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FACULTY OF ENGINEERING

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CONTRIBUTION OF HYDROLOGICAL PROCESSES IN THE OCCURRENCE OF EXTREME HYDROLOGICAL EVENTS IN THE MIDDLE ZAMBEZI RIVER BASIN

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In collaboration with

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by

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

June 2011

DECLARATION

I, **Saneliso Vuyo Makhanya**, declare that this research report is my own work. It is being submitted for the degree of Master of Science in Integrated Water Resources Management (IWRM) in the University of Zimbabwe. To the best of my knowledge, it has never been submitted before for any degree of examination in any other University.

Date: ________________________________

Signature: ____________________________

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

DEDICATION

To my lovely wife; Mrs. Nomcebo Nombuso Makhanya

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God: Who has guided me up to this far, He gave me life and wisdom to do all I have done, for without Him I will not be here.

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ABSTRACT

The middle Zambezi has experienced hydrological extremes in alternating intervals. The impacts are mostly felt by the people who live close to the river and mostly around Lake Cahora Bassa. A study on the analysis of the contribution of the middle Zambezi in the occurrence of these hydrological extremes was carried out to determine the contribution of each middle Zambezi catchment in the occurrence of floods and droughts, in terms of magnitude and frequency. Rainfall analysis was also employed to augment the results obtained from the hydrological analysis. This was because; the middle Zambezi had many impoundments which might contribute in the occurrence of either floods or hydrological drought due to reservoir operation. Hence rainfall was incorporated to discern natural floods and hydrological droughts from those which could be human induced. A total of 33 rainfall stations were analysed to get the average rainfall received in the catchment using the Thiessen Polygon approach. Since the Manyame Catchment was poorly gauged, a Soil Conservation Service Curve Number model was used to compute the runoff from this catchment. The other tributaries of the middle Zambezi which were studied included Luangwa River (as measured from Luangwa Bridge), Kafue River (Kafue Gorge releases) as well as the Zambezi River (Victoria Falls and Kariba releases). Pearson Correlation and a double mass analysis were employed in order to determine the influence of each tributary on the Lake levels of Cahora Bassa, and also contribution of each tributary in terms of magnitude and frequency of occurrence of floods and droughts. The results showed that the levels of the Cahora Bassa were not influenced by individual tributary but were influenced by the combined flows. In terms of magnitude, the releases from Kariba contributed most, but were least frequent, while the Luangwa contributed most in terms of frequency and Manyame River was second to Kariba in both cases; magnitude and frequency. Occurrences of floods and hydrological droughts in the middle Zambezi River basin were correlated with rainfall anomalies within the catchment. This showed that hydrological extremes were a natural result as opposed to human induced. On the contrary, the Kariba dam attenuated most floods which occurred in Victoria Falls and further curtailed the impacts of hydrological droughts by increasing the low flows. In conclusion, the hydrological extreme events experienced in the middle Zambezi were mainly natural and were mainly caused by hydrological processes of the tributaries of middle Zambezi from Kariba to Cahora Bassa

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APFM	: Associate Programme Flood Management
DFID	: Department for International Development
DMC	: Differential Mass Curve
EEA	: European Environmental Agency
FDC	: Flow Duration Curve
GCM	: Global Climate Models
GDP	: Gross Domestic Product
ITCZ	: Inter Tropical Convergence Zone
SADC	: Southern African Development Community
SCS-CN	: Soil Conservation Service Curve Number
SWECO	: Swedish Company
UNDP	: United Nation Development Programme
USGS	: United States Geological Survey
WB	: World Bank
WMO	: World Meteorological Organization
ZAMWIS	: Zambezi Water Information System
ZESCO	: Zambia Electricity Supply Company
ZINWA	: Zimbabwe National Water Authority
ZMWD	: Zimbabwe Meteorological Service Department
ZRA	: Zambezi River Authority

1 INTRODUCTION

1.1 Introduction

Humankind has always been faced with weather and climatic vagaries, and related problems with water resource - having too little, or too much of it. Hydrological extreme events such as floods and droughts have accompanied mankind throughout its entire history and they are cyclic in many cases (Tumbare, 2010). The very philosophy of frequency analysis perceives floods and droughts as the inescapable companion of humankind. When such events occur, the question of assessing its recurrence interval (T) comes about. This means that on the average, the event of the magnitude observed would be exceeded once in the interval, T, (Kundzewicz *et al.,* 1993) which indirectly shows that the event is expected again.

Simulation of hydrological events can be two fold; one can be in the short term say for the next three days or so based on the current prevailing conditions, and the other one can be long term for prediction of the return period based on historical records. In a study carried out by Madamombe (2004), the conclusions were that long term projections appear more accurate than short-term because enough time for preparation of the extreme events is given. The short-term prediction has to be more accurate since repeated inaccuracy leads to people not heeding to warnings since people would still be remembering the last prediction.

The fundamental principle of hydrological extremes is that the natural (unregulated) flow regime, during the event of flood or drought, of large rivers is *predictably unpredictable* (Kundzewicz *et al.,* 1993). The characteristics of hydrologic events depend on the regional climatic conditions and other factors. However, the magnitude, timing, duration, and frequency of hydrological conditions fall within a predictable range and pattern over time (Beilfuss, 2005). This led to hydrological studies which use thresholds to identify the beginning and end of any event trend. An example is that which was introduced by Yevjevich, (1967) to identify the beginning and end of a hydrological drought by a given threshold. This method has also been adopted in meteorological drought assessment such as Pereira and Paulo (2003). Wilson (1990) applied this concept in different approaches of flood analysis. Tumbare (2010) suggested the use of a unitless Differential Mass Curve (DMC) which acts as a filter by reducing the visual impacts of peak floods or extreme low flows making the beginning and end of trends more easily identifiable. The disadvantage of a DMC is that; it is not sensitive enough to show the critical dry periods which have the most severe impacts (SADC, 2011).

1.2 Background

The Zambezi system has undergone profound social, ecological, and hydrological changes over the past centuries but for which limited pre-impact studies are available (Beilfuss, 2005). In its natural stage, the middle Zambezi has had two high flood periods every year; in February and April, but since the Kariba was constructed in 1959, it no longer inundates the floodplain below the wall (Pinay, 1988). The February peak used to come from contribution from tributaries of the Zambezi below Victoria Falls and the April peak came from flows above Victoria Falls. The nutrient carrying sediments are also trapped in the reservoirs, and this makes the flood plains immediately downstream of the lakes less fertile than before impoundment. In a study done by Beilfuss and dos Santos (2001) on flood events prior and post Zambezi regulation in Kariba Gorge; they found that, on average, flood events subsequent to Zambezi regulation were greatly curtailed. This is true to a limited extent because floods of higher magnitude are partially attenuated by the dam, but still result in high flows downstream (Ncube, 2011 and SADC, 2011). In this aspect, only the frequency of occurrence has been lowered.

Magadza (2002) and Tumbare (2010) observed that the Zambezi River reservoirs have also reduced streamflow variation and have reduced the impacts of floods and droughts that would have occurred without the reservoirs. The Kariba scheme regulated well the sharp flood peaks of 1963, 1969, 1970 but could not hold large floods like those of 1978 and 2000 (SADC, 2011). However, since the construction of the Cahora Bassa downstream of Lake Kariba in 1975, large flooding events, downstream of Lake Cahora Bassa, have resulted in extensive social and economic damage (Beilfuss and dos Santos, 2001). Beilfuss and dos Santos (2001) further postulated that medium size flood peaks (3500-14 000 m^3/s) are significantly attenuated by Lake Cahora Bassa. In the processes of flood storage, backwater in the mainstream and tributaries of the lake accumulate and flood the surrounding areas of the lower middle Zambezi which have never been historically occupied by human beings before Lake Cahora Bassa came into being (Beilfuss and dos Santos, 2001).

The high population growth and urbanization rate within the sub-basin are increasing water demand and subsequently amplifying the effects of hydrological droughts (Shela, 2000). Analysis by Sichingabula and Sikazwe (1999) showed that, of late, drought years have become more common that wet years within the Zambezi Basin. Chagutah (2006) made the same conclusion after identifying the 1986-87, 1991-95, 1997-98, and 2003-04 as some of the recent drought years. According to Shela (2000) the dam of Lake Kariba did not spill since 1982 to 1999/2000 with the lowest level recorded in 1994/95. Hydropower plants for Lake Kariba could not generate at full capacity resulting in power shortages, particularly in the 1990s.During the drought of 1991/1992, electricity generation at Kariba fell by 15% causing severe load shedding and as a result, Zimbabwe GDP fell by 11% (Sichingabula and Sikazwe, 1999 and APFM, 2007).

In the future, the impact of drought will become worse than experienced in the 1990s as population, industrialization, urbanization and the need for expanded agriculture/irrigation, water supply and sanitation services, etc., continue to rapidly grow (Sichingabula and Sikazwe, 1999 and APFM, 2007). The prolonged period of reservoir recession, during drought events, as in the case of the droughts that occurred between 1982-1999, forces the people to follow the water, socio-hydrotropism, with an assumption that it will never inundate the land again and these people are then impacted by the effect of the "expanding lake" as happened in 2000 (Sichingabula and Sikazwe, 1999 and APFM, 2007).

1.3 Problem Statement

The middle Zambezi River basin experiences extreme hydrological events which can be natural and/or human induced. This study sought to isolate the natural extreme events from those which are human induced and further investigate how reservoir operations influence the occurrence of the extreme hydrological events; by curtailing or worsening the impacts.

1.4 Justification of the study

This study will isolate and make conclusions whether the hydrological extreme events are human induced or natural. It will further contribute towards the current regional efforts to improve river basin-wide management, particularly driven by the ZRA and supported by other donors and regional bodies such as DFID, Biodiversity Foundation for Africa and SADC. Informed decisions and implementation activities based on this study will be made in; mitigating (effects of) floods and droughts and introducing and implementing flood risk zoning for regulation of settlements, land use, warning and rescue systems. It will also help in effecting the Zambezi basin‐wide policies and legislation to allow and facilitate basin populations to "live with floods”.

1.5 Scope of the Project

The study focused on hydrological processes of extreme events of the major tributaries of the middle Zambezi between Lake Kariba and Cahora Bassa namely; Luangwa, Manyame, Kafue River at Kafue Gorge, Zambezi River at Kariba. These are the rivers that discharge very high flows in the middle Zambezi valley (SADC, 2011).

1.6 Objectives

1.6.1 Main Objective

To analyze the contribution of hydrological processes in the occurrence of extreme hydrological events in the middle Zambezi River basin.

1.6.2 Specific Objectives

1. .To determine the contribution of rainfall in the occurrence of extreme hydrological events in the middle Zambezi River basin.
2. To analyze the contribution of runoff from middle Zambezi catchments in the occurrence of extreme hydrological events in the middle Zambezi River basin.
3. To analyze the frequency of occurrence of extreme hydrological events in the middle Zambezi River basin.

2 LITERATURE REVIEW

2.1 Introduction

The various parts of the hydrological cycle can be quite complicated and man can only exercise some control only on the last part, when the rain has fallen on the land and is making its way back into the sea (Wilson, 1990). This is one of the reasons why computational techniques in hydrology aim to derive river discharge (Shaw, 2004). The next approach is to use the methods of statistical analysis to extend the available data and hence predict the likely frequency of occurrence of natural extreme events. Given adequate records, statistical methods will show that floods of a certain magnitude- may, on average, be expected annually, every 10 years, every 100 years, and so on.

It is important to realize that these extensions are only as valid as the data used. It may be queried whether any method of extrapolation to 100 years is worth a great deal when it is based on (say) 30 years of record (Wilson, 1990). Consequently, the longer the record at a gauging station, the more reliable can be the evaluation of water resources and the estimation of extreme events either of dangerous floods or of harmful droughts (Shaw, 2004). The estimation of flood and drought hazards present examples of application of mathematical methods in water resource practice since water resources are observational rather than experimental (Kaczmarek, 2005). This means there is no possibility to repeat an experiment of a particular destructive flood or prolonged drought.

2.2 Rainfall runoff Processes

The rainfall input is one of the factors influencing the magnitude of the runoff response during a flood event (Mácá and Torfs, 2009). An important question in hydrology is how much streamflow occurs in a river in response to a given amount of rainfall (Tarboton, 2003). Answering the question of how much runoff is generated from surface water inputs requires partitioning water inputs at the earth surface into components that infiltrate- and components that flow overland and directly enter stream. The rainfall runoff question is also at the heart of the interface of linking meteorology and hydrology (Tarboton, 2003). In 1933, Horton presented a model of throughflow (overland flow) in terms of an infiltration excess theorem. Horton (1933) theorized that the rainfall that failed to infiltrate into the soil reached the stream as surface runoff. Hydrological models used in engineering practice implicitly or explicitly assume Horton's overland flow, which occurs on all parts of the watershed (Fennessey and Miller, 2001).

Simulations of floods with rainfall-runoff models using meteorological scenarios often produce enormous discharges with undefined return periods. Different results may emerge if the floods of a river are analyzed either statistically or by looking at the processes of runoff formation. A better understanding of the relevant runoff formation processes helps to assess the magnitude of extreme floods. There are several parameters characterizing an individual flood. These include-highest stage, peak discharge, flood volume, and area inundated. Maximum stage is important for structures like levees, as maximum flow rate is for spillways, bridges, and flood relief channels. Flood volume is of primary importance for such areas as flood control, irrigation, water supply. In comprehensive assessments of impacts and losses, combinations of the above parameters, and of the inundated area, play a role (Kudzewicz *et al.*, 1993).

2.3 SCS-CN Model

The Soil Conservation Service Curve Number (SCN-CN) method (SCS, 1956) is widely used in hydrology and environmental engineering for computing the amount of direct runoff from a given amount of rainfall (Mishra *et al.*, 2006; Silveira *et al.*, 2000; Murwira and Schmidt-Murwira, 2005 and Tan *et al.*, 2001). The SCS-CN procedure depends on relationships between precipitation and runoff, expressed as;

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad \text{If } P>0.2S \qquad 2.1$$

$$Q=0, \qquad \text{if } P \leq 0 \qquad 2.2$$

Where,

$$S = \frac{25400}{CN} - 254 \qquad 2.3$$

And Q is the direct runoff or rainfall excess (mm), P is storm rainfall (mm), S is the maximum potential soil water retention (mm), and CN is the curve number (dimensionless). Equations 2.1 and 2.3 were postulated, because their short-term and long-term behaviours corresponded to experimental evidence (Silveira *et al.*, 2000).

2.4 Extreme Hydrological Events

Hydrological extreme events are typically defined as floods and droughts (Trenberth, 2005). However, there is no precise and commonly accepted definition of neither flood nor drought. Definitions are subjective in the sense that both concepts refer to an arbitrary threshold level, distinguishing a "non-flood" situation from a flood one and "non-drought" from drought (Kundzewicz, *et al.*, 1993). Hydrological variables display a strong spatial and temporal variability. From time to time they take extremely low or extremely high values, exerting considerable and adverse impacts on society and ecosystems (Kundzewicz *et al.*, 1993).

2.4.1 Floods

The United Nations Development Programme (2000) defined flood as an unusually high stage of a river at which the river channel becomes filled and above which it overflows its banks (Figure 2.1). MacDonald (1999) defined floods as those events in which the water in a river or lake covers a much larger geographical region than the normal conditions. This means that, when the flow discharge, exceeds the capacity of the river channel, water overflows into the floodplain. Estrela *et al.* (2001) generally described floods as situations of extreme water run-offs during which human lives, property and infrastructure are threatened. This means that the definition of a flood is related to the impact to human lives and society, and without humans, definitions of floods would be inclined to hydrological processes. The word “flood” is used to refer to the inflow of the tide, as opposed to the outflow or ebb (Kileshye Onema, 2010). Floods are part of the natural processes of any river channel and they are cyclic in many cases.

