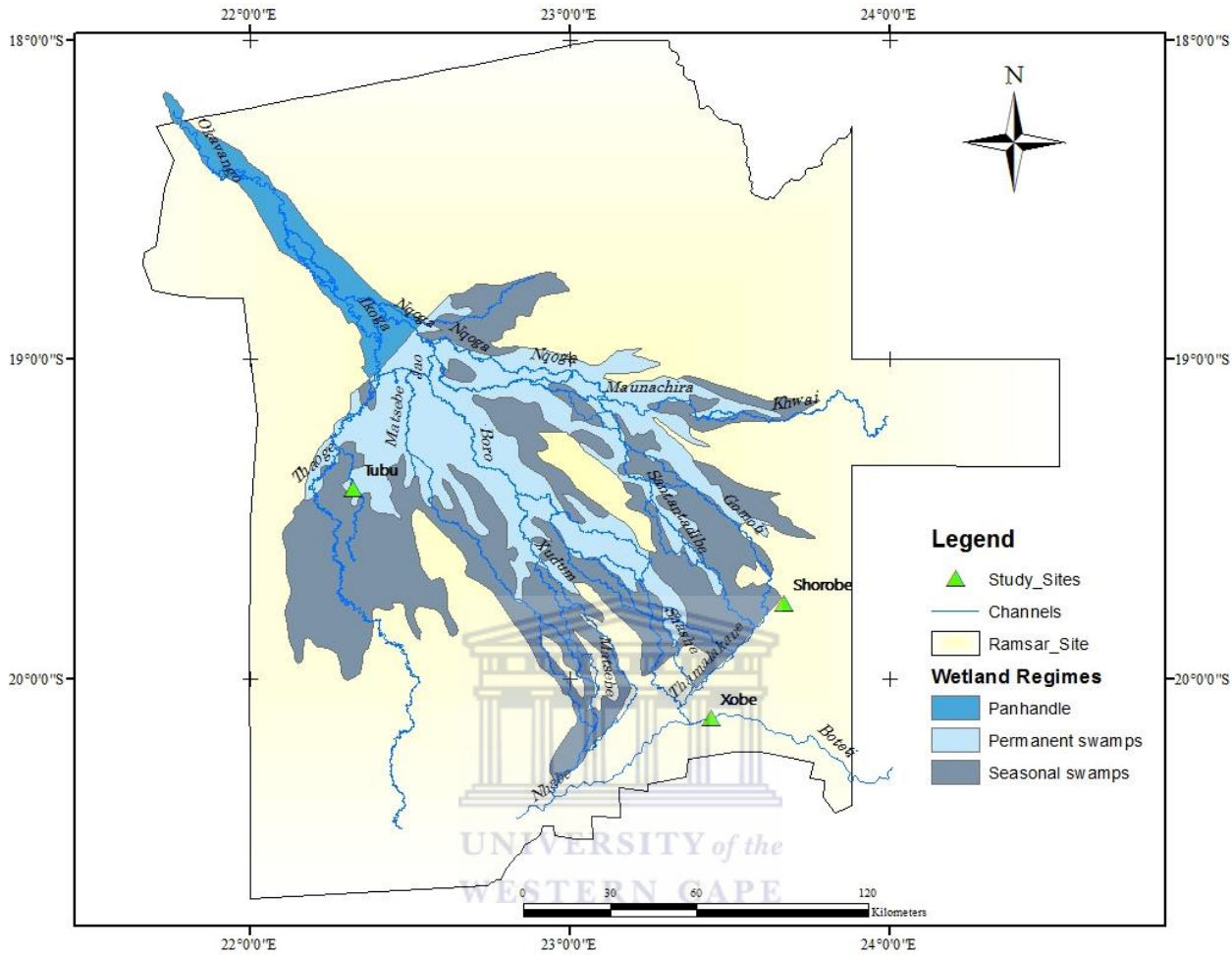

Figure 6.2: The three *molapo* study sites (Thaoge River at Tubu, Gomoti River at Shorobe and Boteti at Xobe where soil moisture and groundwater level monitoring were done.

6.2.1 Tubu floodplains

The Tubu settlement is located on the western fringe of the Okavango Delta, 10 km from Gumare. *Molapo* is practised on the floodplains of Thaoge River and along a series of small channels forming from spillovers of the main Thaoge River (Figure 6.2). The series of small streams are along an almost flat terrain which results in water logging (Figure 6.3) during high flows and the rainy season. The top 0-2 m of floodplain soils typically consist of a fairly shallow A-horizon of dark brown to black loam to clay soil with high silt content. This typically overlies fine white river sand. The vegetation is shrub grassland (Figure 6.3) with swamp vegetation. There is riparian woodland mixed with acacia plants.

Figure 6.3: Waterlogging on a typical flat terrain floodplain *molapo* field of Tubu due to rainfall

The major source of livelihood in Tubu is agriculture (both crops and livestock). Tubu has a series of lagoons which can retain water for a long period. The lagoons provide moisture on the floodplains and as a result *molapo* cultivation is also popular around them. During the drought years, there is no inundation of floodplains, therefore *molapo* cultivation takes place around lagoons.

6.2.2 Shorobe floodplains

The Shorobe village is located on the south-eastern distal part of the Okavango Delta and 36 km northeast of Maun (Figure 6.2). An extensive network of *molapo* farming is practised on the north-western part, on the floodplains of the Gomoti and Santantadibe Rivers and backflows from the Thamalakne River. Soils in *molapo* fields are classified as young alluvial soils. Texture varies from clayey, especially in low-lying areas, through fine loamy to coarse loam. The general soil profile is mainly loose white alluvial sand for the first 0-4 m, followed by sandy calcrete and then white sandstone or siltstone with some gravel. The vegetation in Shorobe is mainly shrub grassland, with riparian *acacia* and *mopane* woodland (Figure 6.4). Inflows do not reach Shrorobe floodplains every year. This causes *molapo* farmers to shift their fields towards the inner channel to occupy more inundated areas. During periods of no flows, molapo farming cannot be sustained and therefore some farmers relocate to upstream floodplains.

Figure 6.4: Shorobe *molapo* fields with typical riparian shrubbed woodland of *acacia* mixed with *mopane* trees

6.2.3 Xobe floodplains

The Xobe settlement is located 13 km east of Maun, along the Boteti River, a river which drains from the Okavango Delta (Figure 6.2). *Molapo* is practised on floodplains of Boteti River which is on the distal drylands. Soils in Xobe are coarse textured alluvial deposits. The general soil profile is made of alluvial sands or deposits for the first 0–3 m followed by greenish calcareous clay with mud stones (3 m to 6 m), calcacrete with silcrete inclusions for 6 m to 10 m, and then an alternation of calcrete and silcrete for the lower depths. The vegetation is grassland on the floodplains with riparian *acacia* woodland. Reeds occur along river banks (Figure 6.5). Livelihood activities for Xobe community include rainfed farming, *molapo* farming, irrigated vegetable production and livestock rearing. *Molapo* farmers cultivate along the river banks as the water flow recedes.

Figure 6.5: Xobe Floodplains with acacia trees and reeds on the near river banks

It is common in Xobe for a household to have both *molapo* and rainfed cultivated lands. There is strategic crop cultivation where crops which require more water are cultivated on floodplain closer to the channel to take advantage of the moistened part of the floodplain whilst those with less water requirements are on the outer part of the floodplain, and can be supplemented by irrigation. Crop cultivation is also seasonal; i.e different crops are cultivated at different times of the year. Vegetable cultivation takes place during the dry season (Winter Season: May- August), then during the wet rainy season (September-April) cereals are cultivated making use of antecedent moisture conditions and rainfall.

6.2.4 Field monitoring

6.2.4.1 Installation of peizometers

In order to investigate the changes in groundwater levels and the response to either local rainfall or incoming flows, piezometers were installed in the floodplains of the study sites. A sketch diagram showing the layout of monitoring piezometer is shown in Figure 6.6. The piezometers were made of 63.5 mm diameter PVC. The PVC was connected to another perforated PVC of diameter 63.5 mm in diameter and inserted in a hole dug by a drilling machine. The PVC was inserted in such a way that the perforated part was crossing the groundwater table (Figure 6.6). The perforated part of the PVC was to allow free movement of water so the groundwater level changes can be obtained. A 165 mm diameter steel casing was inserted inside the ground a few centimetres to protect the PVC pipe from vandalism and being damaged (Figure 6.6). The top of the steel casing was covered with only small opening at the top to allow water level measurements. This was to avoid entry of rain water inside the PVC.

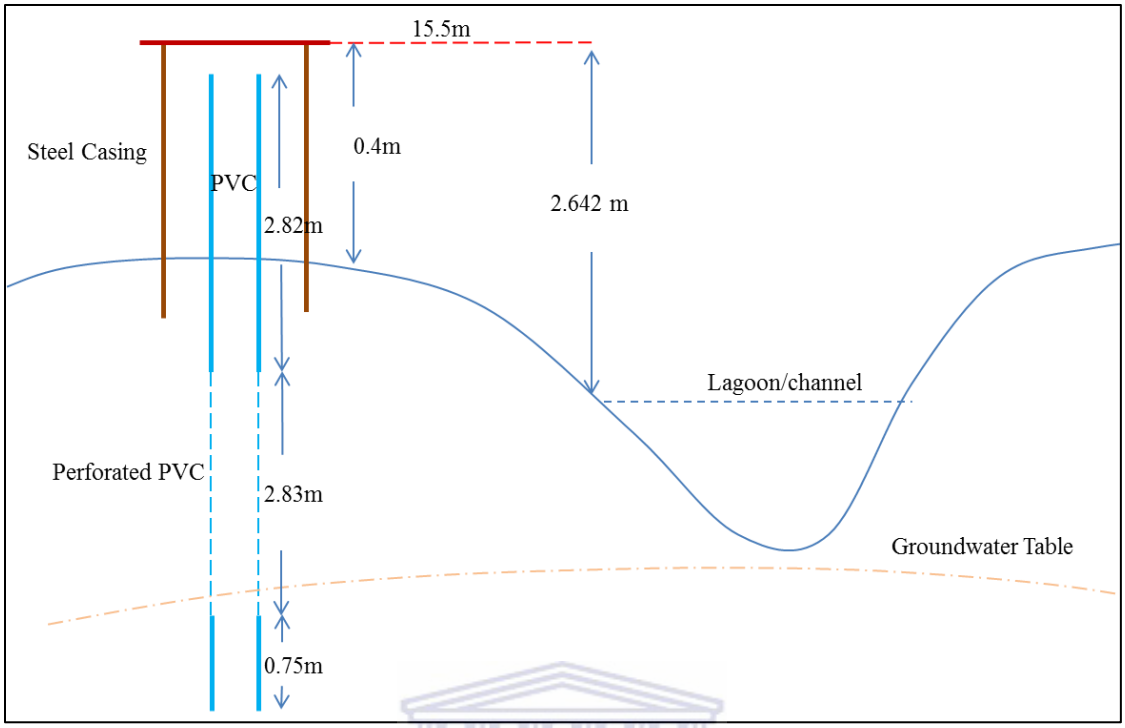

Figure 6.6: A layout sketch of a monitoring piezometer installed at the molapo floodplains of Tubu, Shoroeb and Xobe

Four boreholes were drilled for groundwater table measurements in Tubu, 2 along a 100 m transcect across streams from Xorocha lagoon, with the first borehole 20 m from lagoon (Figure 6.7). The other 2 were installed from an outer stream along a 100 m transcect going towards the riparian drylands (Figure 6.7). In all the boreholes the water struck was between 4 m and 5 m and they were all dug to a depth of 6 m

Figure 6.7: A sketch map of piezometer set up along floodplain of Thaoge Rivers at Tubu. Piezometer BH10830 and BH10833 is next to Xorocha lagoon, and BH10832 and BH10834 on the distal dryland channel (*Source: Google Earth-30/09/2013*).

A set of piezometers (3) were established at Shorobe near the confluence of Gomoti River and Thamalakane River (Figure 6.8). The set was a bit shallow with water struck ranging from 2 m to 5.5 m and dug to a depth ranging from 9 m to 12 m. The other 2 boreholes were drilled upstream on the along Gomoti River with the first piezometer 15 m from the channel having shallow water level at a water struck of 1m and the second one 100 m away from the channel (Figure 6.8) and a water struck of 24 m.