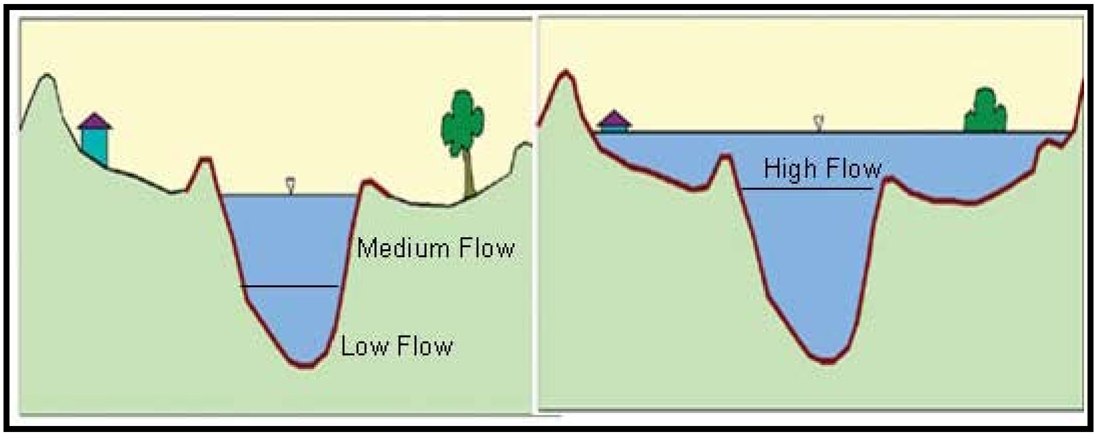

Figure 2.1: Schematisation of the range of flows in the main channel and flood plains (Maidment, 2002)

Normally, the risk of flooding results from a combination of natural factors and human interference. According to Estrela *et al*. (2001), human actions can influence flooding either by affecting the run-off patterns (faster run-offs through deforestation, urbanization, and river training works) or by increasing the possible impact of flooding (greater exposure of human population through the occupation of flood plains. According to the EEA (2001) and Kundzewicz *et al.* (1993) responses to floods can be structural and non-structural.

The response is a function of driving forces, pressures, state, and impacts of floods to society (Figure 2.2). Constructing reservoirs to store excess water allow a regulated temporal distribution of streamflow and help alleviate flooding problems by flattening flood peaks. Possible non-structural flood protection measures include;

- Zoning: regulation of development in flood hazard areas, leaving flood plains with low valued infrastructure,
- Flood mitigation system of forecasting, warning (issuing and dissemination), evacuation, relief, and post-flood recovery.
- Flood insurance, i.e. division of risks and losses among a higher number of people over a long time, and
- Capacity building- improving flood awareness, understanding and preparedness, and enhancing the participatory approach.

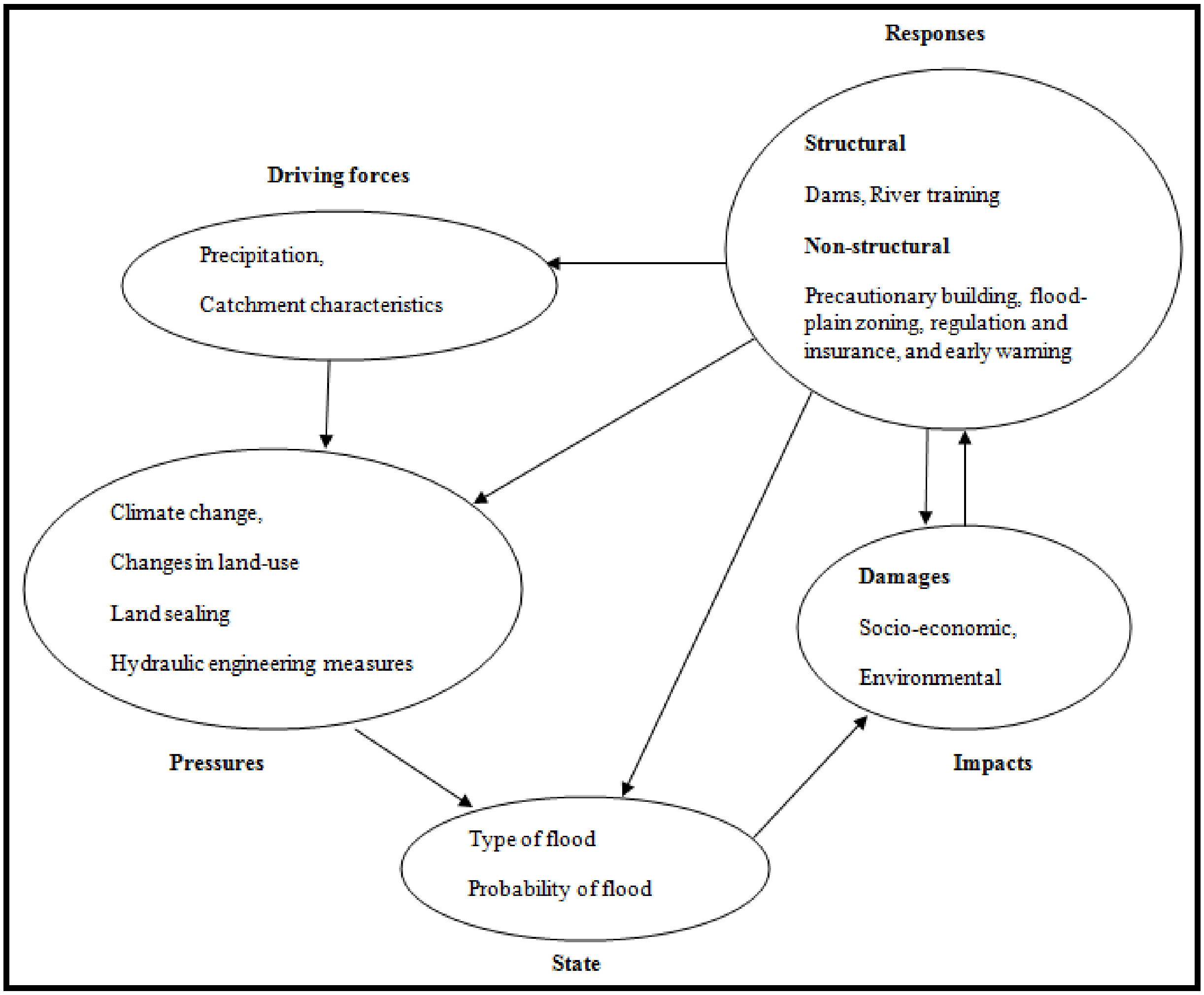

Figure 2.2: Schematic representation of a framework for flood assessment (adapted from EEA, 2001)

Types of Floods

Flooding can be divided into different categories according to their duration or their location (Kileshye Onema, 2010). Types of floods according to their duration include; slow onset, rapid onset and flash floods. According to their location, they include coastal, arroyos, river, and urban floods. Estrela *et al.* (2001) summarized these categories into two groups of meteorological events generating floods namely; floods in large basins and flash floods.

Floods in large basins

Floods, at a given location in a river system, are a function of hydrological processes of that catchment. In this case the catchment characteristics play a major role. The downstream characteristics of the flood differ from the upstream characteristics because of the lag time, catchment size and shape, land cover and use, routing effects of river channel or flood plains and reservoirs, and climate from the headwaters to the outlet.

Flash floods

Flash floods are a sudden onset of flooding that can occur under a broad range of climatological and geographical conditions (Estrela *et al.*, 2001). Flash floods may occur within minutes or a few hours after heavy rainfall, tropical storm, failure of dams or levees or releases of ice jams and they usually cause the greatest damage to society (Kileshye Onema, 2010).

Impacts of Floods

Science and technology are effective for disasters of less than average magnitude, but are powerless for extraordinarily large events (Sugawara, 1978). Mitigation measures take into account the costs and benefits to eradicate the impacts of extreme floods of higher magnitude and infrastructure provide some protection against impacts of floods. Twigger-Ross (2005) outlined the impacts of flooding into a number of broad categories. These included economic impacts which basically include the cost of damage done to a property by a flood. Non-economic losses were referred to as the loss of items of sentimental values like feeling of loss of home. Other impacts outlined included; impacts on physical and psychological health, impacts associated with evacuation and temporary accommodation, household disruption, and, community and neighbourhood changes.

Flood Frequency analysis

Streamflow data are very important for many areas of water engineering such as dam planning, flood mitigation, operation of water reservoirs, distribution of drinking water and drainage water, hydropower generation in dry periods and planning of river transport. They are also imperative in research topics related to hydrology for frequency analysis of floods and droughts (Kilinç *et al.*, 2006).

As one of the methods of statistical analysis, a DMC can be used to predict the future wet and dry period which was credited by (Tumbare, 2010) for its ability to identify the beginning and end of any particular trend. However its limitation is that, it is not sensitive enough to show the critical periods which have the most severe impacts (SADC, 2011). In addition to statistical analysis, Global Climate Change (GCM) models can also be used in frequency analysis in which softwares incorporate the fundamental laws of oceanic and atmospheric physics in a simulated world where weather changes over time are the most critical factors.

The estimation of return periods of extreme events can be improved by combining historical data, rainfall-runoff modelling and flood frequency analysis. Discharge records can often be extended using historical events (Naef, 2002). A better understanding of the relevant runoff processes helps to assess the magnitude of extreme floods. The magnitude of discharge is the amount of water moving past a point per unit time. The flood crest and peak discharge are measures of magnitude. According to Allan (2000), frequency of discharge refers to how often a flow of a specified magnitude occurs over a specified time interval. By analysing many years of river discharge one can estimate how often a flood of a given magnitude occurs. The frequency is oftenly specified to be relatively rare (1 in 10 years, 1 in 100 years, or even 1 in 1000 years) and then the magnitude of this relatively rare event is calculated based on the data records. Allan (2000) further defined the duration to be the time period associated with the specified flow conditions, e.g. one may wish to know the number of days in a year that a floodplain is inundated.

2.4.2 Droughts

Drought is a result of combination of meteorological, physical and human factors. The primary cause of any drought is a deficiency in rainfall and in particularly, the timing, distribution and intensity of this deficiency in relation to storage, demand and water use (Estrela *et al.*, 2001). In the case where there are reservoirs, drought is attributed more to water management than natural processes. Droughts are characterized by the decrease in water availability in a particular period and over a particular area (Beran and Rodier, 1985) and they vary from one region to another. Defining drought is difficult and it depends on region, needs, and disciplinary perspectives (Kileshye Onema, 2010) and such notions always involve a degree of subjectivity and there is no way to objectively choose a threshold of drought. According to Awass (2009) drought can be defined as a naturally occurring phenomenon when the natural water availability is significantly below the normal recorded level. The notion of drought should not be confused with aridity which is restricted to low rainfall regions and is a permanent feature of climate.

The threshold level method introduced by Yevjevich (1967) based on the theory of runs define drought as periods during which the water supply is lower than the current water demand. Yevjevich later simplified this method by applying constant demand that was represented by a threshold level, Q_T, thus droughts are defined as periods during which the streamflow is below the threshold level (Byzedi and Saghafian, 2009).

Types of Droughts

Many classifications of drought from different perspectives exist. As drought propagates through the hydrological cycle, the different classes of drought are manifested: meteorological, agricultural, hydrological and socio-economic. Agricultural, hydrological and socio-economic drought, however, place greater emphasis on the human or social aspects of drought, highlighting the interaction or interplay between the natural characteristics of meteorological drought and human activities that depend on precipitation to provide adequate water supplies to meet societal and environmental demands (Figure 2.3) (WMO, 2006).

Meteorological Drought

Meteorological drought is defined usually on the basis of the degree of dryness (in comparison to some “normal” or average amount) and the duration of the dry period (Kileshye Onema, 2010). Longer time intervals of no, or very little, rain are typically referred to as meteorological drought (Awass, 2009). According to WMO (2006) meteorological drought is defined by a precipitation deficiency threshold over a predetermined period of time. However, the threshold chosen and duration period will vary by location (and) according to user needs or applications.

Agricultural Drought

Agricultural drought links various characteristics of meteorological (or hydrological) drought to agricultural impacts focusing on precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits etc. (Makurira, 2010). The agricultural sector is usually the first economic sector to be affected by drought. Agricultural drought refers to low soil moisture and its effects on cultivated vegetation. The relationship between precipitation and infiltration of precipitation into the soil is dependent on the antecedent soil moisture condition amongst other conditions. The term environmental drought is used to emphasize adverse consequences of water deficits on ecosystems. Nowadays extreme low flow events are diligently analyzed and given focus in the emerging field of eco-hydrology (Awass, 2009).

Hydrological drought

Hydrological drought is associated with the effects of periods of precipitation shortfall on surface (streamflow level) or subsurface water (groundwater level). According to Awass (2009) hydrological drought is a sustained occurrence of below expected natural water availability in rivers, lakes, groundwater level etc. over large areas. Nalbatis (2008) defined hydrological drought as a significant decrease in the availability of water in all its forms appearing in the land phase of the hydrological cycle. WMO (2006) defined hydrological drought as the departure of surface and subsurface water supplies from some average condition at various points in time. Like agricultural drought, there is no direct relationship between precipitation amounts and the status of surface and subsurface water supplies in lakes, reservoirs, aquifers and streams because these hydrological system components are used for multiple and competing purposes, such as irrigation, recreation, tourism, flood control, transportation, hydroelectric power production, domestic water supply, protection of endangered species and environmental and ecosystem management and preservation (Kundzewicz *et al.,* 1993). There is also a considerable time lag between departures of precipitation and the point at which these deficiencies become evident in surface and subsurface components of the hydrologic system (Timilsena *et al*., 1993).