Figure 6.8: A sketch map of piezometer (BH10848, BH10849 and BH10850) set up along Gomoti River at Shorobe (*Source: Google Earth-19/02/2013*)

Eight boreholes were installed at Xobe, 4 upstream along a transcect, 2 on either sides of the channel and the other 4 on the downstream part about 4km from the upstream transcect (Figure 6.9). The first boreholes were drilled within the floodplains about 25 m from the channel then followed by another borehole 100 m away from the river bank towards the riparian dryland. Boreholes close to the river bank were drilled to a depth of 6 m to 6.5 m with water struck ranging from 4.5 m to 5.5 m whilst the ones 100 m away from the river bank had water struck of 14 m to 18 m drilled to a depth ranging from 20 m to 30 m. Groundwater level measurements were conducted bi-weekly for a period of a year from February 2012 to January 2013.

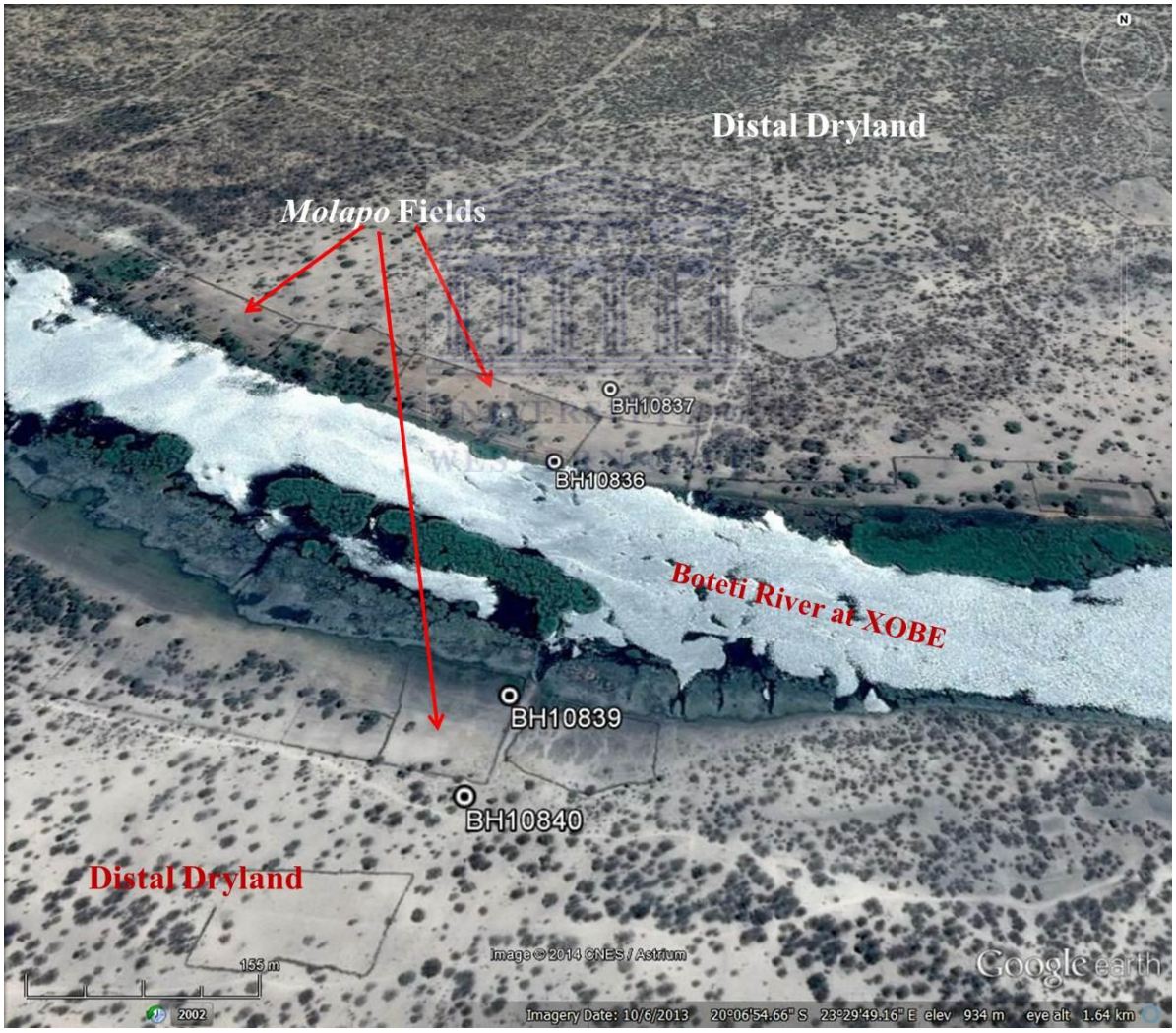

Figure 6.9: A sketch map of piezometer set up along floodplains of Boteti River at Xobe, (BH10836, BH10837, BH10839 and BH10840) another 4 peizometers were drilled 4 kilometers downstream (*Source: Google Earth-06/10/2013*)

6.2.4.2 Installation of soil moisture access tubes

Alongside the boreholes, soil moisture access tubes were installed. A PR2 Soil Moisture Profile Probe (PR2/6) was used to measure percent soil moisture on the floodplains. The access tubes were 100 cm deep buried in floodplain soil column. An HH2 Moisture Meter connected to the Profile Probe (PR2/6), was used to measure soil moisture at 10 cm, 20 cm, 30 cm, 40 cm, 60c m and 100 cm depths. Due to shortage of access tubes, only 3 were installed at Tubu, 8 were installed at Xobe and 4 installed at Shorobe. Soil water monitoring was done every 2 weeks.

6.3 Results

6.3.1 Groundwater response to inundation

The groundwater table was high in February 2012 and declined in March 2012 (Figure 6.10). The groundwater table continued to remain low from March 2012 through to May 2012 until it started rising from June to August 2012 indicating the response to recharge from the river as the peak flows reach Tubu floodplains from June to August 2012 (Figure 6.10). The groundwater table declined in October 2012 before showing a slight increase in December 2012 until January 2013. This pattern shows significant response to recharge from rivers and less to local rainfall.

The groundwater table fluctuation pattern on the floodplains along Boteti River at Xobe, is simillar in all the piezometers. An example of the groundwater fluctuation is shown using piezometer BH10839, 25 m away from the channel and BH10840, 100 m away from the channel (Figure 6.11). However, BH10839 shows shallow groundwater levels, therefore groundwater table close to the channel is shallow. The groundwater table declined in March/April 2012 therefore responding to cessation of recharge by rainfall. A rise in groundwater table was observed in May/June 2012, marking the arrival of the inflows, and therefore recharge from the river. The water table shows minor variations from September 2012 until December 2012 when a sharp rise was observed (Figure 6.11). The groundwater table responded to both recharge from the river and rainfall.

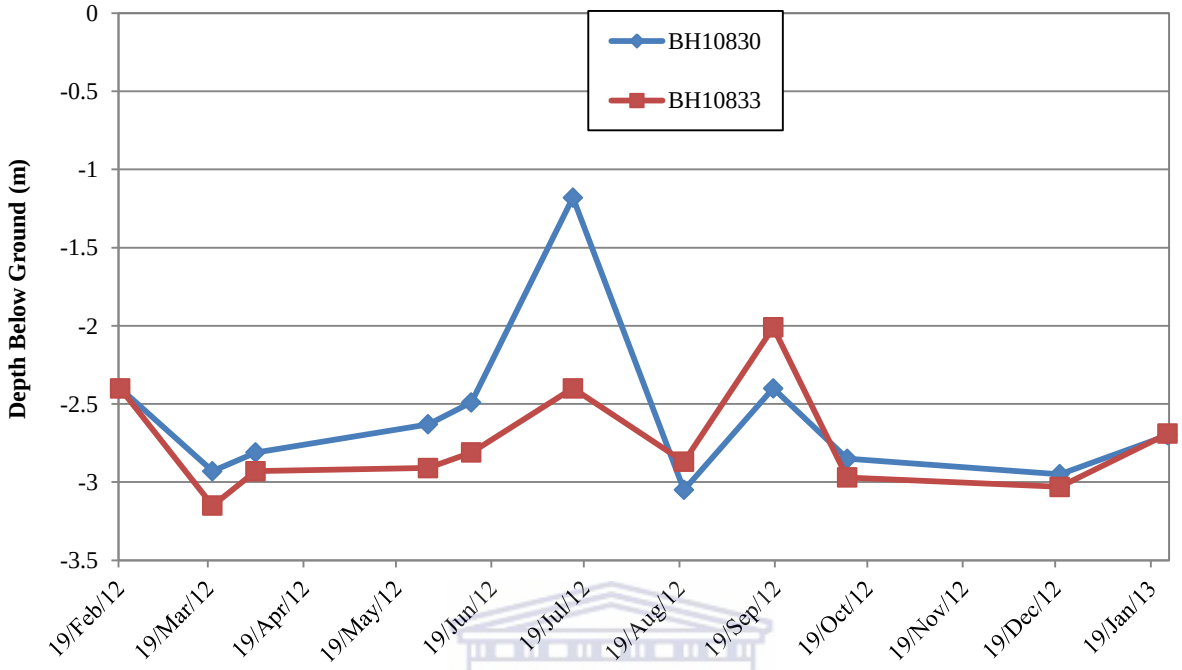

Figure 6.10: Observed groundwater levels on the floodplains along Thaoge River at Tubu

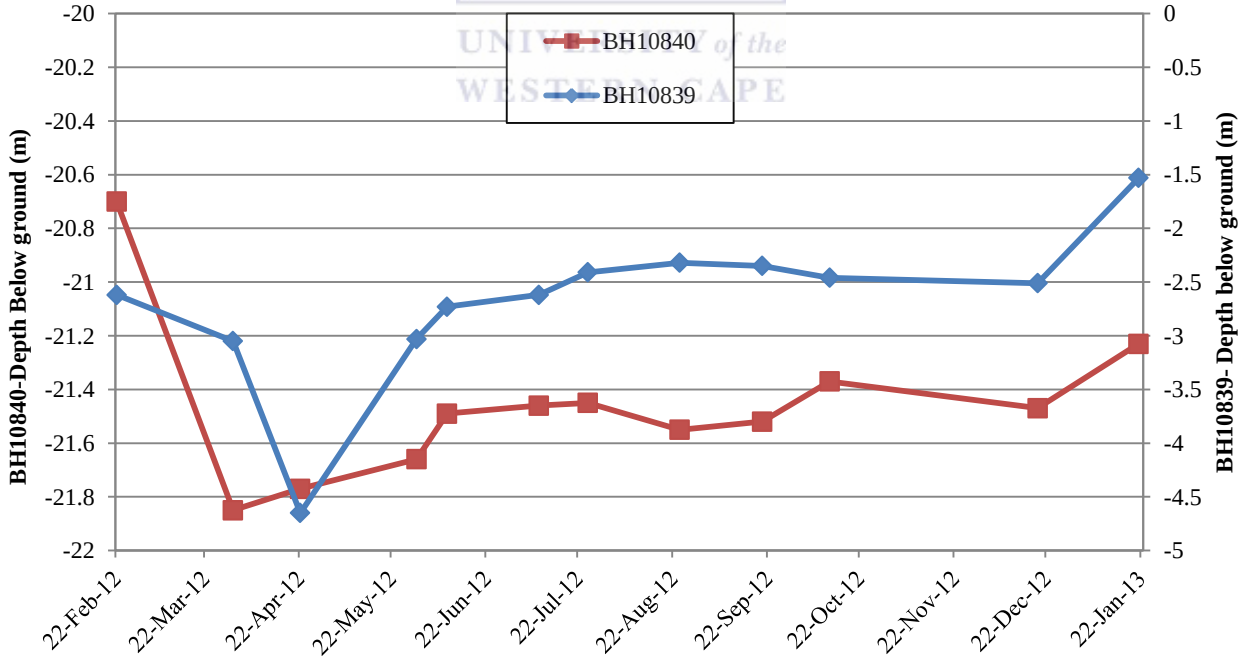

Figure 6.11: Groundwater level fluctuations on the floodplains of Xobe, 25 m (BH10839) and 100 m from the channel (BH10840)

The groundwater table variations on the floodplains along Gomoti River at Shorobe are shown in Figure 6.12. Groundwater tables declined from March 2012 until May 2012 when a slight rise was observed (Figure 6.12). The levels remained stable until August 2012 when they declined until rising again in December 2012. Although the fluctuations can be associated with both incoming flows from June to August and local rainfall from December until March, the rise and falls in groundwater level are rather gradual. During the period of data collection, 2012/2013, flows were still retained in the Boteti River after the 2009, 2010 and 2010 extreme wet years, therefore there was continuous recharge which made the arrival of 2012 and 2013 inflows not to make a sharp change.