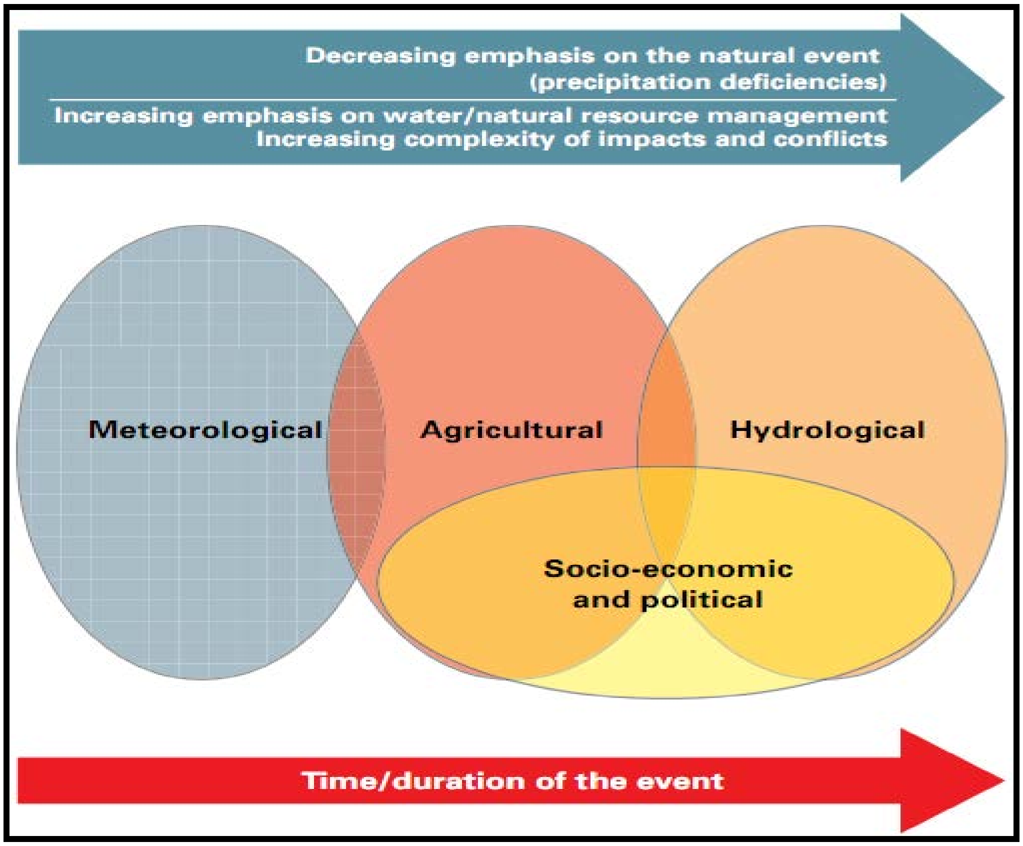

Figure 2.3: Interrelationships between meteorological, agricultural, hydrological and socio-economic drought (WMO, 2006)

Socio-economic drought

Socio-economic drought differs markedly from the other types of drought because it reflects the relationship between the supply and demand for some commodity or economic good, such as water, livestock forage or hydroelectric power, which is dependent on precipitation (WMO, 2006 and Mazvimazvi, 2010)

Impacts of Hydrological Droughts

Protracted droughts on rivers imply decreased annual rates of storage capacity in reservoirs such as lakes, and groundwater reservoirs. The droughts that were experienced in Southern Africa from 1982 to 1999 caused significant decrease on hydropower production of Lake Kariba and Gross Domestic Product (GDP) of Zimbabwe fell by 11% as a result (SADC, 2011). These included widespread failures of crops, loss of livestock and disruption of urban lifestyles due to water rationing, such that measures were required to cushion countries from the whims of nature (Sichingabula and Sikazwe, 1999). As a result of these droughts, the Kafue Gorge dam reviewed and adopted new operating rules in order to cover Zambia in situation like this in the future (APFM, 2007). The main impact of a hydrological drought is the difficulty in facing urban demands under such circumstances. Poor water quality also affects agriculture which is usually considered as a second priority after human supply (Estrela *et al*., 2001). In general, the impacts of hydrological droughts vary among the major sectors, i.e. agriculture, water supply, and society in general (Makurira, 2010).

Frequency analysis of Hydrological Droughts

The frequency and severity of a drought is often defined on a catchment scale as an important random phenomenon in hydrology. The frequency analysis is important in the aim to know about the droughts regime and is based on the analysis of the deficit volume and the corresponding duration (Yahiaoui, *et al.*, 2009). Hydrological droughts are characterized by severity, time of onset and duration, areal extent and frequency of occurrence (Khanna, 2010). According to Awass (2009), the severity of hydrological drought can be computed using Equation 2.4.

$$S_i = \int_0^{d_i} (Q_0 - Q_t)dt \quad \text{2.4}$$

Where S_i is severity of drought event *i*, d_i is the duration of drought event *i*, Q_t is the stream flow at time *t* and Q_0 is the threshold level. No doubt the duration aspect is of importance in terms of frequency characterization and forecasting, yet the severity aspect is no less important. Awass (2009) also added that, severity is the crucial parameter in sizing storage reservoirs towards combating droughts.

Nalbatis (2008) postulated that, the areal extent of a drought event, although very useful for meteorological droughts, is not of interest for hydrological drought since water managers are interested on streamflow only at a small number of points in space (basin outlets, reservoir inlet and outlet, etc.); evidently, streamflow at this point provide an integrated measure of spatially distributed runoff. Furthermore, the river basin is a unit for applying measures for water resource protection and management.

Two main approaches of deriving drought characteristics can be generally be distinguished (Hisdal *et al.*, 2004). The first one involve analyzing low flow characteristics such as the time series of the annual minimum n-day discharge, the mean annual minimum n-day discharge or a percentile from a flow duration curve. These characteristics describe the low flow part of the regime and characterize droughts according to their magnitude expressed through the discharge (Tallaksen *et al.*, 1997). The development in time of a drought event is not considered. The second approach involves viewing discharge series as a time dependant process, and the task is to identify the complete drought from its first day to the last. In this way, a series of droughts events can be derived from the discharge series, and drought can be described and quantified by several properties, such as drought duration or deficit. Deficit volumes are commonly derived by the threshold level method.

The return period of a hydrological drought is computed from the probability of occurrence (Timilsena *et al.*, 2007) as shown by Equation 2.5 and 2.6.

$$p = \frac{m}{n+1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \ 2.5$$

p is the probability of occurrence of the event as a percentage
m is the rank number of the corresponding drought event
n is the total number of years of data

$$T_r = \frac{1}{p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 2.6$$

T_r is the return period
p is the probability of occurrence

3 DESCRIPTION OF THE STUDY AREA

3.1 Location

The middle Zambezi River Basin is one of the three sub-basins of the Zambezi River Basin bound upstream by the upper Zambezi River basin and by the lower Zambezi River basin downstream. It is located in the South Eastern part of Africa (Figure 3.1) and covers an area of 542,800 km² (Beilfuss and dos Santos, 2001). It is shared between Zambia, Zimbabwe and Mozambique and extends from Victoria Falls through the Zambezi Valley up to Cahora Bassa.

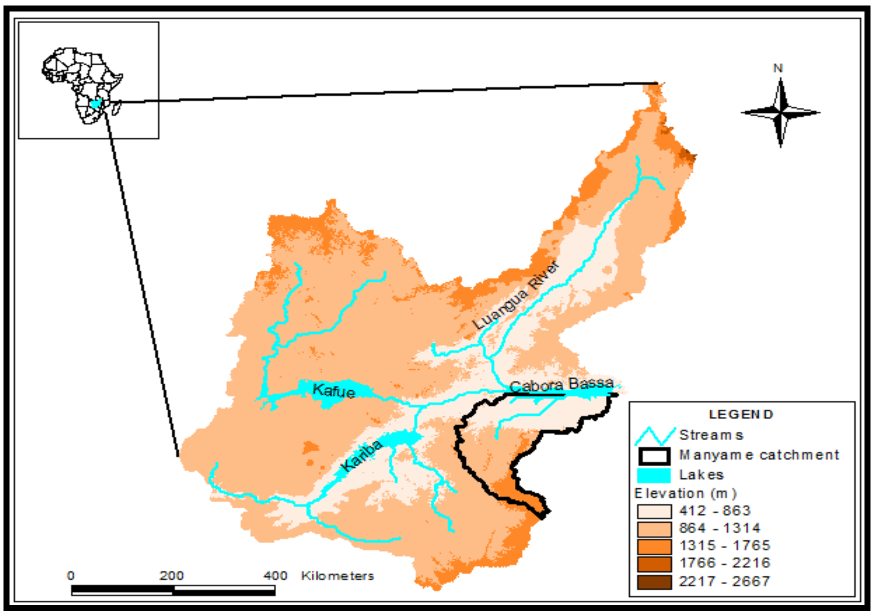

Figure 3.1 : Location of the middle Zambezi River Basin relative to Africa

3.2 Hydrology

3.2.1 Rainfall

Annual rainfall for the catchment ranges from 669 mm/a to 1339 mm/a with the Zimbabwean part receiving lowest rainfall whilst highest rainfall is received in the Zambian part specifically Solwezi in Kafue and Isoka in Luagwa. This could be explained by the fact that different sub-catchments of the two lakes receive rainfall from different sources e.g. either from westerly or from easterly winds, convectional rainfall, or even advected moisture from the ocean (SADC, 2011).

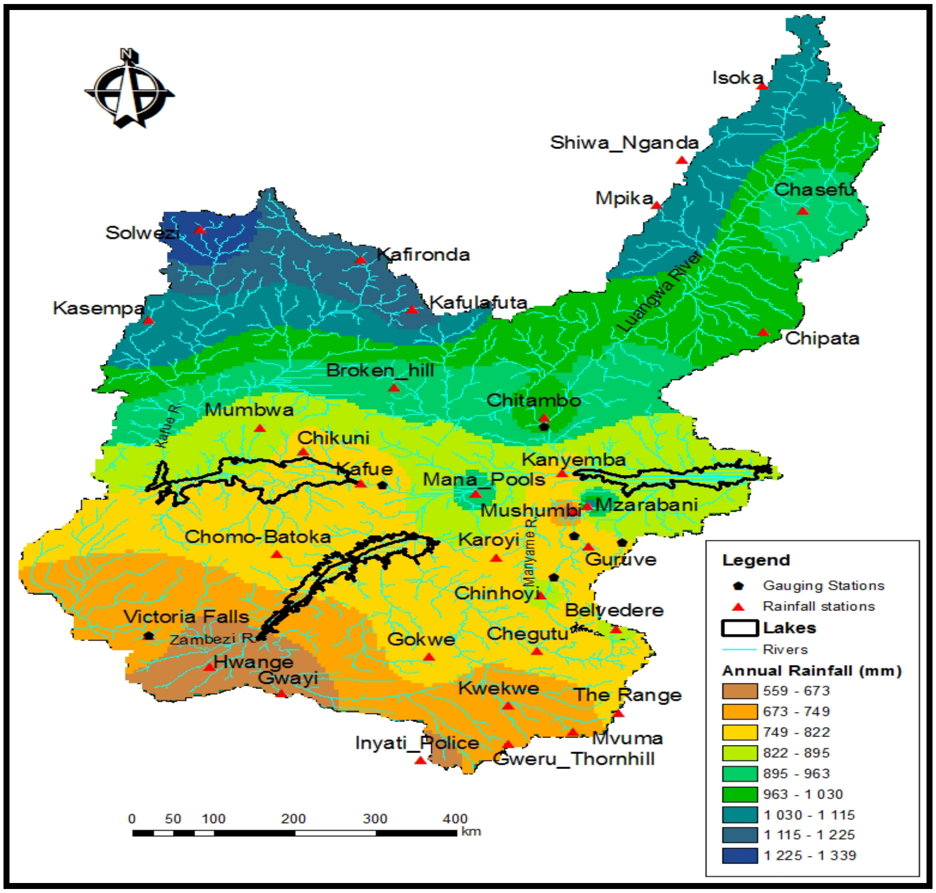

Figure 3.2: Spatial variation of average annual rainfall within the middle Zambezi Basin

3.2.2 Rivers

The middle Zambezi consists of four main rivers namely; the Zambezi, Kafue, Luangwa and Manyame (SADC, 2011) (Figure 3.2) with an average discharge of 1,398 m³/s (Beilfuss and dos Santos, 2001).

Kafue River Basin

The Kafue River basin covers an area of 152,000 km^2 and drains most of the northern portion of the middle Zambezi catchment. The Kafue River headwaters rise on the plateau of the South Equatorial divide in the Copperbelt region of Zambia (APFM, 2007). The Upper Kafue basin covers an area of 50,480 km^2. It includes the Munyonshi and Luswishi tributaries and is largely mountainous and forested with headwater dambos (Balek and Perry, 1973). The Kafue River is deeply incised in this region with fairly steep gradients and rapid runoff (FAO, 1968). Annual rainfall averages 1,100-1,200 mm, and average annual discharge of 350 m^3/s (Shela, 2000). The Kafue catchment is equal in size to the Luangwa but it generates annual discharge which amounts to less than half of the Luangwa (Beilfuss and dos Santos, 2001). Hydrological processes in the Kafue River basin are particularly complex, with extensive floodplain systems and two large dams, Itezhi- Tezhi and Kafue Gorge, upstream and downstream of the Kafue Flats respectively. The Kafue Flats wetlands give a considerable reduction in peak flows (40%) but the retained volume of water is a very small percentage of the total volume of floods (Beilfuss and dos Santos, 2001). The Kafue Flats are therefore not significant for flood retention (SADC, 2011).

Luangwa River Basin

Below the confluence with the Kafue River, the Zambezi flows gently through the Central African plateau for 180 km to its confluence with the Luangwa River just upstream of Cahora Bassa Reservoir (Beilfuss and dos Santos, 2001). Over much of this distance, Lower Zambezi National Park flanks the Zambezi on the left bank and Mana Pools National Park on the right bank. Both parks feature narrow zones of floodplains that were annually inundated by floodwaters prior to Kariba Reservoir regulation. The Luangwa River basin covers an area of 151,400 km^2. It rises on the South Equatorial Divide west of Lake Malawi. The Luangwa generally follows the base of the Luangwa Rift Valley that forms an extension of the East African rift system and links with the Gwembe Rift Valley (Mhango 1977). Much of the Luangwa River is fed by short, steeply falling tributaries draining from the rift escarpment, most notably the Luwumbu, Lundazi, Lukusuzi, and Lutembwe Rivers. In its lower reaches, the Luangwa captures runoff from the vast Lunsemfwa River catchment that drains the Muchinga escarpment in central Zambia (44,000 km^2) (Balek, 1971). The Luangwa River discharges to the Zambezi in the vicinity of Feira at the western end of Cahora Bassa reservoir with an average annual discharge of 620 m^3/s (Beilfuss and dos Santos, 2001). For the last few kilometers it forms the international boundary separating the two riparian countries, Zambia and Mozambique and thus making it a contiguous boundary river. This also qualifies it to be an international river, which in turn is also part of an international river basin, Zambezi. The Luangwa River is unregulated and has big influence on the operation of the Cahora Bassa reservoir (SADC, 2011).

Manyame River Basin

The Manyame River basin is among the seven major river basins that constitute the Zimbabwean hydrological water management systems (ZINWA, 2009). This catchment source is in Marondera and drains into the Zambezi River downstream of the Kariba Dam and upstream of the Cabora Bassa dam to the northern part of Zimbabwe. It has a total estimated catchment area of 40, 497 km^2 (ZINWA, 2009). The Manyame catchment covers areas that are drained by three main rivers; Manyame, Musengezi and Angwa and the latter two, join the Manyame River just before the confluence of the Manyame with the Zambezi. The Manyame River transverse the border separating the two successive countries, with respect to Manyame, Zimbabwe and Mozambique and thus qualifies to be an international river. In Zimbabwe, it is called Manyame whilst Mozambique refers to it as Panhame, formerly Hunyani. It continues as the Panhame River which joins the Zambezi at the town of Panhame in Mozambique.

3.2.3 Major Dams found in the Middle Zambezi Basin

The middle Zambezi is the most dammed sub basin of the Zambezi compared with the upper and lower Zambezi sub basins. The dams that have been included in the study are; Lake Kariba, Lake Cahora Bassa, Itezhi-tezhi, Kafue Gorge, and Lake Manyame as they are considered the ones with the most impact (Beilfuss and dos Santos, 2001 and SADC, 2010). Lake Manyame was constructed for water supply while the other major lakes of the middle Zambezi were primarily constructed for hydropower production. The above mentioned major impoundments, except for Lake Kariba which has a larger capacity, will fill up and spill every year on average (SADC, 2011)

Lake Kariba

This is the largest lake in the middle Zambezi, and is the largest man-made lake in the Zambezi River basin.. It covers an area of about 5,580 km^2 with a storage capacity of 185.6×10^6 km^3 (SADC, 2011). It lies within the boundary that separates riparian Zambia and Zimbabwe. This lake, to a larger extent, influences the flow in the middle and lower Zambezi. Both the Kariba and Cahora Bassa located in the Zambezi mainstream have altered the flow regime of the middle and lower Zambezi drastically reducing the frequency and magnitudes of floods and droughts

(WB, 2010a and WB, 2010b). The capacity of Lake Kariba alone enables it to completely curtail the effects of medium floods but partly attenuates large floods exceeding the 1:10,000 year design flood of 19,600 m^3/s (Beilfuss and dos Santos, 2001). The operation rule curve was modified in 2005 to balance power generation and flood regulation (Figure 3.3). Apart from the floods of 1978 and 2000, Lake Kariba is currently operated way below maximum permissible levels (SADC, 2011).

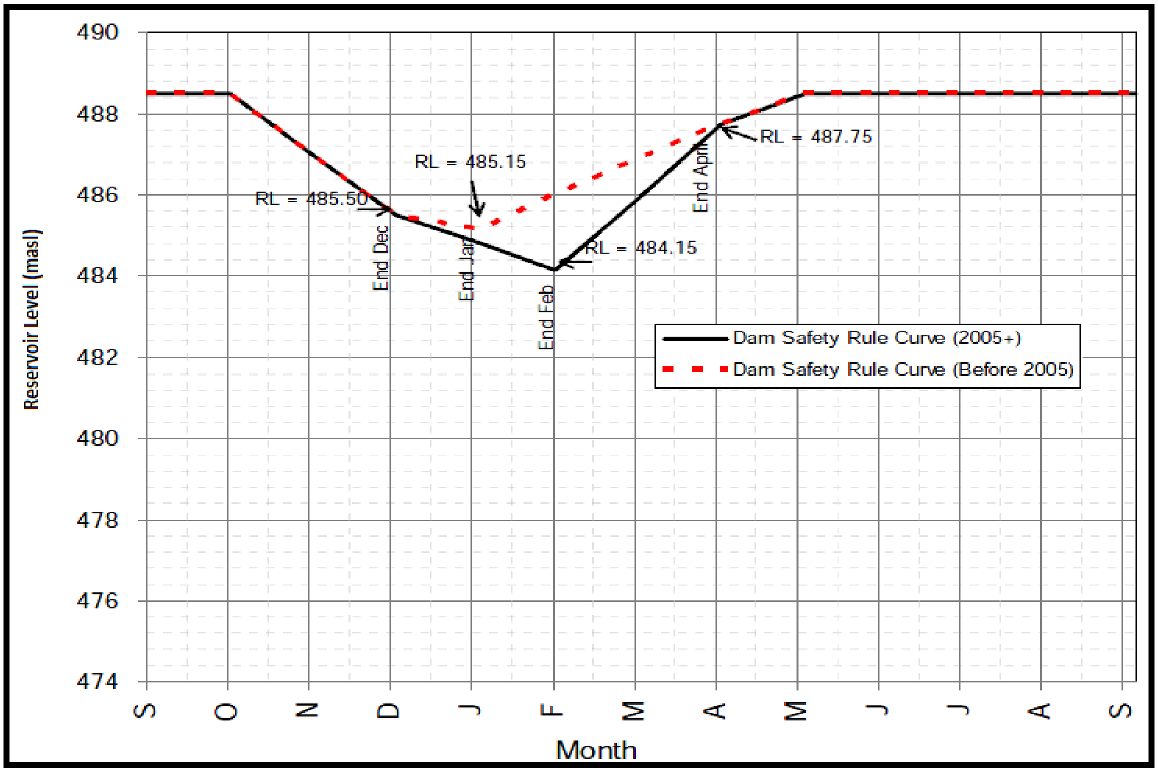

Figure 3.3: Old and new reservoir operating rule curves for Lake Kariba (SADC, 2011)

Lake Cahora Bassa

Lake Cahora Bassa is located 300 km downstream of Lake Kariba and is the second largest man-made reservoir in the middle Zambezi River basin. It covers an area of 4,363 km^2 (Asante *et al.*, 2005) and has a total storage capacity of $72.2*10^6$ km^3 (SADC, 2011). This reservoir lies entirely in Mozambique even though its backwater effect extend to the upstream countries particularly Zimbabwe. The total discharge capacity is about 16,250 m^3/s, which is not sufficient to pass the 1:10,000 year design flood of 30,226 m^3/s (Li-EDF-KP Joint Venture Consultants, 2000). The objective of the existing operating rule curve for Cahora Bassa is to ensure sufficient storage space for flood water and release of water for maximal hydropower production. The releases from the dam are principally governed by hydropower generation and flood rule curve (Figure 3.4) (SADC, 2011). This rule curve has worked well since it was introduced, although in an extremely wet year, with flows higher than the one in 500 year return period, the available storage volume must be increased by lowering the reservoir in advance proportionally to the forecasted inflow (World Bank, 2010c).

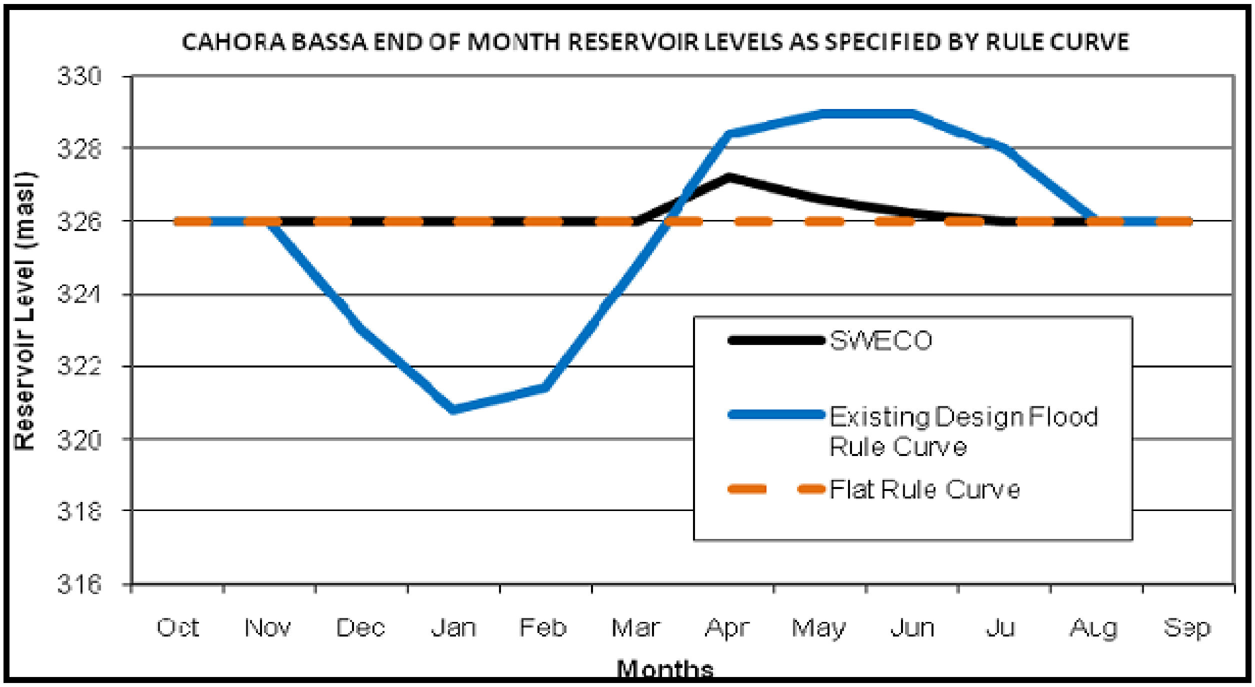

Figure 3.4: Operating rule curve for Cahora BassaFigure (SADC, 2011)

Itezhi-Tezhi and Kafue Gorge Dams

These reservoirs are located entirely in Zambia and have a gross storage capacity of 5.7 km^3 and 1.2 km^3 for Itezhi Tezhi and Kafue Gorge, respectively. They are located in series with the Itezhi-Tezhi upstream and Kafue Gorge downstream. In between them lies the Kafue Flats wetland. The head drop between the two dams is estimated to be just 15 m over a distance of 400 km making it difficult to define the river course (APFM, 2007).

In 1991, Zambia experienced the worst drought ever (SADC, 2011), and power production dropped immensely. The operating rules for these reservoirs (Itezhi Tezhi and Kafue Gorge/Kasaka) were revisited and modified. The operating rule curves were aimed at maintaining maximum storage levels for both reservoirs in order to maximize hydropower production. Both dams are now operated in such a way that water is kept at high level for maximum power production. Even though these reservoirs have operation rule curves (Figure 3.5 and 3.6); they are not strictly adhered to in current practice, but levels are being maintained at a constantly high level whenever possible (SADC, 2011).

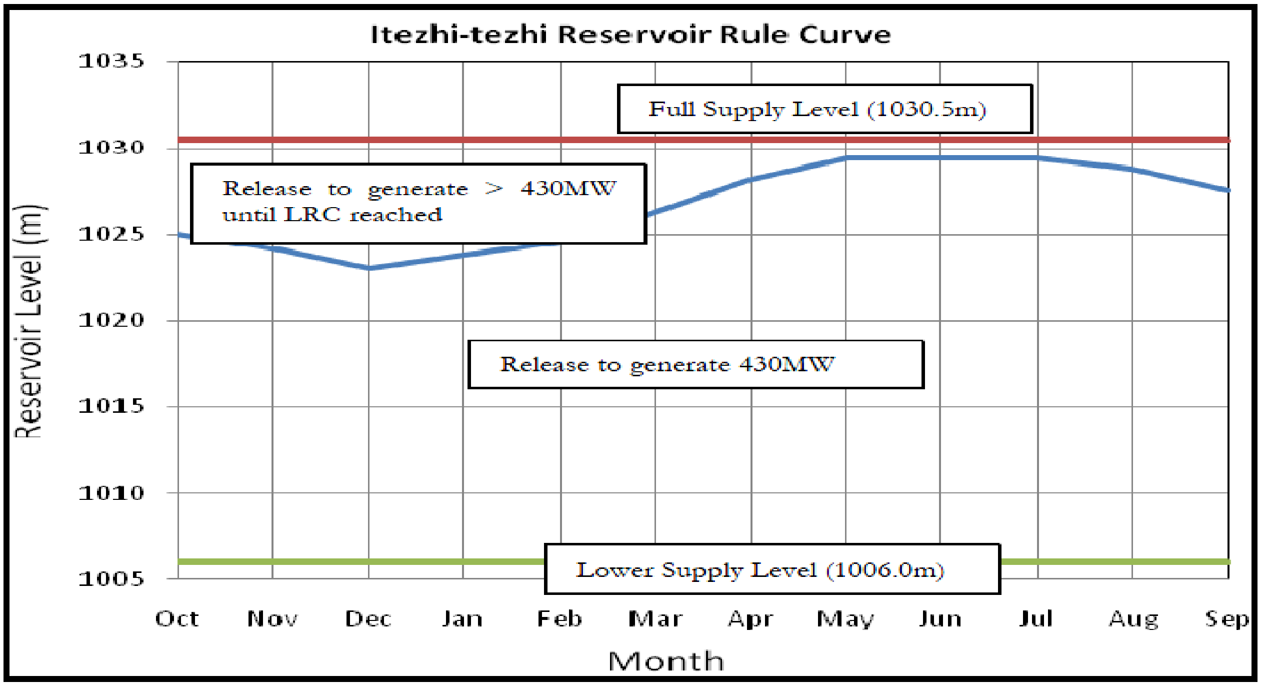

Figure 3.5: Operation rule curve for Itezhi-Tezhi reservoir (SADC, 2011)

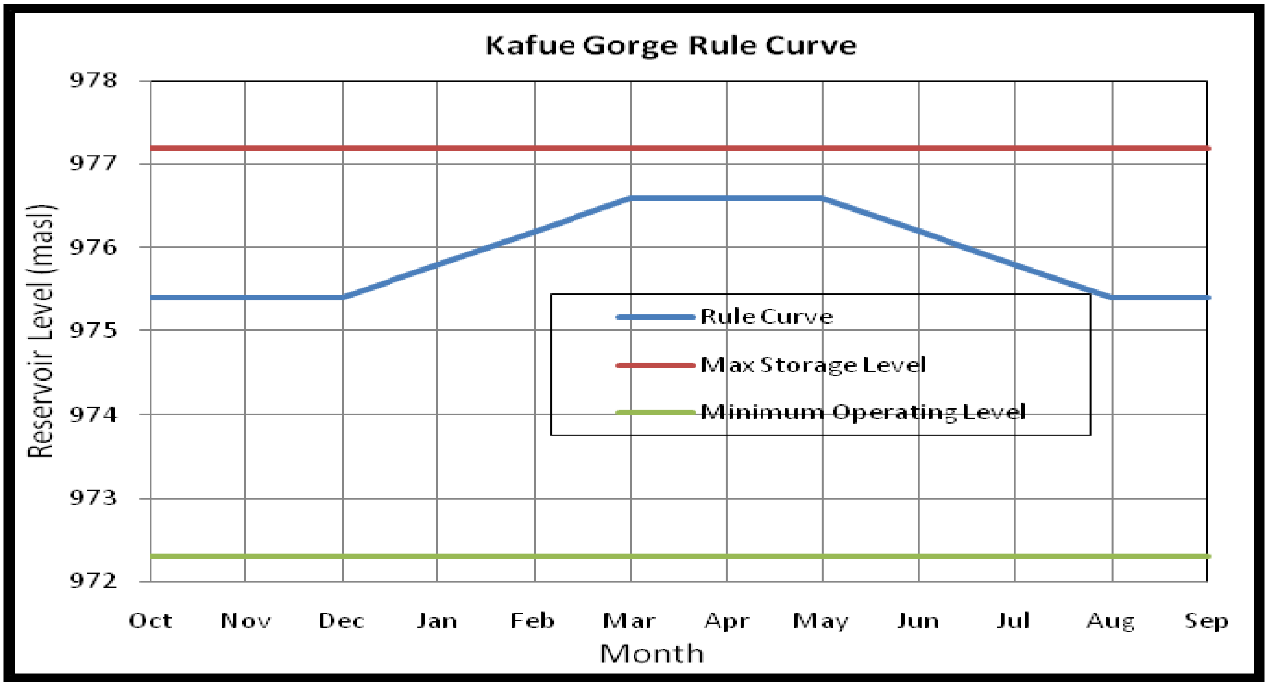

Figure 3.6: Operation rule curve for Kafue Gorge reservoir (SADC, 2011)

Lake Manyame

Lake Manyame was specifically designed for water storage and supply for domestic and irrigation purposes (ZINWA, 2009). The reservoir is operated in such a way to maximize storage of water to meet the demands. Water management requires that upstream dams fill first during the summer period: 14th December to 31st March of every year (ZINWA, 2009). This means that water has to fill up and spill in the most upstream reservoirs except a specified amount that should always be released in order to satisfy primary and environmental water requirements and abstraction by permit holders where there is no storage. Manyame has storage capacity of $480*10^6 m^3$ (Madamombe, 2004).

4 MATERIALS AND METHODS

4.1 Introduction

This Chapter describes the materials and methods employed in data collection data quality check and data analysis.

4.2 Data Collection

Rainfall data was obtained from the Zimbabwe Meteorological Department Services (ZMDS) and the ZAMWIS database. A total of 33 rainfall stations of the middle Zambezi River basin were analysed and their spatial location is shown in Figure 4.1 below. These stations had longest historical data some extending aback to 1890s. For the interest of this study all the stations were harmonized to start from 1910 spanning to 2010.