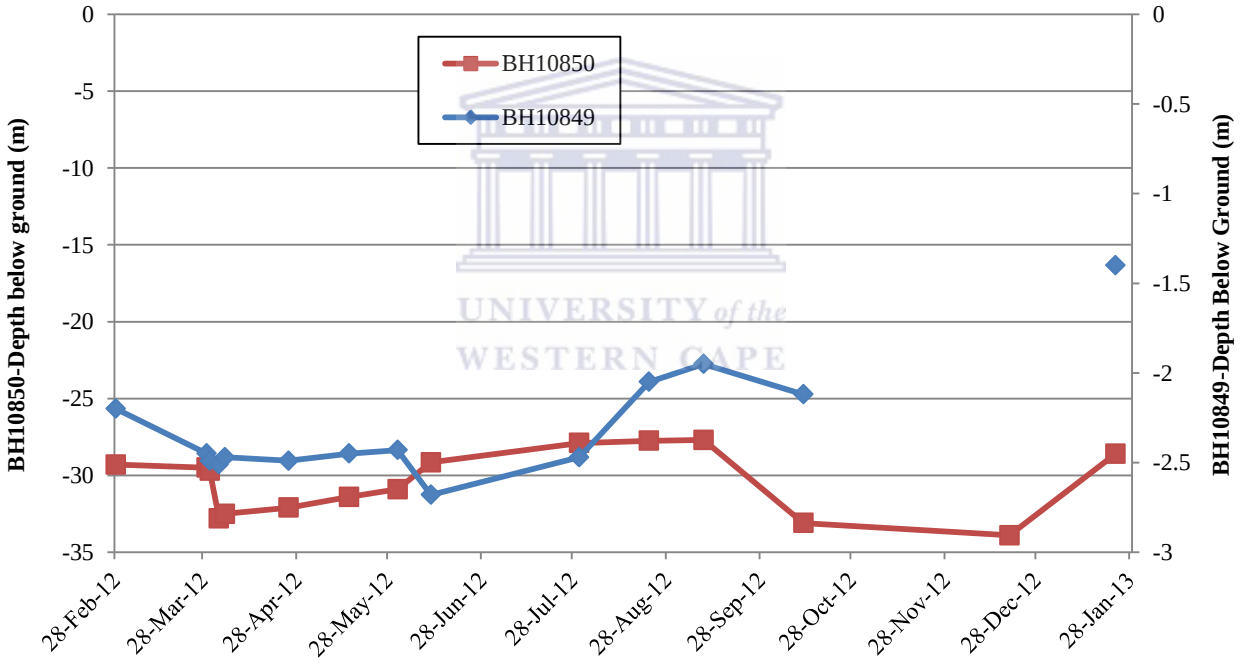

Figure 6.12: Changes in groundwater levels with floodplain inundation along Gomoti River at Shorobe

6.3.2 Soil moisture response to inundation

Soil moisture was monitored along the floodplains of Thaoge River at Tubu as shown in Figure 6.7. Figure 6.13 shows soil moisture variation on these floodplains at different depths during different seasons. Soil moisture decreases in May 2012 and then increase in June until September

2012 followed by decline until an increase in January 2013. The first decrease in May 2012 of soil moisture indicates a response to the end of the rainy season and therefore starting to increase again in June 2012 indicating inundation due to the arrival of the inflows. The observations show the highest moisture content recorded at 60 cm and a different behavioural trend recorded at 100 cm. The soil moisture values at 100 cm depth shows a sharp increase from June until September. Soil moisture values are lowest at 100 cm depth for the rainy season period therefore explained by poor penetration of rain water through the clay top soil layer which is sediment rich forming the top layer of the floodplain soil profile, 0-2 m deep.

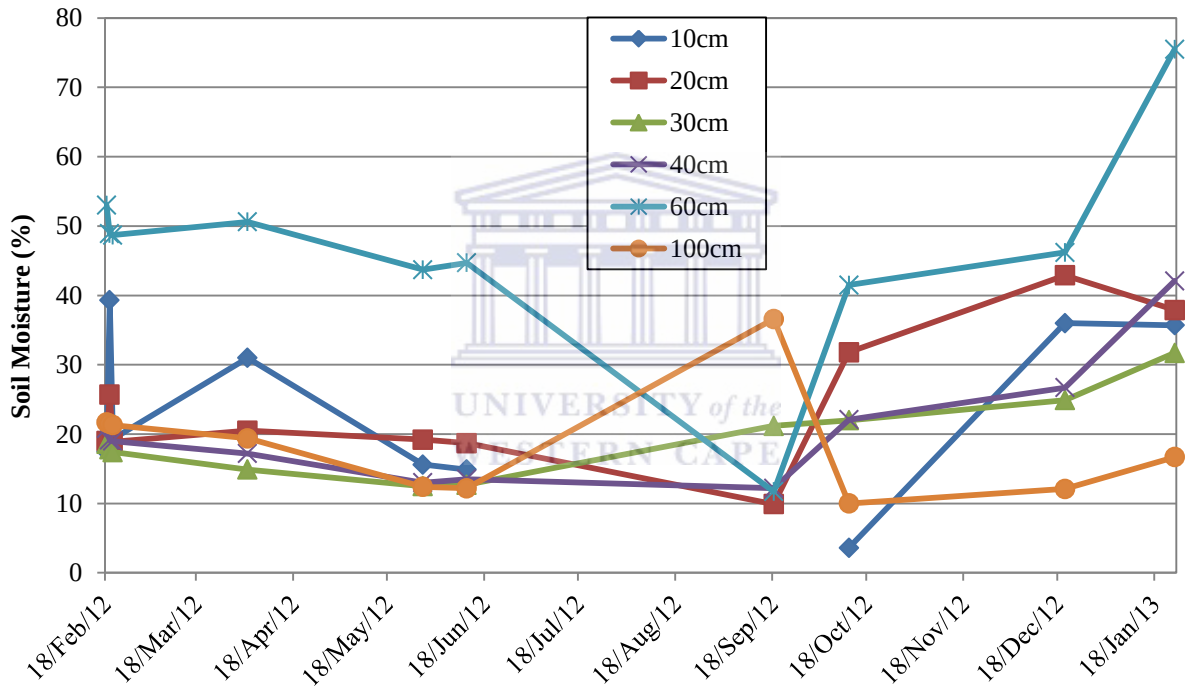

Figure 6.13 Soil moisture variations in response to rainfall and flows on the floodplains along Thaoge River at Tubu

Soil moisture monitored along Boteti River floodplains at Xobe showed response to both incoming flows and local rainfall (Figure 6.14). The access tube 25 m away from the channel responded to both flows and at depths of 20 cm, 30 cm, 40 cm, 60 cm and 100 cm. The soil moisture content at all levels shows an increase in July 2012. This is an indication of response to incoming flows, which reach Xobe floodplains around June/ July. The soil moisture content starts to decrease in September 2012 until December 2012 when it started to rise again therefore

responding to local summer rainfall. High soil moisture content values are observed at 60 cm and 40 cm. The access tube 100 m away from channel responded differently. The soil moisture content remained almost constant until October 2012 when it started rising, therefore responding to local summer rainfall. At 100 m away from channel, soil moisture content is highest at 100 cm and 60 cm.

The soil moisture content variation along Gomoti River floodplains at Shorobe is shown in Figure 6.15. The soil moisture is highest at 100 cm and 60 cm deep (Figure 6.15). The soil moisture declined in April/May 2012 and increased again in June 2012. The soil moisture 15 m away from the channel could not be obtained during the high flow period July to October 2012 due to submerged access tubes. However, there is a sharp decline in soil moisture from November 2012 until January 2013 for the access tube 15 m away from the channel. The sharp decline was observed at all depths except for the 60 cm and 100 cm which rather showed an increase in soil moisture. Soil moisture 100 m away from channel showed no variations until a decrease in March 2012 whilst at 10 cm depth sharp increase was observed. The soil moisture remained almost constant at all depths until August/September 2012 showing a sharp increase eventually decreasing again in November 2012 (Figure 6.15). Soil moisture 15 m from the channels shows response to both inflows and rainfall whilst at 100 m from the channel, there is significant response to rainfall.

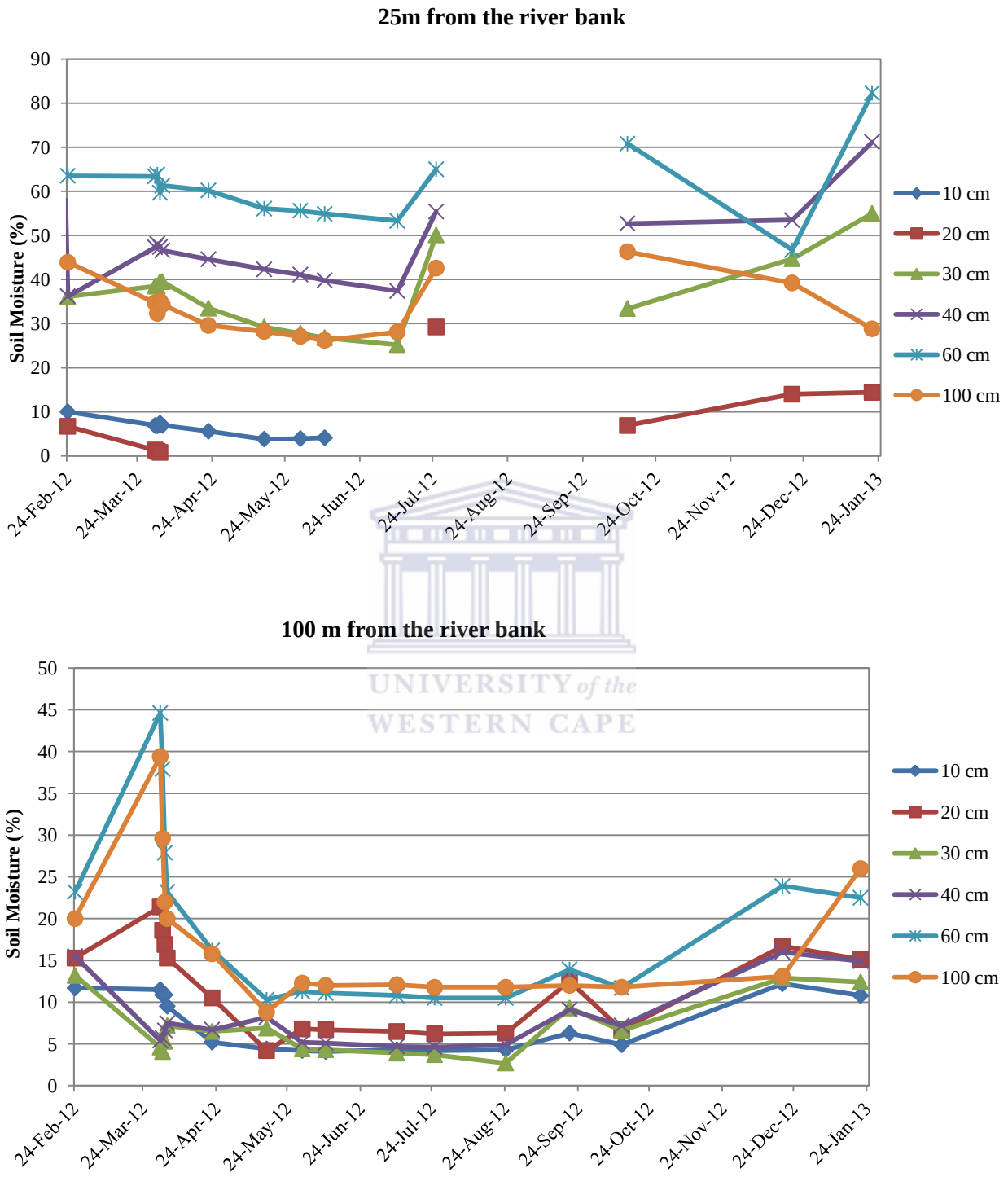

Figure 6.14: Soil moisture variation along Boteti floodplains at Xobe, 25 m and 100 m away from river. Flows reaches the floodplains of Boteti around July/August and therefore the moisture probes at 25 m were submerged