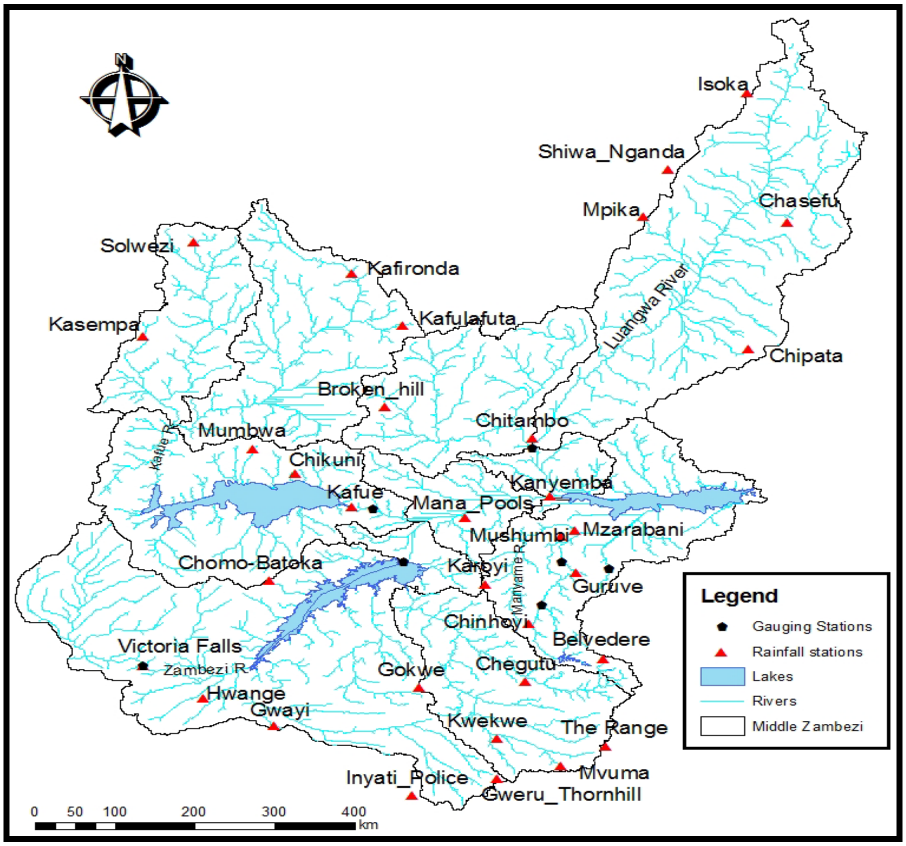

Figure 4.1: Location of rainfall and runoff gauging stations for the middle Zambezi River Basin.

The rainfall data of the middle Zambezi basin was used in analysis of occurrence of extreme hydrological events. This helped in discerning natural floods and hydrological droughts those which were human induced. The method employed in analyzing this is discussed below in the data analysis subsection.

Hydrological data were collected from various institutions. This included the Department of Water Affairs in Mozambique and Zimbabwe National Water Authority (ZINWA). Additional data was obtained from the ZAMWIS database. The gauging stations analyzed are shown in figure 4.1 above.

The data collected from Victoria Falls were used to establish the patterns of frequency of wet years and dry years within the middle Zambezi River basin and also to identify natural extreme hydrological events which were not from the middle Zambezi. Since there were no streamflow gauging stations in the Zambezi Valley, between Lake Kariba and Lake Cahora Bassa, the discharge from Lake Kariba, Kafue Gorge discharge, Luangwa (as measured at Luangwa Bridge) and Manyame catchment, were combined to get the discharge in Cahora Bassa. Cahora Bassa Levels were used to establish the correlation between the individual tributaries (Luangwa, Kafue, Manyame and Kariba discharge) with the Lake levels. Similar analyses were done for the combined flows into Cahora Bassa. Because of the difference in lag time from the respective streamflow gauging stations (or releases) to Cahora Bassa inflow, monthly flows were used in the analysis instead of daily flows to minimize the effects of lag time. This was to minimize the error which might have arisen in using daily flows because of the difference in distances from the respective stations into Cahora Bassa.

4.3 Data Quality Check

Data quality check was carried out to ensure consistency in the data, identify missing gaps, and possible errors which might have occurred during data processing. Data errors were identified through visualization and the inconsistent value was eliminated and replaced through correlation with nearby stations. Missing gaps were similarly filled using regression analysis by correlating with the nearby stations. The correlation results are presented in Appendix 2, Table 8.7.

4.4 Data Analysis

4.4.1 Rainfall Data analysis

Rainfall data was principally used in the analysis of extreme hydrological events as well as in modeling. This subsection deals with extreme hydrological events, whereas the modeling part is described in the subsequent subsection. All the rainfall data collected for the study were converted into annual values for simplicity of the analysis. This was to minimize errors (numerical instability) in the analysis since the rainfall data series were long i.e. 100 years and the stations were many (33).

Thiessen Polygon method was used in the calculation of average rainfall received within the catchment. This involved multiplying the rainfall received in each station with the area and then dividing the total sum of the products with the total catchment area as shown by equation 4.1.

$$P = \frac{1}{A}\sum_{i=1}^{n}(P_i * A_i) \qquad \ldots\ldots 4.1$$

P is the catchment average precipitation (mm)

A_i is the area of polygon *i* (km^2)

P_i is the precipitation measured in station *i*

n is the number of polygons

A is the total area of the catchment (km^2)

To obtain the area of each polygon, a GIS software called Ilwis was used to execute the calculation process. This involved interpolation with the neighboring station and this automatically calculated for the whole catchment. The total area was obtained using the following Equation 4.2;

$$A = \sum_{j=1}^{n} A_j \qquad \ldots\ldots 4.2$$

A is the total area (km^2), *n* number of polygons and A_j is area of polygon *j* (km^2)

4.4.2 Modeling of Manyame Catchment

Since the Manyame was poorly gauged (Madamombe, 2005), a Soil Conservation Service Curve Number (SCS-CN) model was employed to convert the rainfall received in the Lower Manyame catchment (Figure 4.2) into runoff to make it possible for the analysis of the runoff contribution of the Manyame catchment in the middle Zambezi.

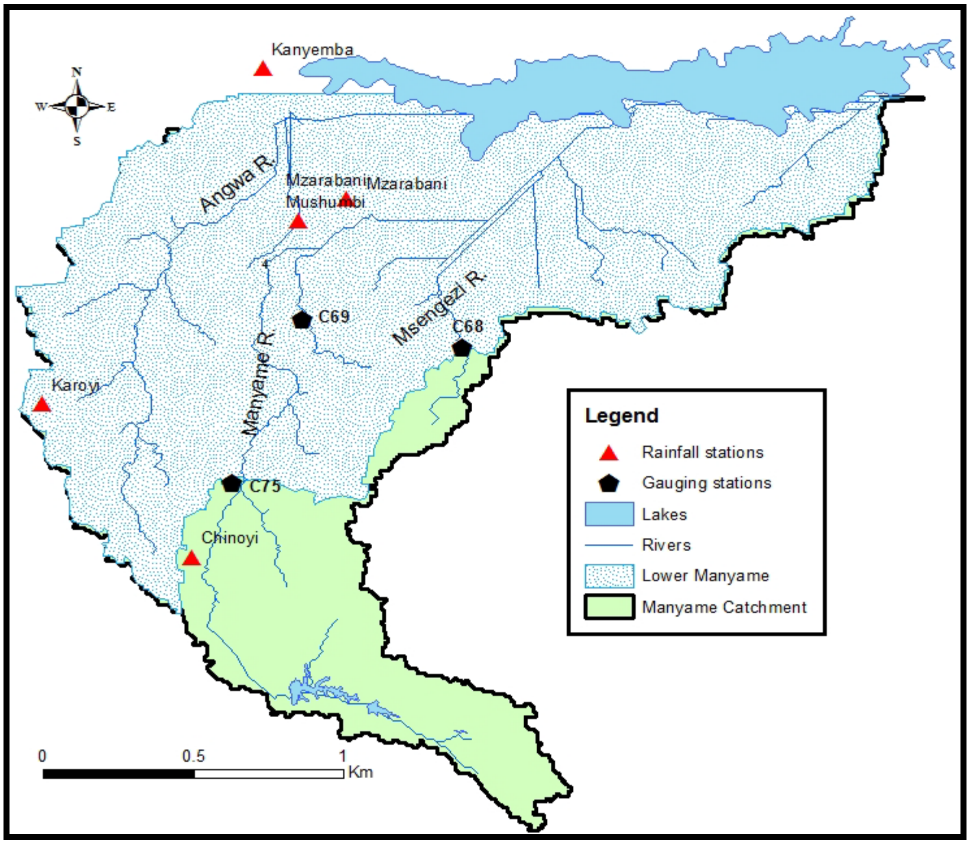

Figure 4.2: Location of the Lower Manyame, rainfall and runoff gauging stations within the Manyame catchment.

The model inputs were; landuse/landcover, Hydrologic Soil Group, and Antecedent Soil Moisture Content (AMC) to get the curve number from a lookup table (Table 4.1). The landuse/landcover was categorised into five classes according to the USGS (2009) landcover classification. Classes obtained were Agricultural Land (1), Rangeland (2), Forest Land (3), Water Bodies (4), and Barren Land (5). The Soil Map was classified into Hydrologic Soil Group A, B, C, D, with respect to soil type. The Hydrologic Soil Group Map and land use land cover map were overlaid in ILWISS 3.3 Academic using the crossing function and the resultant map was land cover-soil group map. Antecedent soil moisture was obtained by summing the first five raining days of a hydrological year, and this was done for all the years to get the AMC for each year which was used to get the CN from a table as referred above. This was done for each land cover and the weighted CN for the whole catchment was given by equation 4.3;

$$CN = \frac{1}{A}\sum_{j=1}^{n} CN_j A_j \quad \ldots\ldots\ldots \quad 4.3$$

CN is a unitless Curve number ranging from 0 to 100 and obtained from Table 4.1.

CN_j is the curve number corresponding to land type *j* and hydrologic soil group *j*,

A*j* is the corresponding area of land cover *j* and soil type *j*, and,

A is the total catchment area.

Table 4.1: Curve Numbers for the SCS-CN Method (Tan *et al.*, 2001).

HSG	A			B			C			D		
AMC / LULCC	I	II	III	I	II	III	I	II	III	I	II	III
Agricultural Land	52	72	86	64	81	91	75	88	94	81	91	96
Rangeland	18	35	55	35	56	75	49	70	84	58	77	89
Forest land	19	36	56	39	60	78	53	73	86	61	79	90
Water	100	100	100	100	100	100	100	100	100	100	100	100
Barren land	58	77	89	72	86	93	81	91	96	87	94	97
Wetland	100	100	100	100	100	100	100	100	100	100	100	100
Urban	77	89	95	83	92	96	86	94	97	89	95	98

The Curve number was then substituted in the following Equation 4.4

$$S = \frac{25400}{CN} - 254 \quad \ldots\ldots\ldots \quad 4.4$$

S is the maximum potential water storage of the catchment (mm).

The value of S was then substituted in Equation 4.5 to get the runoff coefficient, Q.

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{.......... 4.5}$$

Q is the runoff coefficient (mm), and,

P>0.2S otherwise there would be no flow.

Precipitation, P, was calculated using the Thiessen polygon method as shown in Equation 4.6,

$$P = \frac{1}{A}\sum_{i=1}^{n}(P_i * A_i) \quad \text{.......... 4.6}$$

P is the catchment average precipitation (mm)

A is total area of the catchment (km^2)

P_i is the precipitation measured in station *i*

A_i is the area of polygon *i*

To obtain the area of each polygon, a GIS software called Ilwis was used to execute the calculation process. This involved interpolation with the neighboring station and this automatically calculated for the whole catchment. The total area was obtained using the following Equation 4.7;

$$A = \sum_{j=1}^{n} A_j \quad \text{.......... 4.7}$$

A is total area (km^2), *n* is number of polygons and A_j is area of polygon *j* (km^2)

4.5 Model Calibration

The method discussed above of converting runoff was first employed in the Dande River subbasin in order to calibrate the model parameters comparing with the observed flow at Dande gauging station, C69 (see Figure 4.2 above) using a four-year record of monthly flows from 1969/70 to 1972/73. Relative Volume error was used to assess the percentage of overestimation (Equation 4.8) and Root Mean Square Error (Equation 4.9) was used to assess the deviation, in depth, of the simulated from the observed.

$$RV_E = \frac{\sum(Q_{sim} - Q_{obs})}{\sum Q_{obs}} \qquad \text{.......4.8}$$

RV_E (%) is the relative volume error ranging from -∞ to ∞ with best values between -10 and 10.
Q_{sim} is the simulated volume or discharge
Q_{obs} is the observed volume or discharge.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i} - x_{2,i})^2}{n}} \qquad \text{.......4.9}$$

RMSE is the root mean square error
n is the total number of observations
$x_{1,i}$ and $x_{2,i}$ are the simulated and observed volumes (m^3), respectively.

The model was then applied in the conversion of rainfall into runoff in the lower Manyame. Monthly flows from upper Manyame (upstream of gauging station C75) and also those accumulated in Msengezi subcatchment, which is upstream of gauging station C68, were summed up with those obtained from the model to get the total monthly flows from the whole Manyame catchment at the outlet in Cahora Bassa (Figure 4.2).

4.6 Contribution of Catchments in the Occurrence of Extreme Hydrological Events in the middle Zambezi River Basin

The term extreme hydrological events, was used to refer to floods and hydrological droughts. For the purpose of this study, floods were defined as those flows which were exceeded 20% of the time as postulated by Kundzewicz *et al.* (1993) and Shaw (2004) that floods can be distinguished from a non-flood event by an arbitrary threshold. For the purpose of this study, drought was defined as those anomalies below a long-term average (Timilsena *et al*., 2007) of the respective drought.

Two approaches were used in analyzing contribution of catchments in the occurrence of extreme hydrological events; Pearson Correlation and Double Mass Analysis.

4.6.1 Pearson Correlation

A sample Pearson Correlation coefficient was used to determine the relationship between Manyame flows (with rainfall incorporated, including Msengezi, and Angwa), Kafue Gorge discharge, Kariba discharge, and flow from the Luangwa, with Cahora Bassa levels from the period 1975 to 2008 using Equation 4.10.

$$r = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - (\sum x_i)^2}\sqrt{n\sum y_i^2 - (\sum y_i)^2} \quad \text{……………………………………… 4.10}$$

r is the correlation coefficient ranging from -1 to 1. And when r=-1, it means there is a perfect negative correlation, r=1 means there is a perfect positive correlation, and when r=0 there is no relationship between the two variables. Table 4.2 shows the interpretation of values of Pearson's correlation coefficients and Figure 4.3 shows the minimum values of Pearson correlation coefficient against sample size at 95% confidence level.

n is the number of observations, and
x_i and y_i, are the two variables of the samples

Depending on the size of samples used, sometimes this method can be numerically unstable (Rodgers and Nicewander, 1988).

Table 4.2: Classification of Pearson correlation Coefficient (Rodgers and Nicewander, 1988).

Correlation	**Negative**	**Positive**
None	-0.09 to 0.0	0.0 to 0.09
Small	-0.3 to -0.1	0.1 to 0.3
Medium	-0.5 to -0.3	0.3 to 0.5
Large	-1.0 to -0.5	0.5 to 1.0

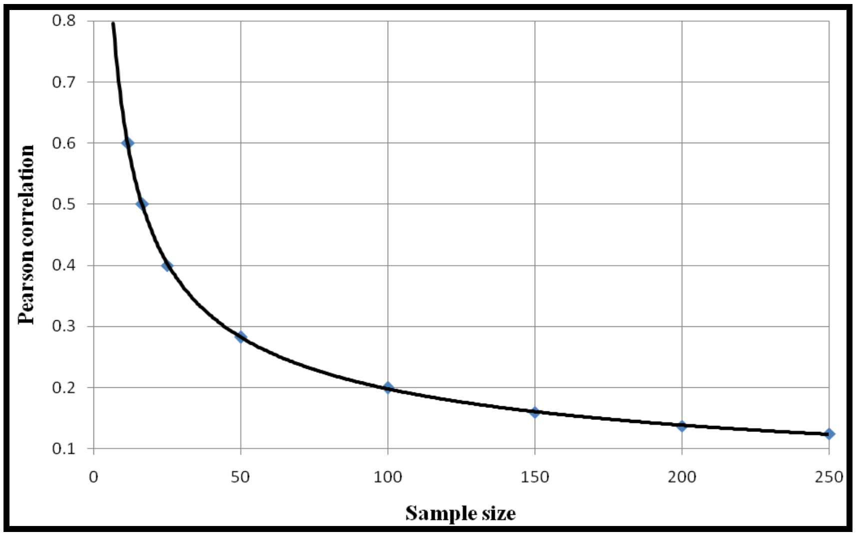

Figure 4.3: Minimum values of Pearson's correlation coefficient that is significantly different from zero at the 0.05 level, for a given sample size (Rodgers and Nicewander, 1988).

4.6.2 Double Mass Analysis

A double mass analysis of contribution of each of the tributaries (Manyame, Luangwa, Kafue Gorge releases and Kariba releases) to the total combined flows (inflows to Cahora Bassa) was used to find out the contribution of each of the streams in the occurrence of extreme hydrological extremes. A flow duration curve, which plots the empirical cumulative frequency of streamflow as a function of percentage of time that the streamflow was equaled or exceeded, for the combined flows was plotted to get the corresponding flows which were exceeded 20% and 80% of the time from 1975-2009. The 20% was a threshold for a flood, whilst the 80% was for a drought. This was done in order to get the corresponding values of each tributary in the occurrence of the hydrological extremes.

With this method (double mass analysis), the scatter points are expected to concentrated on the low flow region and they are expected not to have any pattern. This is because on average, a river experiences low flows much of the period of the hydrological year as compared to high flows and only experience high flows for 3 months on average. For the Zambezi, the flows are largely dependent on how the reservoirs are operated upstream and this obviously causes the correlation (R^2) with the combined flows to be weak. However, during periods of high flows, and depending on the capacity of the tributary, the scatter are expected to follow a certain trend as you move outwards of the graph and this is because during high flows (flows equaled or exceeded only 20% of the time) the discharge is more of a function of the input from upstream than reservoir operation and thus it can be predictable that time. This can be graphically explained by Figure 4.2, whereby flow duration curves for the various tributaries under study were superimposed with the flow duration curve of the combined flow. In the case of the combined flows at Cahora Bassa, the idea explained above was valid for flows exceeded less than 30% of the time as speculated by Shaw (2004) of which 20% lied within the range.

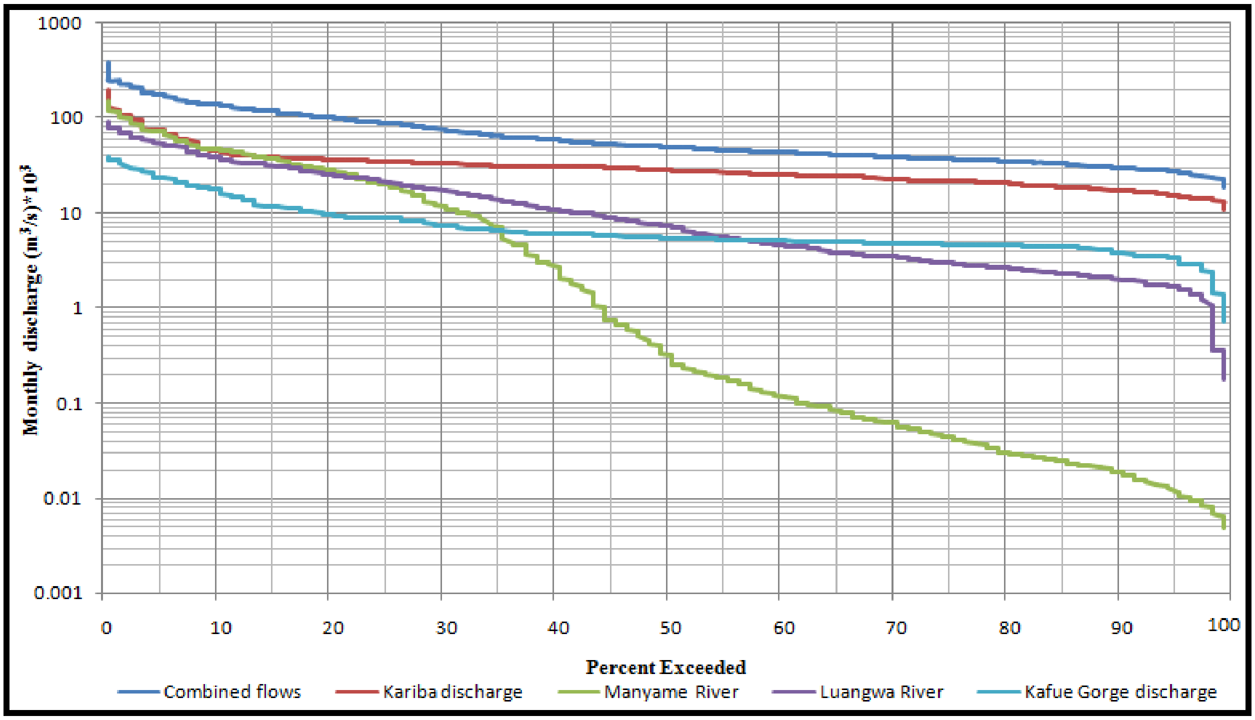

Figure 4.4: FDC of the main tributaries of the middle Zambezi superimposed on the FDC of the combined flows

4.7 Frequency Analysis of Hydrological Extremes

To get the sequence of natural flows in the middle Zambezi River basin; flows recorded at the Victoria Falls were used to get the pattern of the cycle of wet and dry periods in the middle Zambezi Valley from 1924 to 2009. In addition to that, a flow duration curve of the inflows and outflows from Lake Kariba was plotted to see the impact of the reservoir in the occurrence of hydrological extremes.

From the total inflows to Cahora Bassa (sum of Luangwa, Kafue Gorge releases, Manyame, Kariba releases), a differential mass curve (sometimes referred to as residual mass curve) was plotted to get the sequence of wet and dry years. The assumption was that, floods are expected to occur during wet years and conversely droughts on the dry years. The same data set was used to analyze the frequency of occurrence of floods and hydrological droughts. The approach for flood frequency analysis was different from that of analyzing hydrological drought. For floods, plotting was used as outlined by Wilson (1990). And for hydrological droughts frequency analysis were done by ranking as applied by Timilsena *et al.* (2007). These two methods are discussed in details in the subsequent subsections.

4.7.1 Flood frequency analysis

The annual maximum series method was used in the frequency analysis of floods. This involved selecting the highest peak in each hydrological year and were listed each accorded a ranking *m*, starting with *m*=1 for highest value, and *m*=2 for the next highest and so on in descending order. Recurrence interval, T_r, was computed using Equation 4.11 by Gringorten (1963)

$$T_r = \frac{(n+0.12)}{(m-0.44)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 4.11$$

T_r is the return period in *r* years
m is the rank number of the value
n is the total number of years of data

The probability, *p*, of an *N*-year event was calculated using the return period T_r, as applied by Wilson (1990) in Equation 4.12;

$$p = \frac{100}{T_r} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 4.12$$

p is the probability as a percentage
T_r is the return period in years.

The discharge, Q, was plotted against return period, T_r, on a semi-logarithmic scale

4.7.2 Hydrological Drought Frequency analysis

Hydrologic drought was typically defined as consecutive series of years during which the average annual drought variable was is continuously below some specified threshold, such as the long-term mean (Dracup *et al.*, 1980). In this study, the long-term mean (1975-2010) was assumed to be the threshold. Hydrologic drought was characterized by duration (years), magnitude (the cumulative deficit below the threshold for consecutive years), severity (average deficit below the thresholds) and frequency for each drought variable.

The first step in the analysis was to define periods of drought. As mentioned previously, drought was defined as the cumulative deficit relative to long-term mean. The long-term mean (threshold) was obtained first by taking the average of the adjoined historical data of the drought variable. Then, anomalies with respect to the long-term mean were obtained by subtracting the long-term mean from the annual value of the hydrologic variable (streamflow quantity for the year). After obtaining the anomalies of each drought variable, droughts were defined as the consecutive negative anomalies for at least 2 years. The magnitude was obtained by adding up all the anomalies during the drought. The duration was defined as the elapsed time between the first year with a negative anomaly and the last year with a negative anomaly. Lastly, the severity was obtained by dividing the drought magnitude by the drought duration.

The determination of frequency was considered using the ranking approach as applied by Timilsena *et al.* (2007). Drought were ranked according to their magnitude, with the highest accorded the first rank. The corresponding probability and return period were computed using Weibull distribution as shown by Equation 4.13 and 4.14, respectively.

$$p = \frac{m}{n+1} \qquad 4.13$$

p is the probability of occurrence of the event

m is the rank number of the corresponding drought event

n is the total number of years of data

$$T_r = \frac{1}{p} \qquad 4.14$$

T_r is the return period

p is the probability of occurrence

5 RESULTS AND DISCUSSIONS

5.1 Rainfall Results

The middle Zambezi basin is characterized by extreme variation of rainfall spatially and temporally. The temporal distribution of rainfall within the middle Zambezi sub basin demonstrated a cyclic behavior when studied from 1910 to 2010 having a long-term average value of 901.7 mm/a (Figure 5.1). From 1910 to 1925, the basin was experiencing a dry period. This was followed by a long wet period from 1926 to 1960. From 1960 to 1980, the basin was experiencing a combination of short-term dry and wet period. From 1980 to 1999, the period was relatively dry, whereas from 1999 to 2010, the cycle was indifferent. Occurrence of floods and hydrological droughts within these periods is discussed in the next subsections.

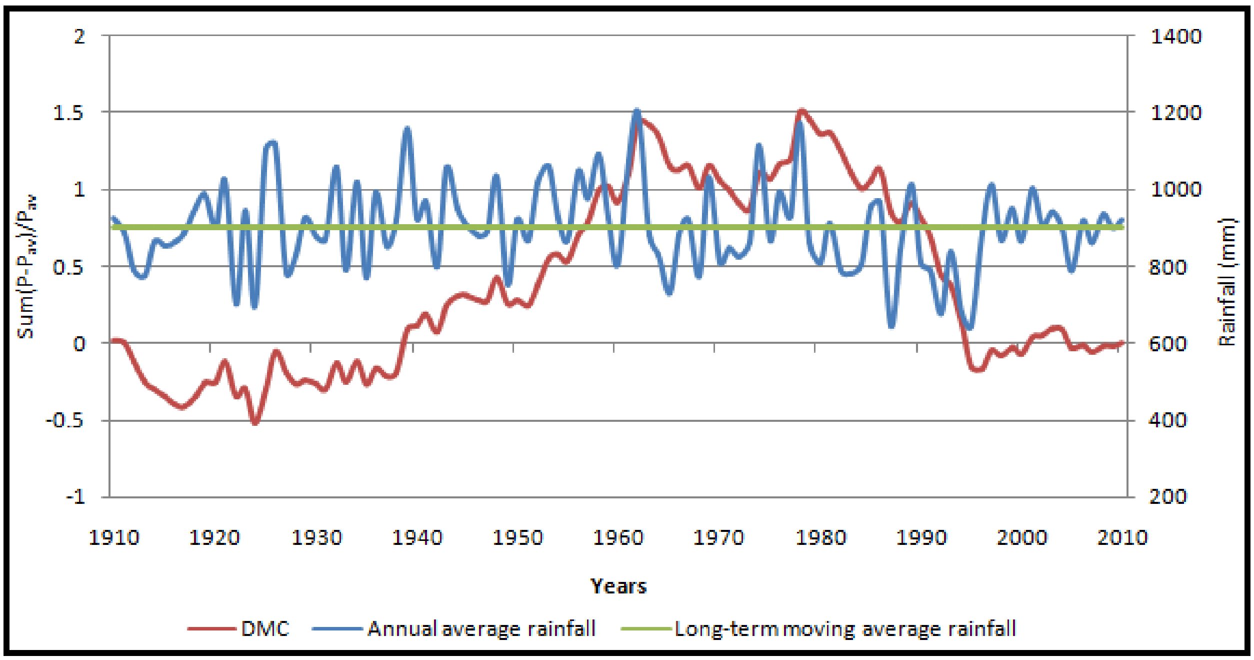

Figure 5.1: Temporal rainfall distribution of the middle Zambezi River Basin.

The 33 rainfall stations studied showed a wide range of spatial variation in rainfall distribution within the catchment (Figure 5.2) with annual average values ranging from as low as 669 mm/a to as high as 1339 mm/a. The highest rainfall was received in the northern part of the catchment, whereas the southern part received the lowest average rainfall. According to APFM (2007) and SADC (2011), the catchment receives rainfall from various sources. Some of these areas are influenced by rainfall from westerly or easterly winds, advected moisture from the sea whilst others experience rainfall from the inter-tropical convergence zone (ITCZ).

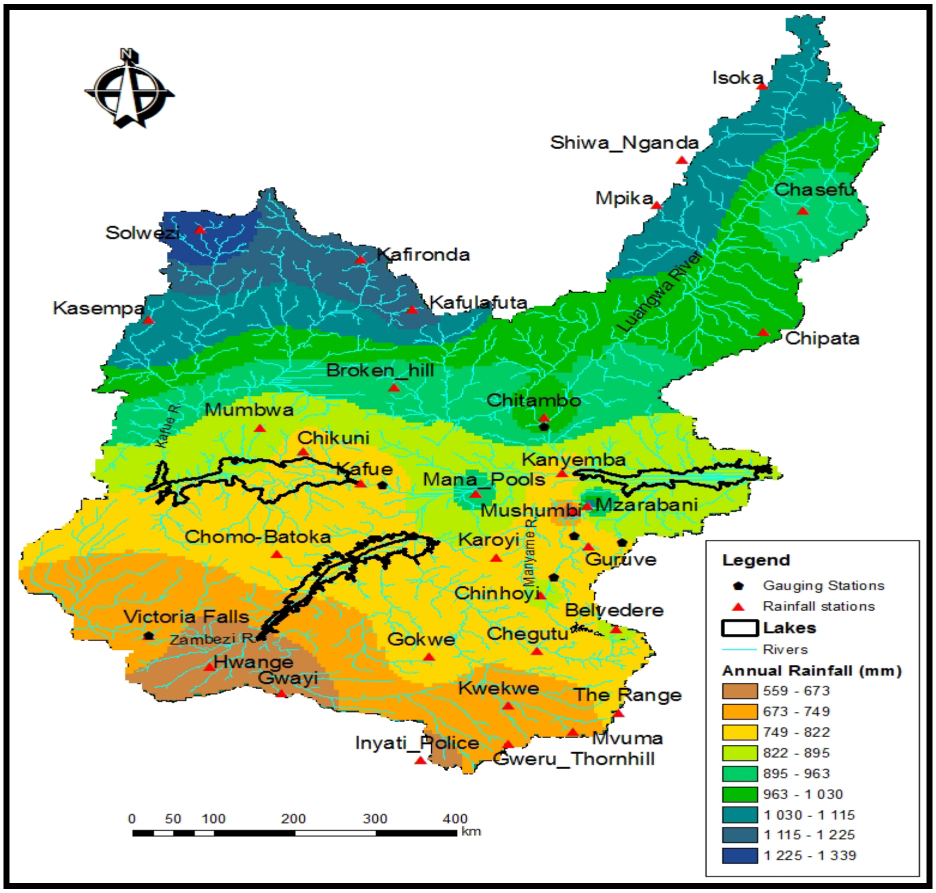

Figure 5.2: Spatial variation of rainfall within the middle Zambezi River basin.

The middle Zambezi rainfall and the runoff in Cahora Bassa followed the same trend from 1975-2010 (Figure 5.3). Using a Pearson Correlation coefficient, the results showed that there was a high correlation between rainfall and runoff with *r = 0.65*. According to Rodgers and Nicewander (1988), this correlation is very large at 95% confidence level. This showed that the runoff in the middle Zambezi was largely influenced by rainfall supply.