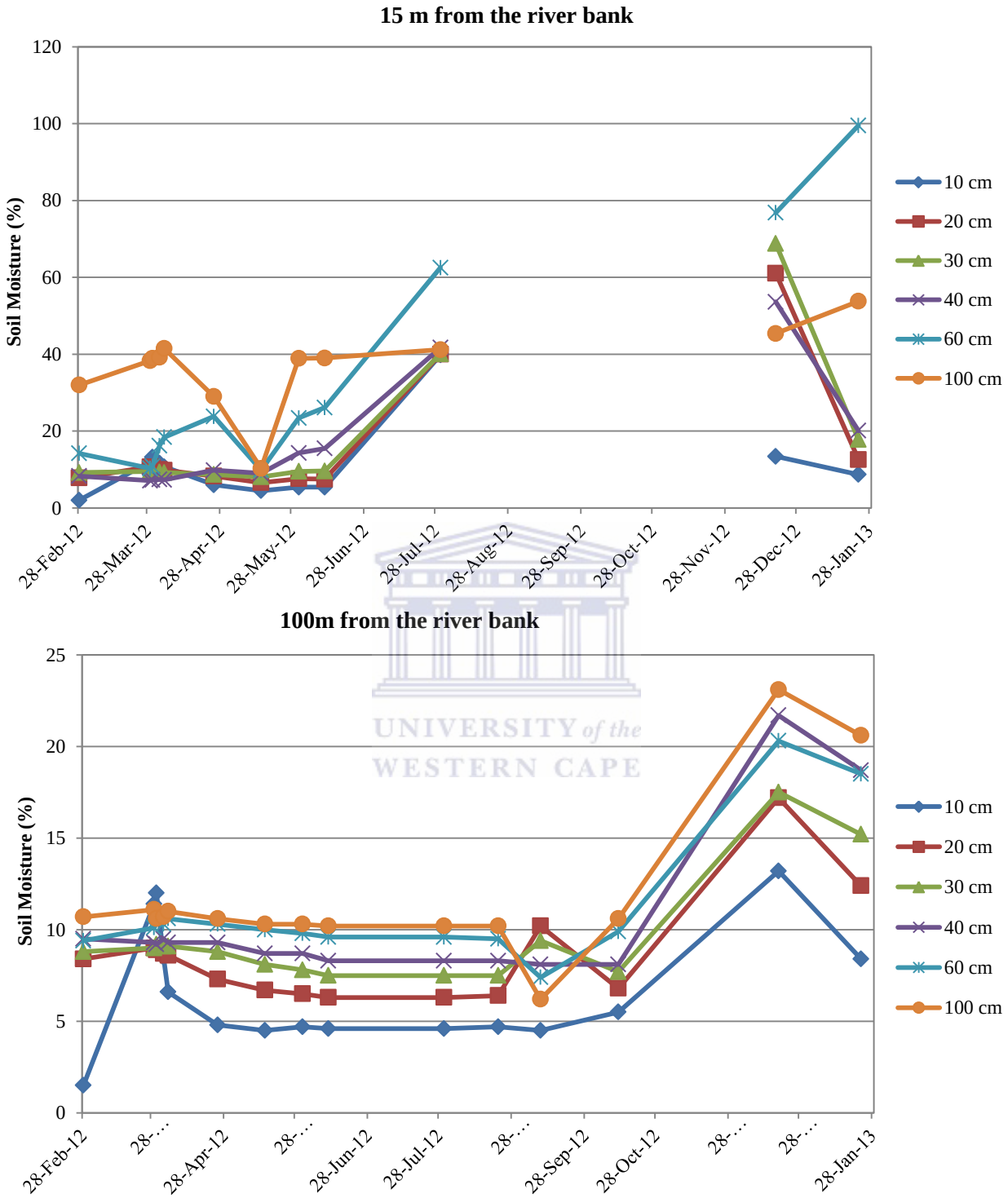

Figure 6.15: Observed soil moisture changes along the floodplains of Gomoti River at Shorobe. Flows reaches the floodplains of Shorobe around July/August and therefore the moisture probes at 15 m were submerged

6.4 Summary

Soil moisture content is mainly high at 60 cm and 100 cm depths at all floodplains and responds significantly to both rainfall and incoming flows at Tubu floodplains. At Sorobe and Xobe soil moisture responded significantly to both rainfall and river flows for floodplains close to the wetted channel whilst the ones far from wetted channel responded more to rainfall. However groundwater levels at Tubu responds significantly to flows than rainfall. Soil moisture and groundwater levels pattern at Shorobe and Xobe respond to rapid infiltration of incoming flows and rainfall. The sub-surface water at *molapo* floodplains indicate response to both flows and rainfall, even though water levels along the distributary channels correlates poorly with rainfall.

7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

The ecological integrity of wetlands relies greatly on floodplain inundation (Powel *et al.*, 2008). The duration, frequency, timing and extent of flooding are important aspects in understanding floodplain inundation and this can be achieved through understanding catchment flows and maintaining flooding cycles. Water resources developments have significantly altered flow patterns of many river systems and therefore affecting ecological communities (Jungwirth *et al.*, 2002; Powel *et al.*, 2008). Tropical wetlands contribute considerably to the welfare of a significant number of humankind but their ecological intergrity is threatened by the uninformed use of these resources (Junk, 2002). Therefore improving understanding and predictability of floodplain inundation improves sustainable utilization of resources (Junk, 2002) especially in seasonal wetlands of semi-arid regions which support plants, animals and humans. The Okavango Delta is such an example of a wetland which supports plants, animals and humans, as some floodplains can remain dry for decades, yet when the water arrives, the characteristic flora and fauna of the wetland reappears. When the water arrives at certain floodplains after years of dryness, the wetland livelihood activities such as floodplain cultivation are re-established.

As stated at the beginning of this thesis, the main goal of this study is to improve understanding of floodplain inundation as a result of Okavango River inflows and local rainfall in the Okavango Delta. The findings of this study are therefore useful for sustainable utilization and management of the Okavango Delta resource. Recently complex hydrological models have been used to improve understanding floodplain inundation, however their high data demand and uncertainty remains a challenge (Hunter *et al*, 2007; Powel *et al*, 2008). The use of remote sensing techniques in mapping flooding and inundation extent has also demonstrated usefulness but the lack of availability of data for calibration is a challenge (Horrit and Bates, 2002). In this study statistical approaches have been used to establish the characteristics of local rainfall and flows within the Okavango Delta and assess the implications on floodplain inundation with special reference to floodplains used for *molapo* cultivation. The following broad conclusions have been drawn out of this study;

7.2 Rainfall variability and implications to floodplain inundation

The summer months rainfall has a pattern which is influenced by the ITCZ. Monthly spatial variation of rainfall during the rainy season changes following the movement of the ITCZ, hence the seasonality of rainfall induced floodplain inundation. However rainfall pattern shows a scattered pattern due to localized thunderstorms. This is reflected by a poor correlation between neighboring stations even within a distance of 150 km. The detected change points in rainfall regimes can be associated with ENSO episodes hence rainfall induced floodplain inundation may vary with El Nino and La Nina episodes. Although rainfall does not show trends and cyclicity, high rainfall years tend to follow each other and low rainfall years also following one another. Three rainfall sub-regions were identified. There is a high rainfall sub-region up north, a low rainfall sub-region in the middle, and a medium rainfall region in the low northern part and low southern fringe of the Okavango Delta.

7.3 Okavango River flow characteristics and implications to floodplain inundation

The Okavango River flows at Mohembo do not have significant trends except for minimum flows which show a decreasing trend. Change points are identified and they cannot be associated with any major developments or land use change since there has never been any in Okavango River Basin upstream which can cause any flow alterations. Rather, the change points can be associated with the cyclic behavior of the flows. Three major significant cycles are identified and they can be associated with the periodic drying and wetting of the Okavango Delta floodplains which has been experienced in the past. The general characteristics of floodplain inundation in the Okavango Delta can be explained by the cycles. Floods which have a potential of inducing maximum inundation in the Okavango Delta floodplains have recurrence intervals of 10 and 40 years within a period of 40 years.

7.4 Implications of flow partitioning and distribution on floodplain inundation extent

The Okavango River flows at Mohembo travel through the panhandle eventually partitioning into three main distributory channels; Thaoge River on the west, Jao-Boro River in the middle and the Ngoqa-Maunachira River on the eastern side. Due to topographic differences, most of the water flows towards the Noqa-Maunachira River, followed by the Jao-Boro River whilst the Thaoge River receives the smallest share. Every year, flows of the Okavango River inundate the floodplains of Thaoge River all the way to Qaakhwa station. During periods with extreme high flows, the water manages to reach the floodplains of Tubu. There are periods when flows do not reach Tubu and remain dry for over 10 years. Therefore Tubu floodplains are occasionally flooded.

River flows inundate the floodplains along the Jao-Boro River depending on the flow magnitudes of the Okavango River at Mohembo. Every year, seasonal flows inundate Jao-Boro River floodplains all the way to Thokatsebe station. During periods with extreme high flows, water reaches Maun Bridge along Thamalake River and Samedupi along Boteti River. Extreme high flows create maximum inundation conditions in the Okavango Delta and therefore resulting in flows reaching all the way to Rakops and reaching the Makgadikgadi pans. After a year of extreme high flows at Mohembo, water can remain in the whole Jao-Boro River system for subsequent years maintaining river flows up to Rakops, even if magnitudes of annual flows have reduced at Mohembo. Persistent low flows of the Okavango River at Mohembo cause gradual receding of water in channels until downstream floodplains become dry for periods of over 10 years before another extreme high. The floodplains below Thokatsebe station along the Jao-Boro River are considered as ocassionally flooded.

Flows of the Okavango River reach most of the floodplains along the Ngoqa-Maunachira River every year, except for the very downstream stations such as Ditshiping along Sanatantadibe River and Santawani along Gomoti River. During extreme high flow years, flows through Santandibe and Gomoti Rivers connect to Thamalakane River. Flows can be retained in the Ngoqa-Maunachira River system for subsequent years after a high flow year and therefore

maintaining inundation of floodplains for a long period. When low flows persist at Mohembo, channel flows gradually recede, drying out the downstream floodplains, therefore downstream floodplains below Txaba station are ocassionally flooded

7.5 Sub-surface water response to inundation and molapo sustainability

Sub-surface water responds significantly to both rainfall and inflows along *molapo* floodplains. The highest soil moisture conditions are at 60cm and 100cm depth responding to both rainfall and flows. *Molapo* farmers sow crops depending on the inundation from rainfall and together with prevailing moisture conditions for germination, and then crop growth and maturity is supported by inundation induced by incoming flows. *Molapo* farming remains sustainable during years with high flows. After a year with extreme high flows causing significant inundation of floodplains in the Okavango Delta, *molapo* farming can remain sustainable for another 5 years before cessation of channel flows. If the Okavango River annual peak flows are persistently low, outflows are reduced, drying out on the downstream floodplains where *molapo* is practised. The outflows can remain with low flows or dry for a long period e.g 1993-2003 period, before another extreme high. Water can be retained in lagoons during the period of low flows and *molapo* fields concentrate around the lagoons such as in Tubu, whilst in areas like Xobe and Shorobe, there is shifting of *molapo* fields towards the channel with pools. As the downstream ocassionally flooded floodplains dry out due to lack of flows, farmers relocate to upstream seasonal floodplains, *molapo* farming therefore becoming completely unsustainable in the downstream floodplains.

7.6 Recommendations

The following recommendations are suggested

- This study recommends further work on assessment of suitability of different floodplain areas for *molapo* farming. Most of the Okavango River flows go towards the Ngoqa-Maunachira system, making most the channel perennial and floodplain inundation can be sustained for long periods. However *molapo* farming is practiced in just a small portion

around Khwai. Assessment of suitability of such areas for *molapo* farming will assist local communities to identify sites for crop production.

- This study recommends further work on a detailed analysis of processes that take place in the floodplains resulting in inundation. Floodplain inundation is not only important for *molapo* farming, it is important for a variety of livelihood activities including suitability of grazing areas. Improving the understanding of characteristics of different hydrological process including evapotranspiration, infiltration, and groundwater recharge can help in understanding the dynamics of soil moisture availability in the floodplains. Sediment transport processes is another important aspect which affect soil moisture availability in floodplains. This can lead to understanding of changing flora and fauna due to long term changes of floodplain inundation as a result of interaction of hydrological processes.

- The study recommends improved monitoring of different hydrological process within the Okavango Delta in general. Extended coverage of rainfall measurements in the Okavango Delta is suggested especially in areas in the middle of the delta. Extended coverage of other parameters such as evapotranspiration is suggested as it plays a very important role in floodplain inundation. A general review of the hydrological monitoring network is suggested. Although accessibility is a challenge, there are still areas which are not monitored in term of flow measurements and water levels. A review of monitoring network is recommended to cover shifting of channel flows. Improvement of monitoring procedure is also recommended to account for channel-floodplain flows. The use of GIS and remote sensing in conjuction with earth and land-based observation systems is also crutial in helping to fill up the data gap due to inaccessibility of stations within the delta during high flows and high water levels.

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APPENDICES

APPENDIX 3.1: Location, record length and elevation of stations in the Okavango Delta analysed

Station	Location		Period of Data	Elevation (m)
	Latitude	Longitude		
Shakawe	18° 22’S	21° 50’E	1931-2012	987
Seronga	18^0 49′S	22^0 24′E	1973-2012	985
Ikoga	18^0 51′S	22^0 17′E	1989-2011	971
Sepopa	18^0 44′S	22^0 10′E	1959-2011	979
Etsha	19^0 16′S	22^0 08′S	1971-2009	970
Gumare	22° 29’S	28° 42’E	1959-2012	962
Nokaneng	19° 39’S	22° 11’E	1955-2009	955
Tsau	20^0 10′S	22^0 29′E	1987-2012	941
Sehitwa	20° 20’S	20° 24’E	1958-2012	928
Toteng	20^0 26′S	27^0 15′E	1983-2011	937
Maun	19° 33’S	26° 05’E	1921-2012	928
Matsaudi	22^0 22′S	27^0 35′E	1983-2011	900
Shorobe	19^0 43′S	23^0 39′E	1972-2009	930
Xakanaxa	19^0 06′S	23^0 14′E	1992-1998	947
Maqwee	19^0 58′S	23^0 24′S	1992-2012	945
Khwai	19^0 09′S	23^0 46′S	1992-2000	933
Gaenga	19^0 14′S	22^0 49′E	1970-1985	950
Txaba	19^0 22′S	23^0 15′E	1972-1984	950
Kwihum	19^0 02′ S	22^0 34′ E	1970-1983	972

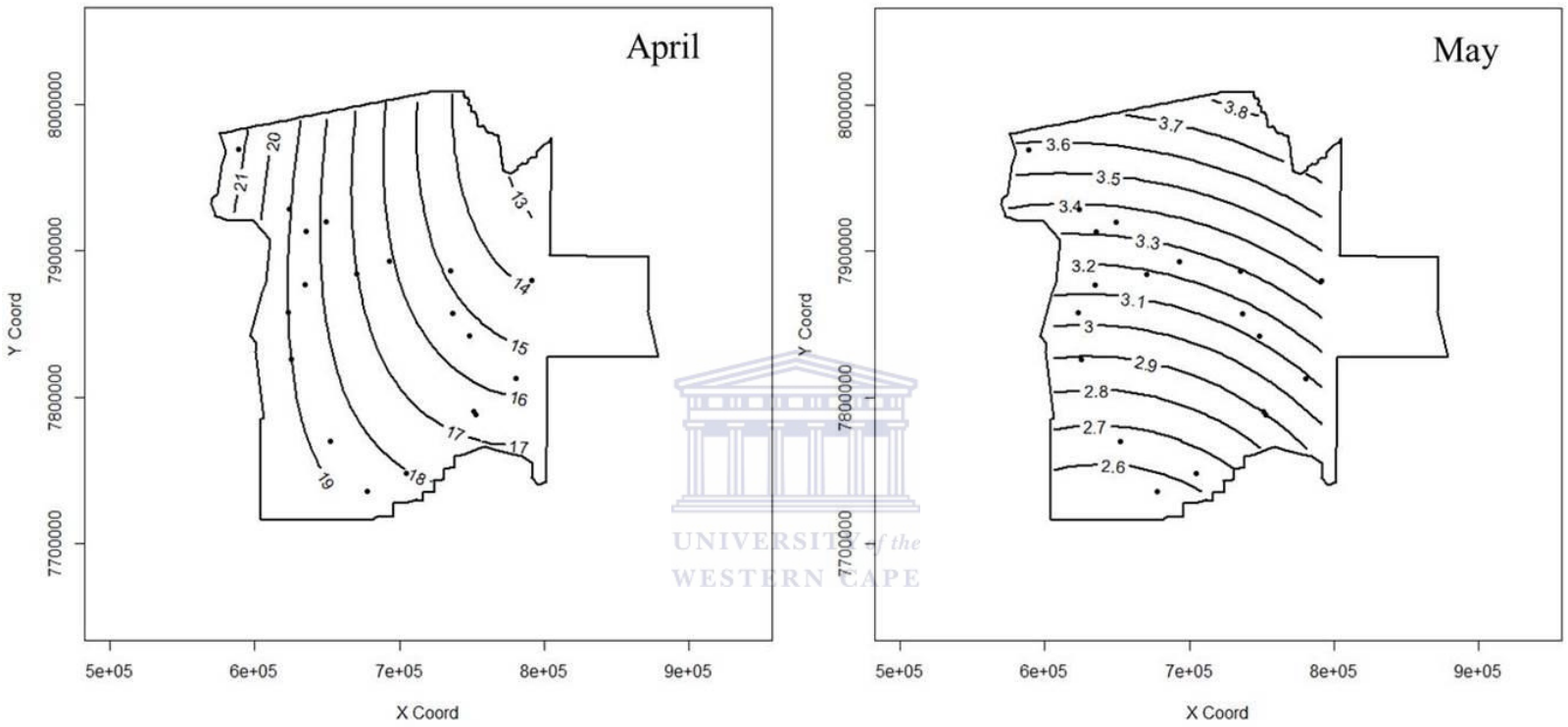
APPENDIX 3.2A: Individual Stations Summary Statistics

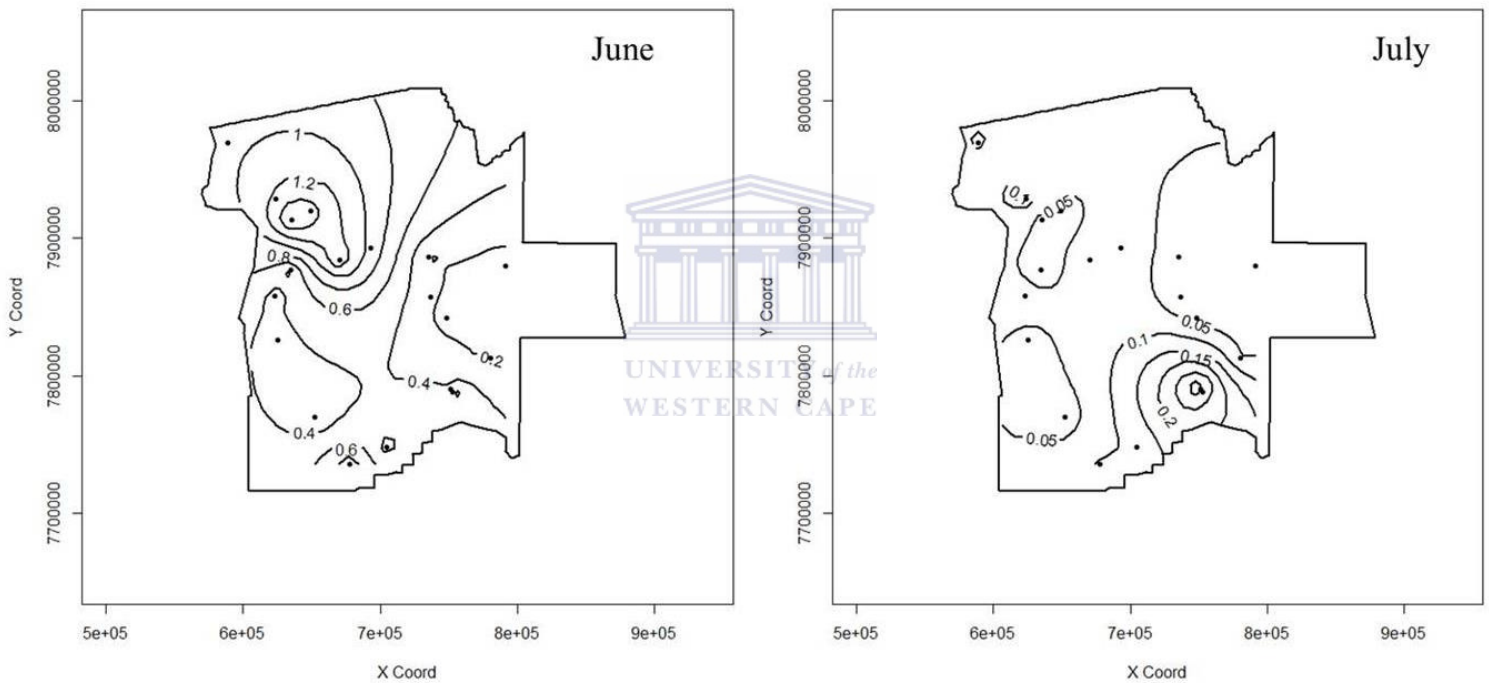
	Oct			Nov			Dec			Jan			Feb			Mar			Annual		
Station	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
Shakawe	13.4	15.5	115.6	60.2	46.6	77.5	106.1	59.0	55.6	138.9	84.8	61.1	125.7	86.5	68.8	80.1	59.1	73.8	523.6	185.8	35.5
Seronga	15.0	20.3	135.4	46.1	35.4	76.7	94.2	68.6	72.8	138.6	102.7	74.1	101.5	74.5	73.4	66.9	52.4	78.3	461.3	168.0	36.4
Ikgoga	9.3	10.4	111.6	65.5	54.0	82.5	119.9	67.2	56.0	119.3	78.7	66.0	104.1	98.2	94.3	60.0	63.7	106.2	467.2	300.2	64.3
Sepopa	14.6	28.1	192.1	54.9	50.3	91.7	79.7	52.5	65.9	138.6	109.2	78.8	99.6	77.0	77.3	63.4	64.7	102.1	429.6	198.9	46.3
Etsha	11.6	12.5	107.8	40.0	44.6	111.4	75.4	74.0	98.1	128.1	110.7	86.4	69.9	61.6	88.1	57.0	49.0	86.0	350.4	170.6	48.7
Gumare	11.4	14.9	131.5	46.1	39.9	86.5	82.9	68.2	82.2	101.2	66.9	66.1	97.5	73.1	75.0	63.7	55.3	86.9	429.4	164.1	38.2
Nokaneng	13.5	15.9	118.1	42.8	38.6	90.2	76.2	54.3	71.3	104.7	92.8	88.6	97.5	100.3	102.9	64.7	62.0	95.8	366.9	194.0	52.9
Tsau	10.0	13.5	134.7	32.9	31.9	96.9	48.3	41.7	86.4	98.1	78.8	80.3	89.6	101.0	112.8	49.0	55.9	113.9	363.1	150.0	41.3
Sehitwa	12.8	19.2	150.4	35.0	29.1	83.3	64.1	41.5	64.8	94.2	67.9	72.0	73.3	69.1	94.3	53.4	76.0	142.4	359.8	151.8	42.2
Toteng	13.6	18.1	133.2	33.9	22.6	66.7	55.2	39.3	71.3	74.9	68.8	91.9	62.6	58.5	93.4	47.7	38.0	79.7	300.1	114.8	38.3
Maun	15.3	19.3	126.3	46.4	34.1	73.6	79.4	47.1	59.4	111.6	70.3	63.0	97.3	77.2	79.3	67.4	59.8	88.7	446.6	165.5	37.1
Matsaudi	11.8	13.4	113.0	53.6	38.5	71.9	66.5	38.5	57.9	115.2	77.8	67.6	86.9	68.0	78.2	62.9	53.9	85.7	396.6	149.9	37.8
Shorobe	22.0	34.7	157.4	65.5	57.1	87.2	89.7	39.9	44.5	120.8	91.8	76.0	105.4	76.1	72.2	91.3	67.0	73.4	436.2	229.9	52.7
Xakanaxa	3.4	5.0	146.2	40.9	34.2	83.8	63.1	43.3	68.6	113.3	50.2	44.3	71.7	80.9	112.8	42.5	41.9	98.7	301.1	154.6	51.3
Maqwee	9.8	16.3	166.2	40.8	28.1	68.9	80.8	54.8	67.8	116.3	93.9	80.8	79.7	60.0	75.3	79.5	63.6	80.0	400.1	172.1	43.0
Khwai	20.1	21.6	107.7	35.2	33.3	94.6	39.6	31.9	80.4	142.4	117.3	82.3	89.0	94.2	105.9	38.7	59.7	154.1	300.3	242.6	80.8
Gaenga	13.3	22.6	170.6	25.0	28.7	114.8	53.6	47.6	88.8	48.9	49.6	101.4	73.5	56.2	76.4	73.1	91.9	125.7	309.0	105.9	34.3
Txaba	5.0	4.4	88.6	23.9	24.8	104.0	63.1	68.3	108.3	68.7	81.7	118.8	65.2	84.2	129.1	32.5	25.7	79.1	274.9	168.6	61.3
Kwihum	6.7	13.3	198.9	34.6	60.2	174.3	88.0	85.4	97.0	78.6	79.4	101.0	70.2	89.5	127.5	69.9	65.3	93.3	354.5	226.1	63.8