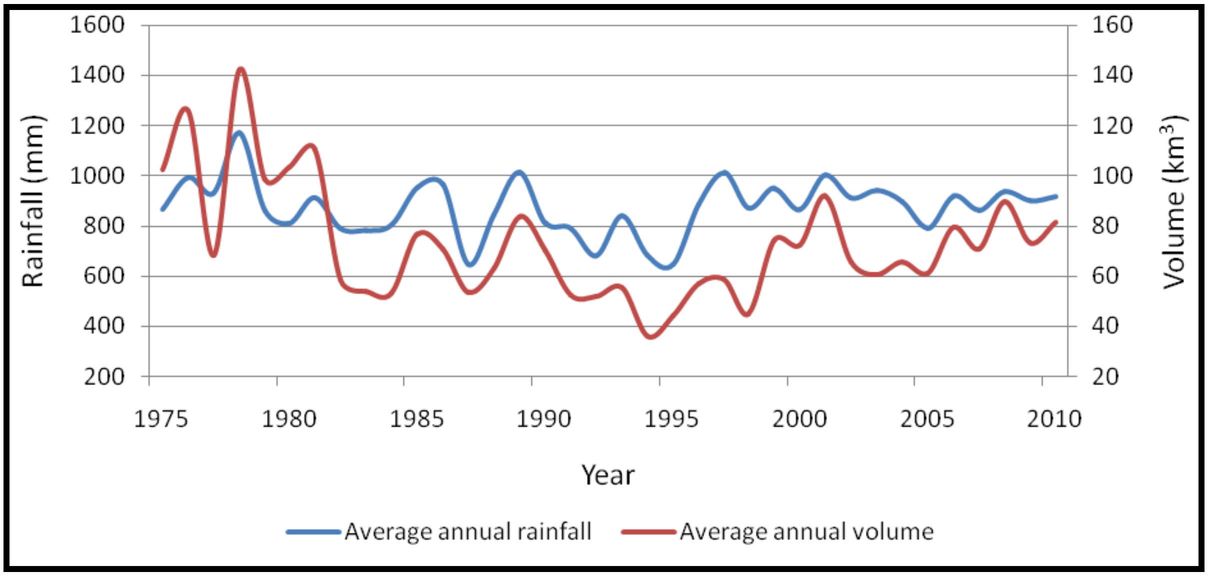

Figure 5.3: Hydrographs of average annual rainfall of the middle Zambezi and runoff volume in Cahora Bassa

5.2 Model Results

The observed and simulated results followed the same trend but the magnitudes were different (Figure 5.4). The simulated results were higher than the observed. Before the model was calibrated, the Relative Volume (RV) error was 12% which was outside the limits of a good performing model (-10% to 10%). Using the Root Mean Square Error (RMSE), the result was 20 mm which was high. The model was then adjusted so that it could give better results. This was done by refining the landuse/landcover values and the hydrologic soil group classification. The model was re-run and it gave excellent results. The RV error was 9.6% which was equivalent to 10 mm ($8.06*10^6$ m^3 in a catchment area of 1279 km^2) overestimation of runoff using the RMSE. Figure 5.4 and 5.5 show the comparison of the observed and simulated volumes before and after model calibration. These results are based on the 4-year data from Dande River gauging station (C69) which was used in model calibration as discussed in the Materials and Methods Section.

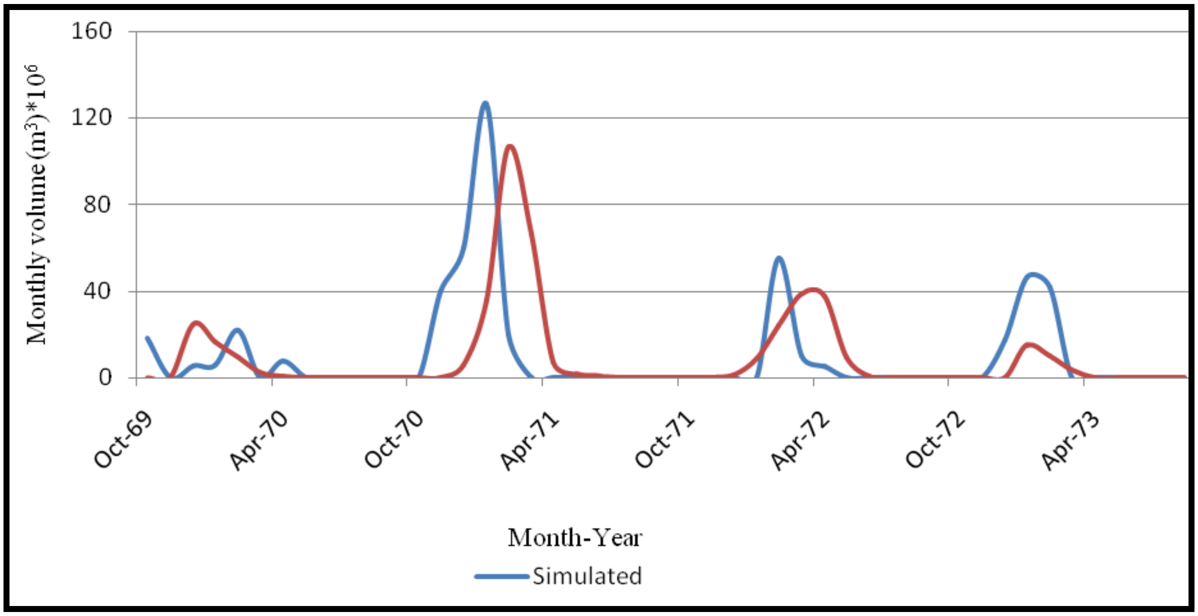

Figure 5.4: Comparison of simulated and observed volumes before model calibration

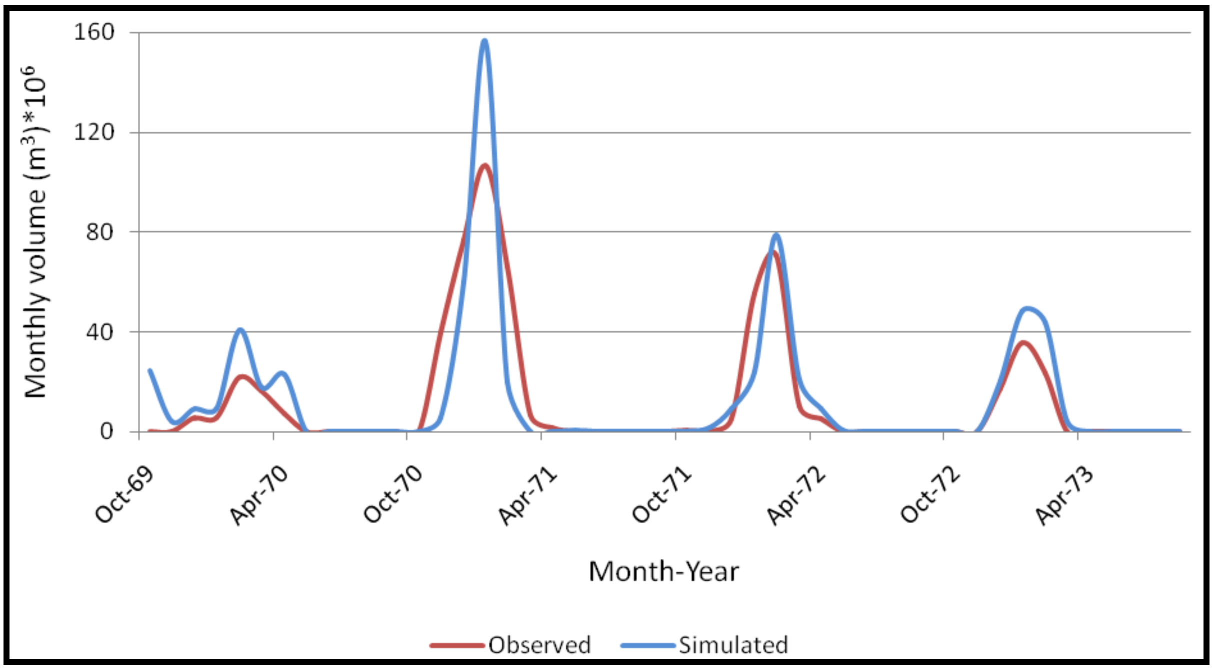

Figure 5.5: Observed and simulated volumes after model calibration

Figure 5.6 presents the runoff results of the Upper Manyame (as measured from station C75), Lower Manyame (modelled results) and runoff from Msengezi (C68). From the figure, it can be observed that the lower Manyame rainfall contributed the highest when compared with runoff from station C68 and C75.

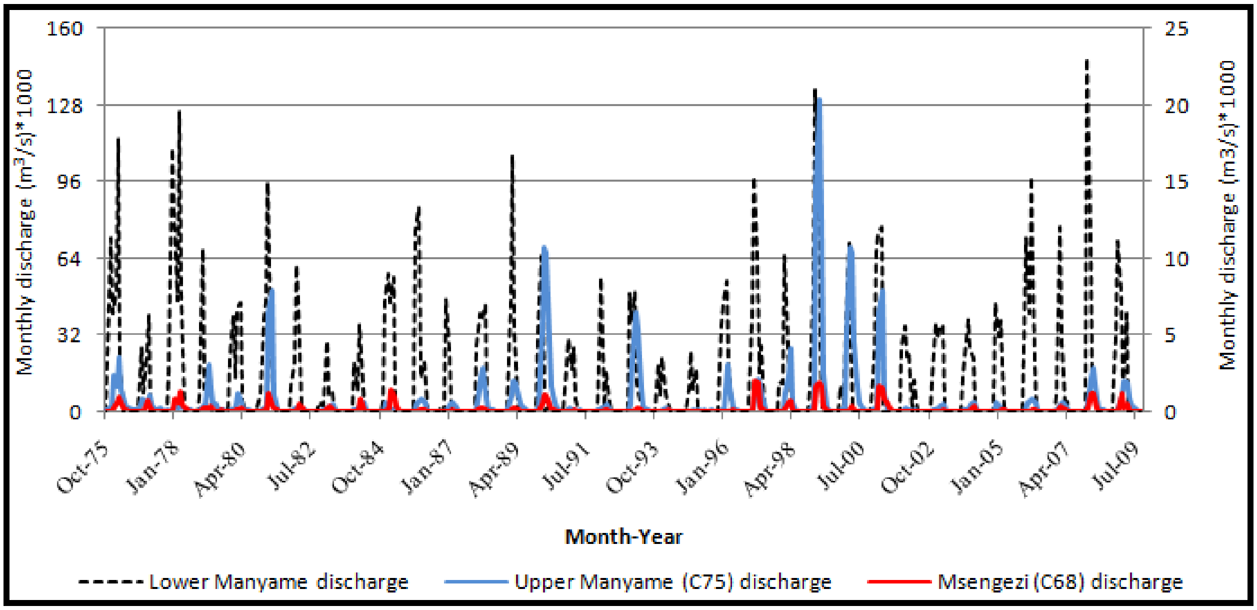

Figure 5.6: Comparison of runoff accumulated within the Manyame catchment.

It can be deduced that the lower Manyame had the highest contribution in the total runoff accumulated within the Manyame catchment. Two factors might account for this; the first one being that, the lower Manyame is larger in size and constitutes 75% of the total Manyame catchment. The other reason was that, on average, highest rainfall was received in the lower Manyame as per results from Mzarabani rainfall station (Figure 5.7). This in turn showed that the Manyame catchment is largely dependent on rainfall for significant runoffs. This also identifies the need for this catchment to be gauged in order to monitor the runoff from the catchment particularly from the lower Manyame. Figure 5.8 shows the combined flows of the whole Manyame catchment i.e. sum of upper Manyame runoff, Msengezi and Lower Manyame Catchment.

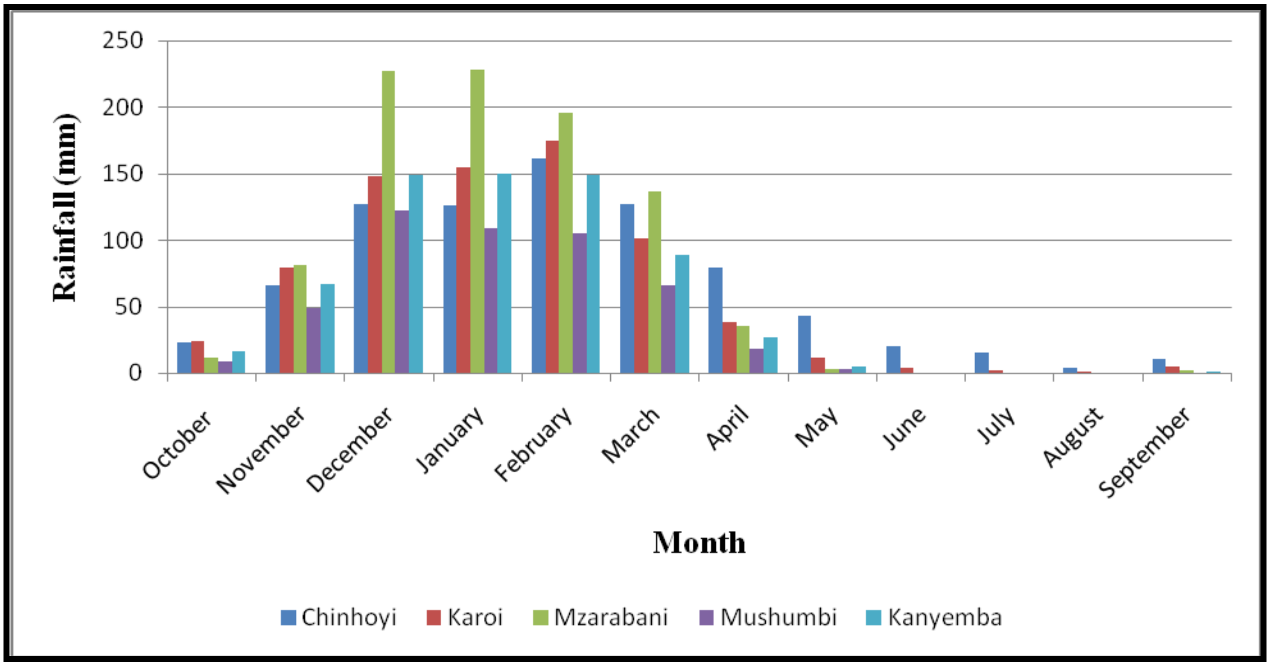

Figure 5.7:Average monthly rainfall recorded in five stations of the Manyame catchment from 1970-2009

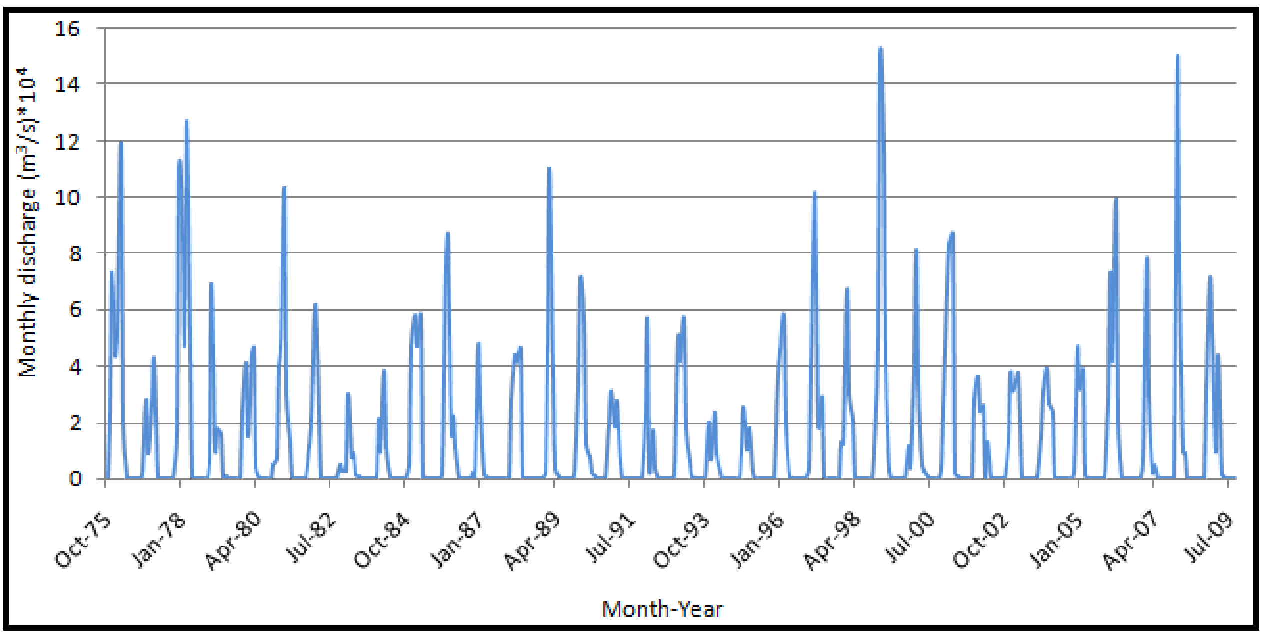

Figure 5.8: Combined flows of the Manyame catchment as observed in the outlet of the catchment.