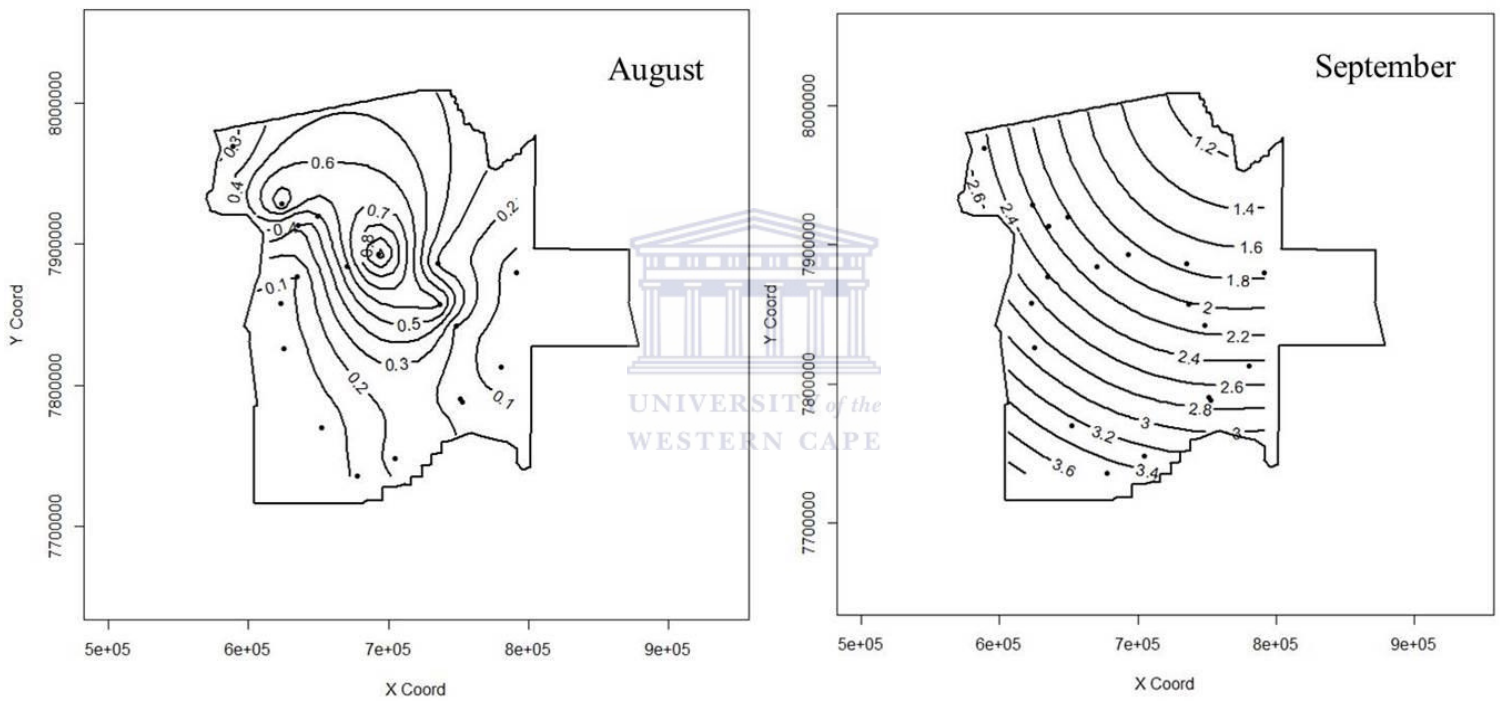
APPENDIX 3.2B: Individual stations summary Statistics used to establish the Okavango Delta rainfall summary statistics

Station	October	November	December	January	February	March	April	May	June	July	August	September	**Annual**
Shakawe	13.4	60.2	106.1	138.9	125.7	80.1	23.8	2.4	1.0	0.0	0.2	2.8	**523.6**
Seronga	15.0	46.1	94.2	138.6	101.5	66.9	14.1	2.2	1.6	0.0	0.5	2.8	**461.3**
Ikoga	9.3	65.5	119.9	119.3	104.1	60.0	28.9	13.7	2.1	0.0	0.0	0.9	**467.2**
Sepopa	14.6	54.9	79.7	138.6	99.6	63.4	17.8	1.4	1.2	0.2	1.2	2.3	**429.6**
Etsha	11.6	40.0	75.4	128.1	69.9	57.0	14.9	3.7	0.0	0.0	0.0	2.0	**350.4**
Gumare	11.4	46.1	82.9	101.2	97.5	63.7	26.6	1.9	0.2	0.1	0.0	3.1	**429.4**
Nokaneng	13.5	42.8	76.2	104.7	97.5	64.7	18.7	2.1	0.3	0.0	0.0	3.4	**366.9**
Tsau	10.0	32.9	48.3	98.1	89.6	49.0	6.4	2.8	0.0	0.0	0.0	3.9	**363.1**
Sehitwa	12.8	35.0	64.1	94.2	73.3	53.4	24.6	3.6	1.3	0.1	0.1	3.0	**359.8**
Toteng	13.6	33.9	55.2	74.9	62.6	47.7	12.9	1.4	0.2	0.1	0.3	3.1	**300.1**
Maun	15.3	46.4	79.4	111.6	97.3	67.4	24.0	5.0	1.3	0.1	0.3	2.7	**446.6**
Matsaudi	11.8	53.6	66.5	115.2	86.9	62.9	18.2	1.8	0.0	0.0	0.0	2.1	**396.6**
Shorobe	22.0	65.5	89.7	120.8	105.4	91.3	34.7	5.5	0.0	0.0	0.0	2.0	**436.2**
Xakanaxa	3.4	40.9	63.1	113.3	71.7	42.5	7.0	0.0	0.0	0.0	0.0	1.6	**301.1**
Maqwee	9.8	40.8	80.8	116.3	79.7	79.5	12.4	0.6	0.0	0.7	0.0	4.4	**400.1**
Khwai	20.1	35.2	39.6	142.4	89.0	38.7	1.9	6.2	0.0	0.0	0.0	2.3	**300.3**
Gaenga	13.3	25.0	53.6	48.9	73.5	73.1	26.7	1.7	1.4	0.2	2.4	2.2	**309.0**
Txaba	5.0	23.9	63.1	68.7	65.2	32.5	12.6	1.6	0.3	0.0	1.3	0.7	**274.9**
Khwihum	6.7	34.6	88.0	78.6	70.2	69.9	17.2	2.4	1.9	0.1	0.6	1.7	**354.5**
Mean	**12.7**	**44.8**	**76.2**	**109.7**	**89.3**	**62.9**	**18.9**	**3.2**	**0.7**	**0.1**	**0.4**	**2.6**	**393.5**
STD	**4.9**	**13.6**	**20.1**	**26.4**	**18.6**	**16.3**	**9.0**	**2.9**	**0.7**	**0.2**	**0.6**	**1.2**	**82.8**
CV	**38.6**	**30.3**	**26.4**	**24.0**	**20.9**	**25.9**	**47.7**	**92.2**	**111.1**	**166.7**	**166.3**	**44.9**	**21.0**

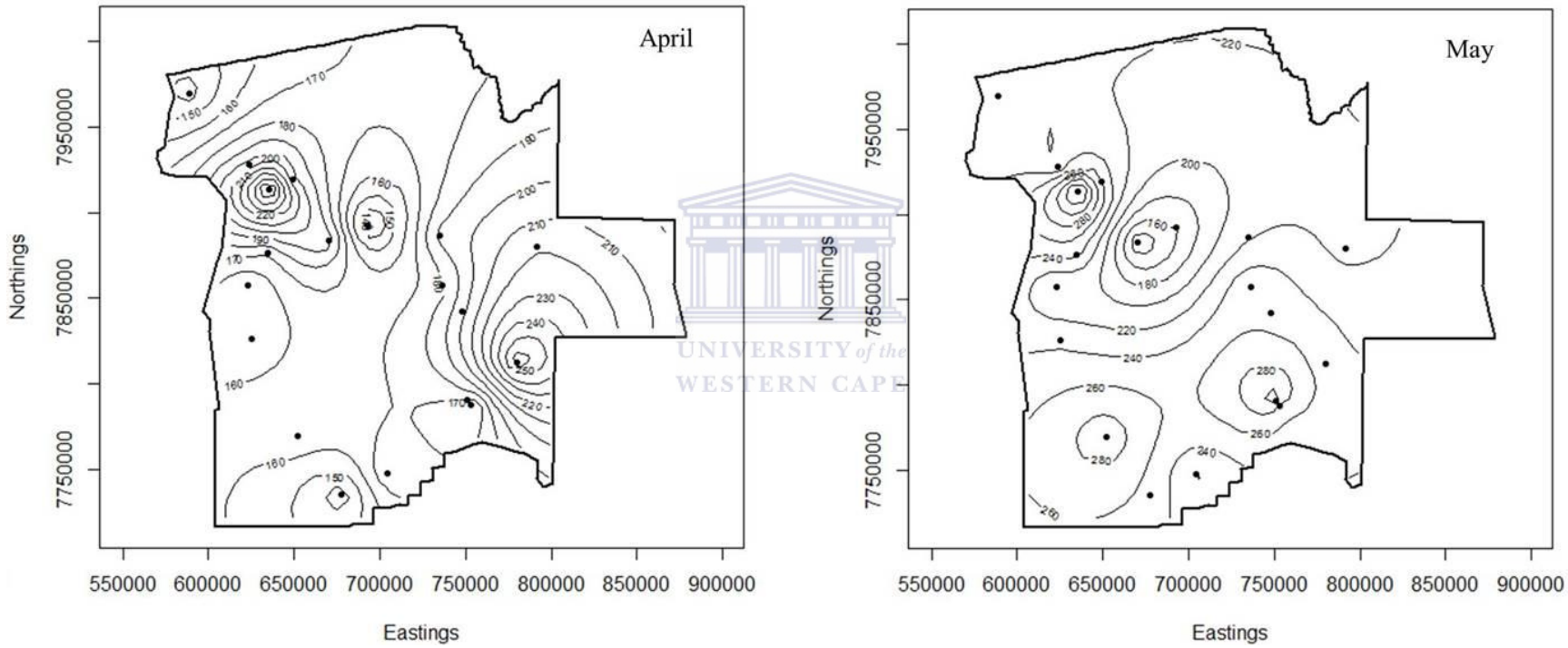
APPENDIX 3.3A: Aerial interpolation of monthly rainfall of the Okavango Delta with the ODRS boundary

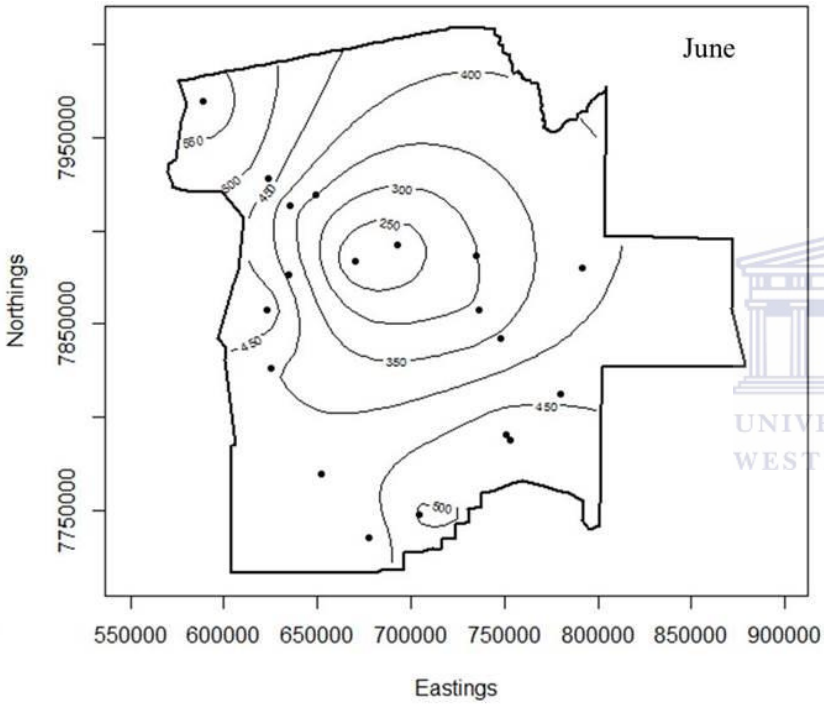


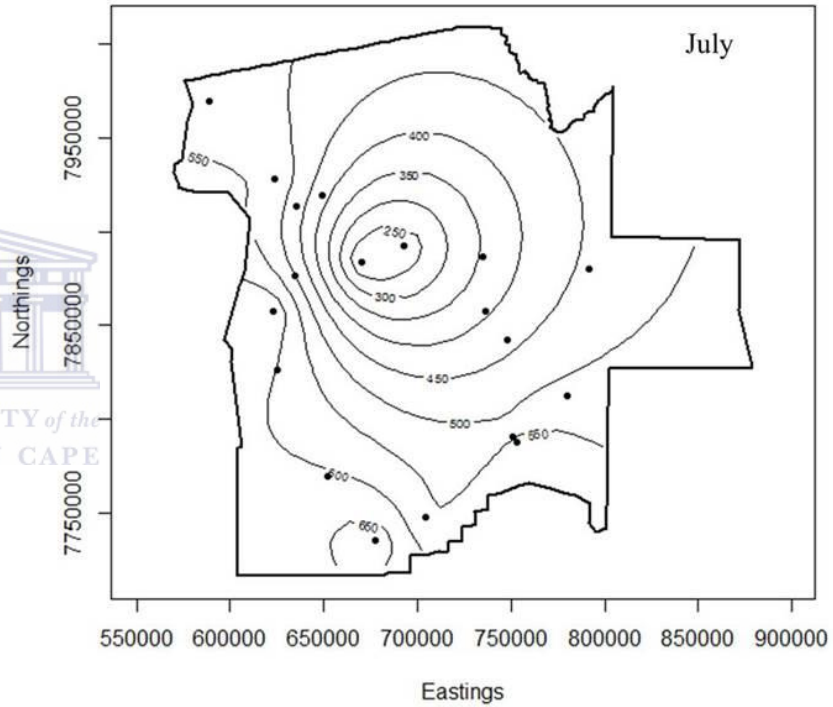


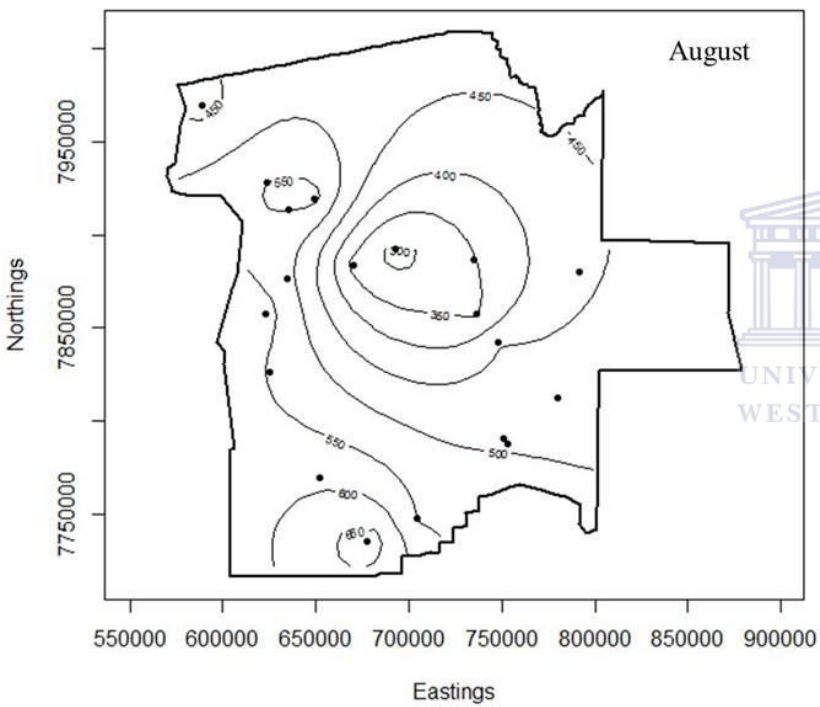


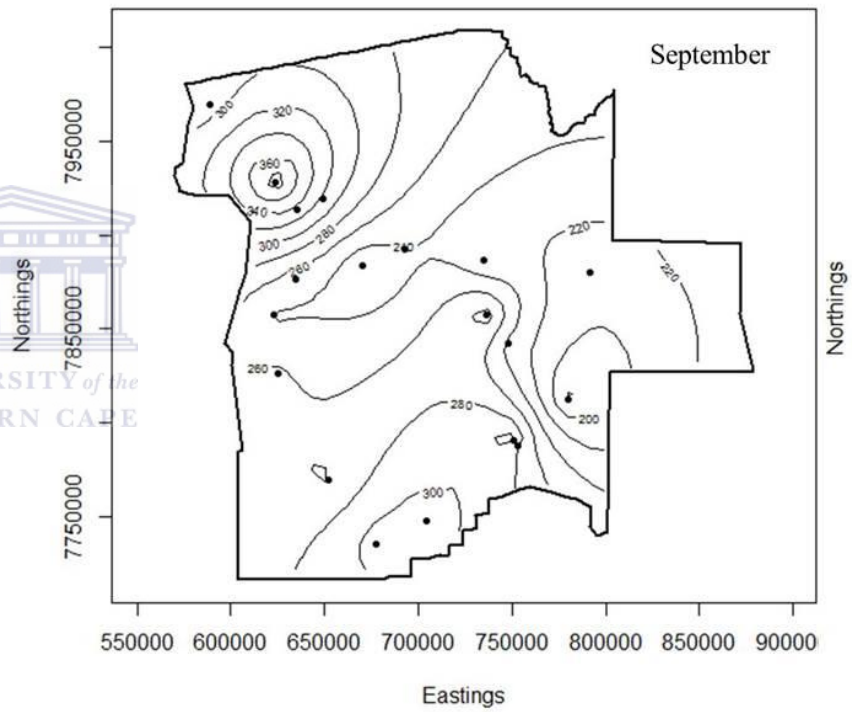
APPENDIX 3.3B: Coefficient of Variatiopn dry months











APPENDIX 3.4: Test statistics for Pettit, SNHT and BR compared to the critical values for significance of identified change point

Station	Record Length	Sample Size	Pettit		SNHT		BR		
			X_k	*Critical Value*	*T*	*Critical Value*	*R*	$R/\sqrt{n}$	*Critical Value*
Shakawe_A	1930-2012	81	315	393	5.241	8.95	11.639	1.293	1.585
Shakawe-B	1971-2012	40	228	167	3.54	8.151	10.447	1.652	1.53
Seronga	1973-2012	38	119	167	4.582	8.081	8.868	1.439	1.53
Ikoga	1989-2011	22	112	57	11.247	7.257	7.567	1.613	1.43
Sepopa	1959-2012	25	84	107	9.169	7.529	7.238	1.448	1.465
Etsha 6	1971-2009	38	63	167	5.123	8.081	4.554	0.739	1.53
Gumare	1959-2012	53	178	235	4.375	8.502	10.986	1.509	1.55
Nokaneng	1955-2009	54	111	235	2.060	8.524	5.334	0.726	1.55
Tsau	1987-2012	24	37	57	3.968	7.400	5.164	1.054	1.43
Sehitwa	1958-2012	53	210	235	3.909	8.052	9.885	1.358	1.55
Toteng	1983-2011	28	70	107	4.724	7.643	4.899	0.926	1.5
Maun_A	1921-2012	90	448	677	5.11	9.067	13.676	1.442	1.62
Maun-B	1970-2012	40	136	167	6.319	8.151	9.732	1.539	1.53
Matsaudi	1983-2011	28	61	107	5.194	7.643	5.402	1.021	1.5
Shorobe	1972-2009	37	87	167	10.142	8.045	8.848	1.455	1.53
Xakanaxa	1992-1998	6	6	57	1.804	5.637	1.968	0.803	1.28
Maqwee	1992-2012	20	36	57	2.483	7.089	4.829	1.080	1.43
Khwai	1992-2000	8	6	57	4.812	5.637	2.194	0.776	1.28
Gaenga	1970-1985	15	35	57	7.903	6.674	5.015	1.295	1.315
Txaba	1972-1984	12	40	57	6.391	6.668	4.729	1.365	1.28
Khwihum	1970-1983	13	21	57	1.779	6.402	4.168	1.156	1.28

APPENDIX 3.5: Quantile regression statistics at different percentiles for the tested rainfall stations

Station	Quantile (θ)	Slope Coefficient ($\beta(\theta)1$)	*t*-statistic	*p*_value
Shakawe	10	3.22	2.2	0.03
Shakawe	20	1.55	1.01	0.32
Shakawe	30	0.43	0.34	0.74
Shakawe	40	-0.56	-0.45	0.65
Shakawe	50	-0.37	-0.34	0.73
Shakawe	60	-1.2	-1.11	0.27
Shakawe	70	-1.84	-1.38	0.17
Shakawe	80	-1.98	-1.09	0.28
Shakawe	90	-0.11	-0.06	0.95
Gumare	10	2.22	1.14	0.26
Gumare	20	3.19	1.17	0.25
Gumare	30	3.87	1.92	0.06
Gumare	40	3.05	1.82	0.08
Gumare	50	2.01	0.9	0.37
Gumare	60	1.04	0.55	0.58
Gumare	70	0.58	0.22	0.83
Gumare	80	-0.5	-0.16	0.88
Gumare	90	-1	-0.32	0.75
Sehitwa	10	-0.07	-0.05	0.96
Sehitwa	20	-0.12	-0.06	0.97
Sehitwa	30	-1.72	-0.85	0.4
Sehitwa	40	-0.04	-0.02	0.98
Sehitwa	50	-2.46	-1.54	0.12
Sehitwa	60	-1.95	-1.09	0.28
Sehitwa	70	-2.41	-1.55	0.13
Sehitwa	80	-2.77	-1.18	0.25
Sehitwa	90	-1.88	-527	0.6
Maun	10	0.13	0.13	0.9
Maun	20	0.62	0.56	0.58
Maun	30	0.69	0.64	0.53
Maun	40	1.03	0.9	0.38
Maun	50	1.56	1.09	0.28
Maun	60	0.38	0.3	0.77
Maun	70	1.75	1.15	0.26
Maun	80	0.37	0.11	0.91
Maun	90	4.25	1.46	0.15

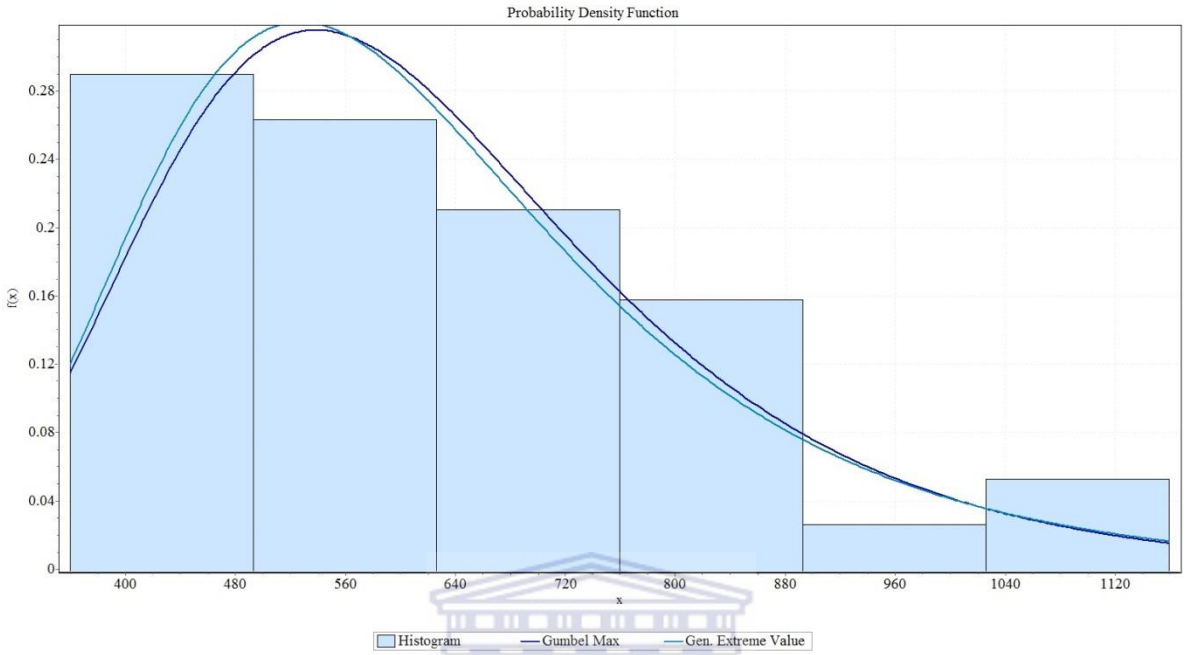
APPENDIX 3.6: Regional Growth Curve for Sub-Region1, Sun-Region 2 and Sub-Region 3 estimated using GEV, GAP and P3 probability distributions

Non-Exceedance Probability	Sub-Region 1	Sub-Region 2	Sub-Region 3
0.999	1.912	1.991	3.006
0.998	1.873	1.978	2.821
0.995	1.809	1.948	2.569
0.990	1.749	1.913	2.371
0.980	1.676	1.859	2.165
0.960	1.587	1.778	1.948
0.950	1.554	1.744	1.875
0.900	1.437	1.605	1.638
0.850	1.354	1.492	1.488
0.800	1.287	1.394	1.374
0.750	1.230	1.306	1.280
0.700	1.178	1.224	1.200
0.650	1.129	1.148	1.127
0.600	1.084	1.076	1.061
0.550	1.039	1.008	0.999
0.500	0.996	0.943	0.939
0.450	0.953	0.880	0.882
0.400	0.910	0.820	0.826
0.350	0.865	0.762	0.770
0.300	0.818	0.705	0.713
0.250	0.769	0.650	0.654
0.200	0.714	0.597	0.591
0.150	0.651	0.544	0.522
0.100	0.573	0.494	0.441
0.050	0.460	0.444	0.332
0.020	0.337	0.414	0.225
0.010	0.258	0.405	0.162
0.005	0.187	0.400	0.110
0.002	0.102	0.397	0.054
0.001	0.044	0.396	0.019

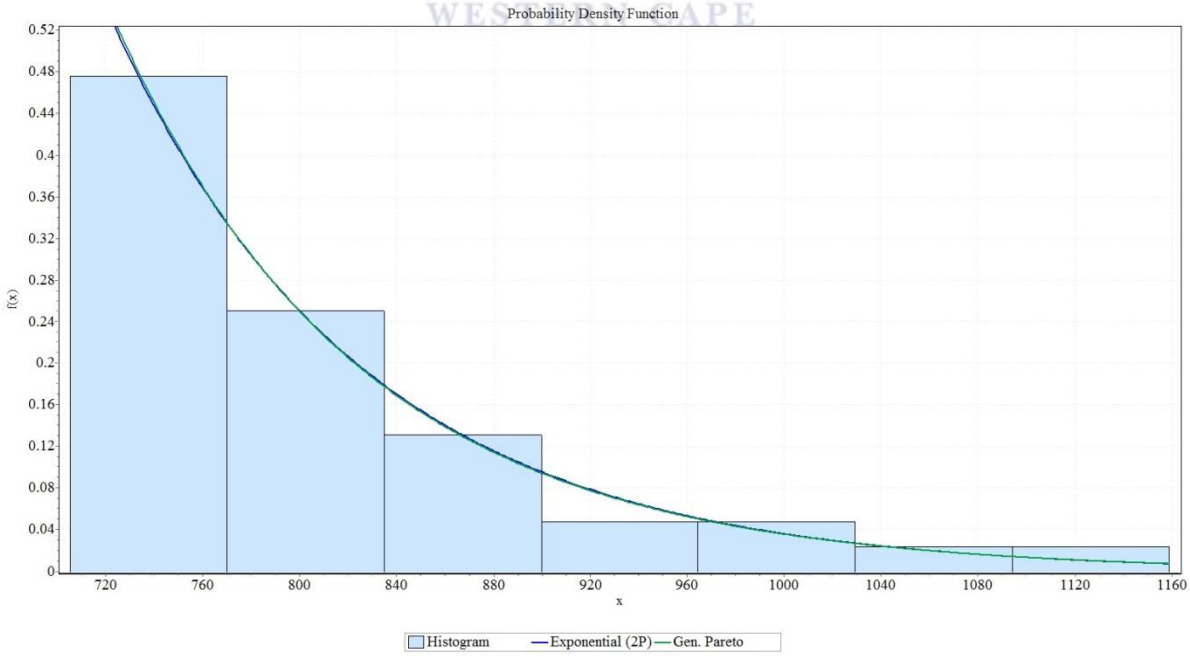
APPENDIX 4.1: Descriptive Statistics for Monthly Flow at Mohembo Station

VARIABLE	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Long Term Mean (1933-2014)	146.48	147.07	195.05	283.64	369.13	483.15	534.09	441.97	300.43	236.81	198.57	167.01
Standard Deviation -STDV (1933-2014)	37.68	42.69	64.25	116.15	148.84	161.08	186.07	141.17	87.49	64.14	50.14	40.64
Coefficient of Variation-CV (1933-2014)	0.26	0.29	0.33	0.41	0.40	0.33	0.35	0.32	0.29	0.27	0.25	0.24
Mean Monthly Maximum (1933-2014)	350.18	362.45	374.72	491.81	670.18	733.34	939.89	779.14	528.13	359.61	325.54	337.91
Mean Monthly Minimum (1933-2014)	85.86	82.71	97.01	126.58	164.17	233.67	302.18	241.38	152.30	130.90	115.34	102.94
Annual Maximum Series(1974-2014)	356.21	368.29	418.87	652.68	727.00	1017.20	1159.04	1058.42	647.27	433.84	331.67	343.74
Annual Minimum Series (1974-2014)	77.84	73.53	80.84	103.9	130.95	213.21	246.33	175.16	139.81	122.45	103.96	93.79

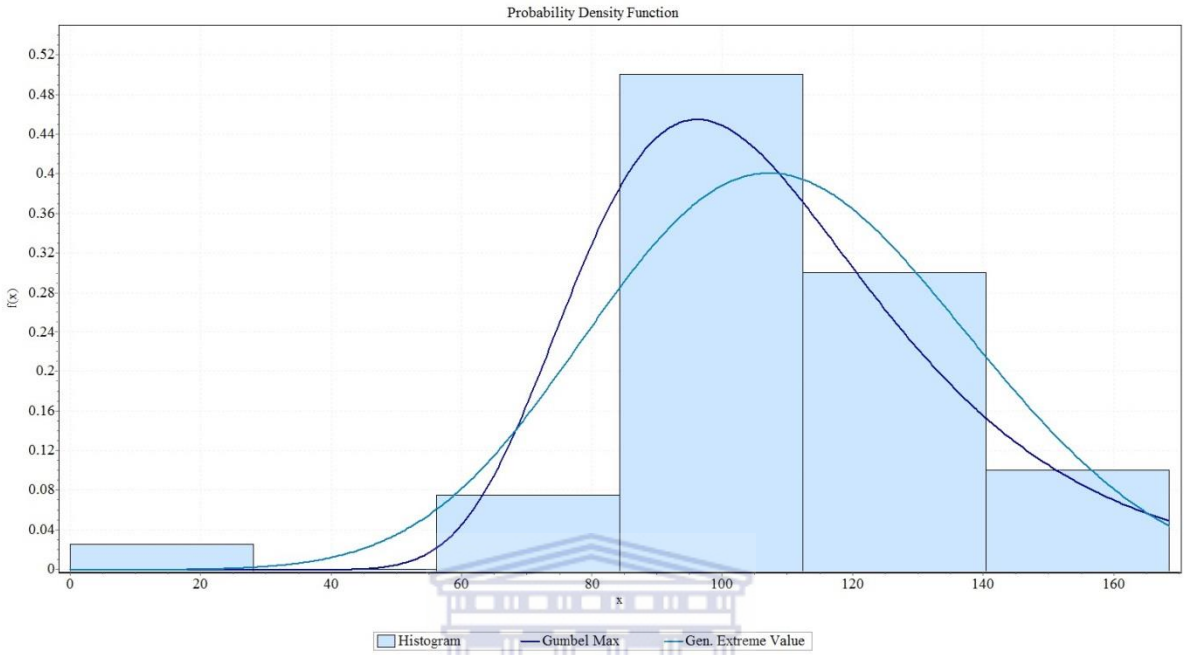
APPENDIX 4.2A: PDF Fitting For AMS (GEV and Gumbel (EV1) Distributions)



APPENDIX 4.2B: PDF Fitting For POT (GPA and EXP Distributions)



APPENDIX 4.2C: PDF Fitting For AMIN (GEV and Gumbel (EV1) Distributions)



APPENDIX 4.3: Statistical Parameters for the fitted distributions and estimated return flows

Series	Distribution	Parameters			Return Period, T (Years)								
					2	**5**	**10**	**20**	**30**	**40**	**50**	**100**	**200**
					% Probability of Exceedance								
		Shape	Scale	Location	99.99	99.98	98.52	87.15	74.23	63.68	55.43	33.10	18.17
		k	α	ξ	Q_T (m^3/s)								
AMS	GEV	0.04	153.17	533.45	712.87	874.32	977.15	1072.84	1126.62	1163.99	1192.58	1279.34	1363.34
	EV1	–	155.3	538.6	595.52	771.54	888.07	999.86	1064.17	1109.51	1144.56	1252.99	1361.02
POT	GPA	0.01	102.32	705.41	850.71	942.56	1011.45	1079.82	1119.58	1147.68	1169.42	1236.62	1303.31
	EXP	–	103.73	705.2	854.06	949.11	1021.01	1092.91	1134.97	1164.81	1187.96	1259.86	1331.76
AMIN	GEV	-0.26	26.78	99.42	137.16	185.38	226.09	268.61	304.84	329.16	349.27	419.5	503.38
	EV1	–	22.73	96.15	104.48	130.24	147.3	163.66	173.08	179.71	184.84	200.71	216.52

APPENDIX 5.1: Water level and flow measuring stations in the Okavango Delta used for interpretation of flow propagation amongst the three main distributary channels

Station	River	Latitude (DMS) South	Longitude (DMS) East	Datum (m)	Water Level Preriod	Discharge Period
Mohembo	Okavango	18 16 40.40	21 47 13.34	992.84	1974-2014	1933-2014
Duba	Nqoga	18 58 26.86	22 34 22.83	972.59	1970-2007	2004-2007
Jao-Boro	Jao	19 02 28.20	22 32 22.90	-	-	2004-2007
Qaakhwa	Thaoge	19 02 46.20	22 23 28.50	-	-	1988-2008
Tubu Bridge	Thaoge	19 21 52.00	22 13 46. 00	-	-	1988-1996
Madinare	Jao	19 11 07.60	22 40 16.10	967.17	1972-2011	1978-2009
Thapagadi	Xudum	19 32 36.60	22 51 27.10	951.06	1995-2007	1973-2007
Thokatsebe	Boro	19 47 37.20	23 19 35.30	938.00	1990-2011	1972-2007
Matsebe	Matsebe	20 02 48.15	22 59 51.88	937.49	1972-2001	1972-2007
Toteng	Kunyere	20 21 48.18	22 57 05.50	922.75	1970-2014	1970-2014
Mogapelwa	Nhabe	20 24 28. 40	22 55 10.81	927.03	1974-2014	1974-2014
Maun Bridge	Thamalakane	20 00 18.20	23 25 33.21	928.53	1970-2014	1970-2014
Samedupi	Boteti	20 06 40.71	23 31 30.41	927.54	1970-2014	1970-2014
Gaenga	Nqoga	19 04 02.23	22 49 19.74	963.95	1969-2007	1969-2007
Gadikwe	Maunachira	19 09 18.25	23 15 08.21	954.33	1973-2007	2004-2007
Xakanaxa	Khwai	19 10 52.40	23 24 31.50	947.62	1996-2014	1972-2014
Lopis	Mboroga	19 09 48.47	23 07 58.80	956.28	1968-2007	2004-2007
Txaba	Santantadibe	19 22 30.11	23 14 12.50	948.62	1970-2007	1970-2007
Santawani	Gomoti	19 49 28.30	23 33 55.80	952.85	2007-2010	2007-2010
Ditshiping	Santantadibe	19 39 54.77	23 27 40.19	939.38	1983-2009	1983-2009
Rakops	Boteti	19 09 48.47	23 07 58.80	952.85	1970-2014	1970-2014

APPENDIX 5.2: Greater Okavango Delta area