5.3 Occurrence of Extreme Hydrological Events

5.3.1 Floods

The middle Zambezi, to a larger extent strongly depends on the rainfall received within the catchment as far as floods are concerned. This was evidenced by the Pearson correlation coefficient which demonstrated the relation between the rainfall and runoff in the catchment (Section 5.1 and Figure 5.3 above). A further analysis of years of high rainfall and runoffs in the middle Zambezi produced a correlation of *r=0.86* using the Pearson correlation. This show that the occurrence of floods strongly depended on the rainfall supply (Figure 5.9)

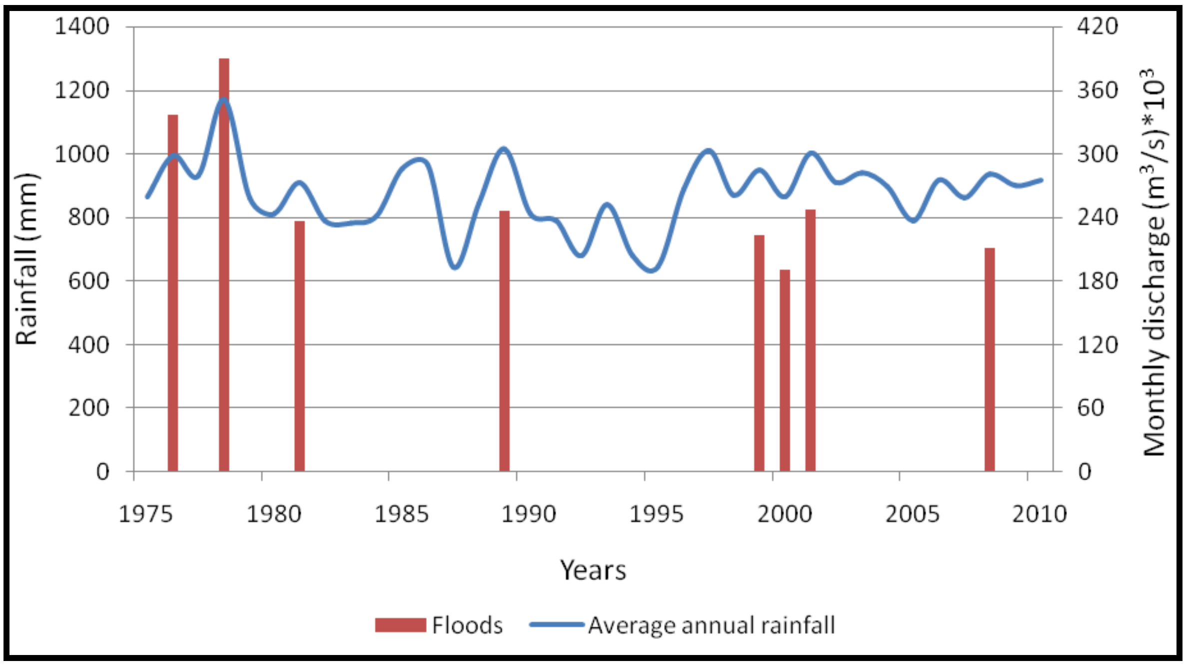

Figure 5.9: Average annual rainfall of the middle Zambezi showing the years when floods were experienced.

Most floods were experienced during the wet period of the DMC cycle and some exceptional ones occurred during the dry (recession-limb) period of the curve (Figure 5.10 and Figure 5.11).

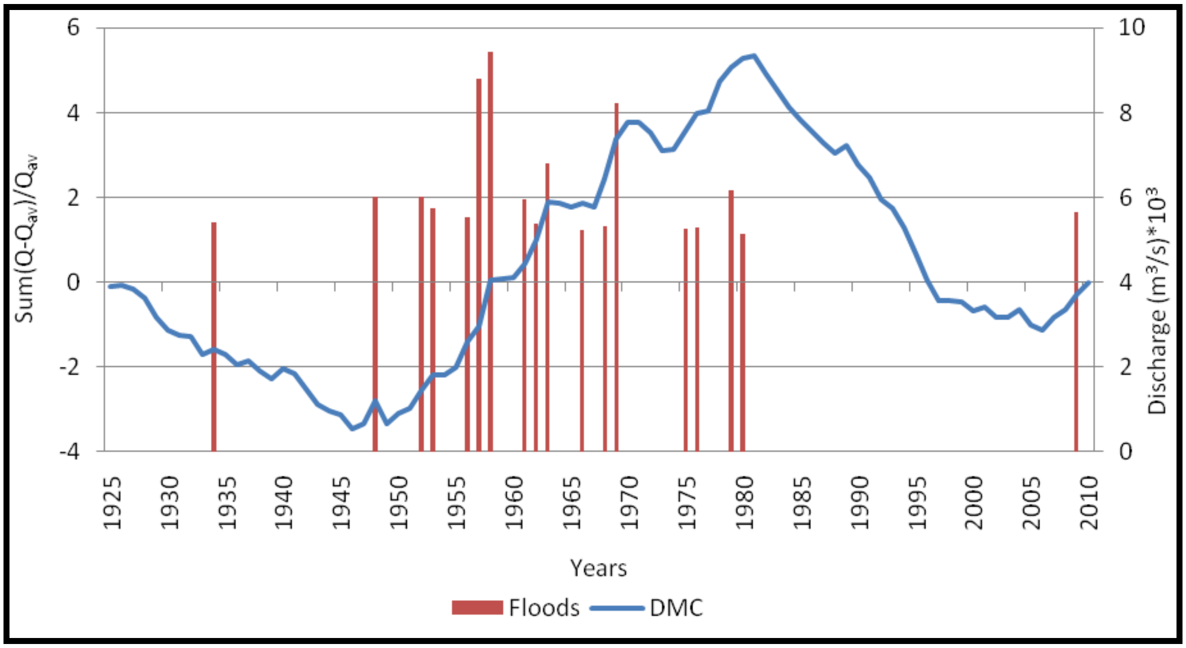

Figure 5.10: Occurrence of floods in Victoria Falls within the DMC cycle

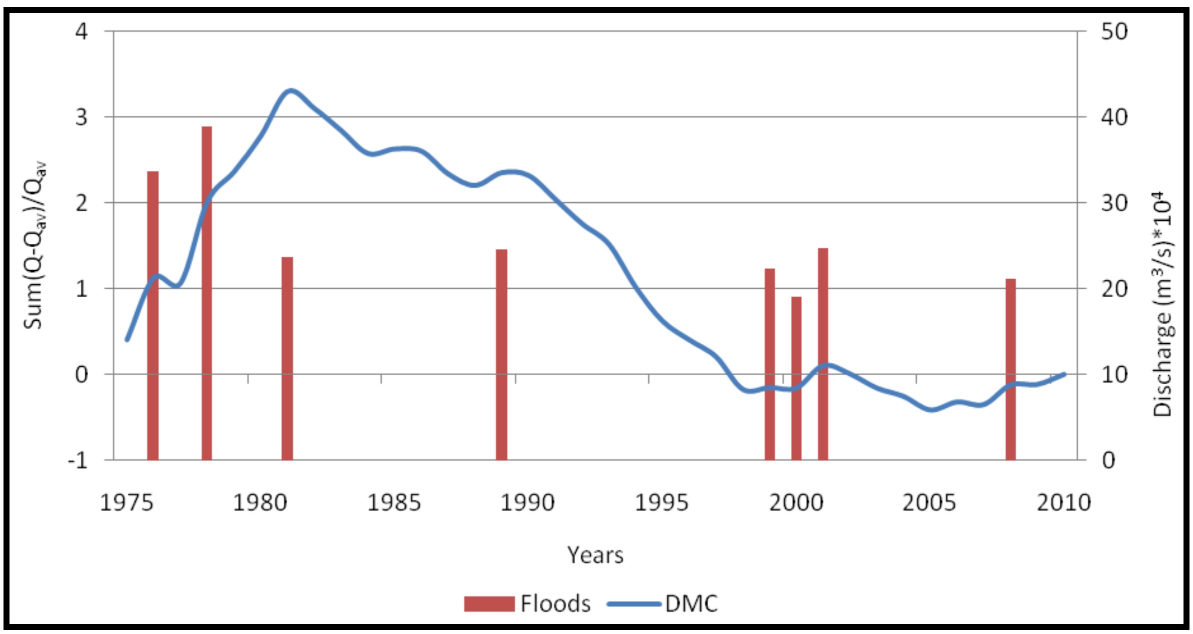

Figure 5.11: Occurrence of floods in Cahora Bassa within the DMC cycle.

A proportion of 63% of the total floods were observed both in Victoria Falls and Cahora Bassa between 1975 and 2010. This showed that, the Zambezi River alone has a potential of causing extreme events irrespective of the middle Zambezi tributaries. On the contrary, these might be floods which were experienced in the whole SADC region thus occurring in Victoria Falls and

Cahora Bassa. However, some floods observed in Victoria Falls did not reach Cahora Bassa and these are examples of the purpose of Lake Kariba in flood attenuation as shown in Figure 5.11. Example of floods which were “absorbed” by Lake Kariba includes the 1975 and 2009 floods (Figure 5.9 and 5.10). There were some floods which were accumulated in the middle Zambezi and did not occur in Victoria Falls. Examples include the 1999, 2000, 2001, and 2007 floods. This shows that, the middle Zambezi River Basin had a significant contribution in the occurrence of floods. This was obviously associated with rainfall influence since these floods correlated with the rainfall peaks of the middle Zambezi as previously explained. From this, it can be deduced that, the occurrence of floods was solely associated with rainfall within the catchment, as opposed to dam operation, and also contribution from upper Zambezi as measured in Victoria Falls. This showed that even if the dams were not there such floods would have still been experienced. However, the advantage the dams have brought is in reduction and attenuation of high flows (Tumbare, 2010).

Lake Kariba has reduced the occurrence of hydrological drought by increasing the lowest flows due to hydropower generation (Figure 5.12). For example, the inflow into Lake Kariba increases on average from 210 m^3/s to 500 m^3/s as outflow. As seen from the flow duration curve below, small and medium floods are completely attenuated by Kariba dam, but high flows are partially attenuated and still results in high flows downstream. Beilfuss and dos Santos (2001) made the same observations for Lake Cahora Bassa which is 300 km downstream of Lake Kariba (Asante *et al.*, 2001) that most small and medium-sized floods are modified by Lake Cahora Bassa. These results are in line with those from SADC (2011), that Kariba Dam management practices attenuate (essentially capturing) the unregulated small to medium floods including the 1:5 and1:10 year flood events. While they also alter the basic hydrological characteristics of larger flood events, they cannot fully control them due to insufficient storage capacity. They do not have sufficient storage capacity to hold the great floods that periodically move through the Zambezi system.

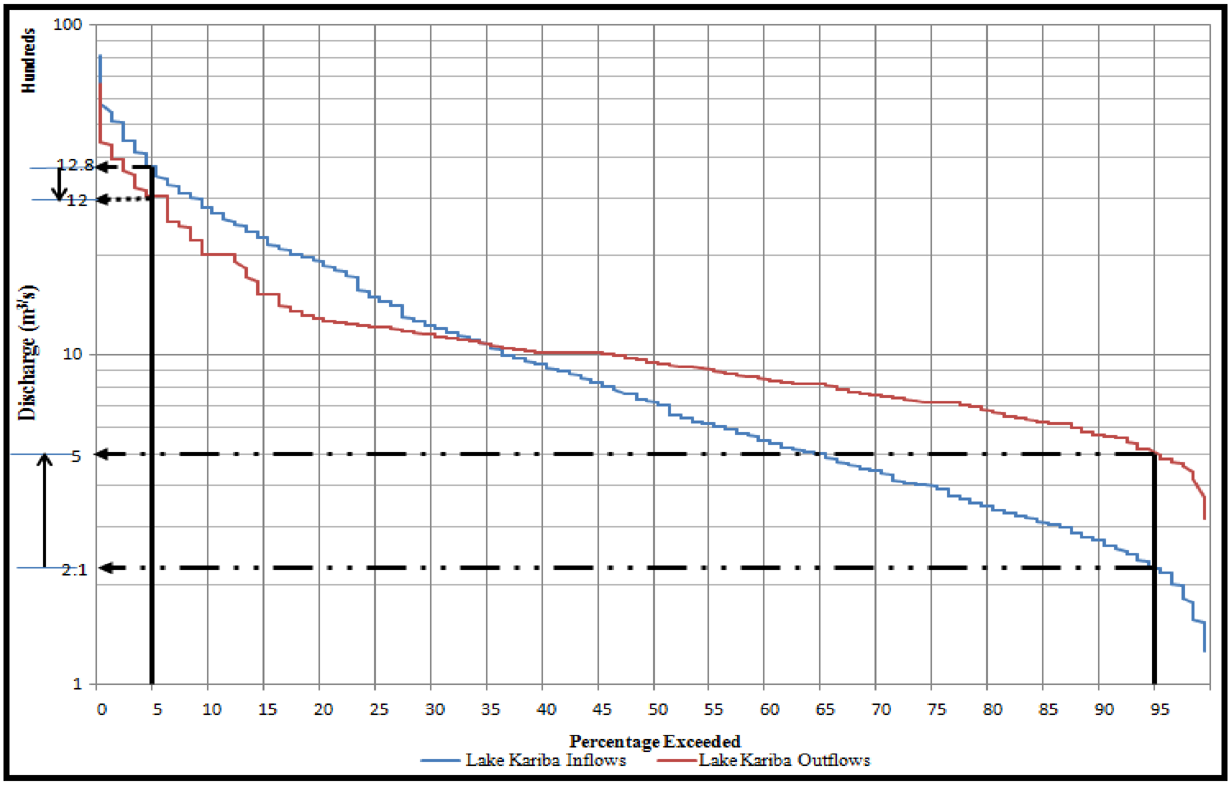

Figure 5.12: FDC for inflows and outflows from Lake Kariba (1961-2009)

5.3.2 Droughts

Most droughts, meteorological or hydrological, were experienced during the dry periods of the DMC cycle (Figure 5.13, and Figure 5.14). Droughts occurrence in the middle Zambezi was associated with deficit in rainfall distribution within the catchment. For example, the 3-year meteorological drought of 1982-1984 was also reflected in hydrological droughts of Victoria Falls and Cahora Bassa. On the contrary, there were hydrological droughts which occurred in Victoria Falls, concurrently with meteorological droughts in the middle Zambezi but were not translated into Cahora Bassa. Example was the drought of 1985-1988 which did not occur in Cahora Bassa. This could be solely accredited to the importance of Kariba dam in curtailing effects of hydrological droughts as demonstrated in Figure 5.11 above.

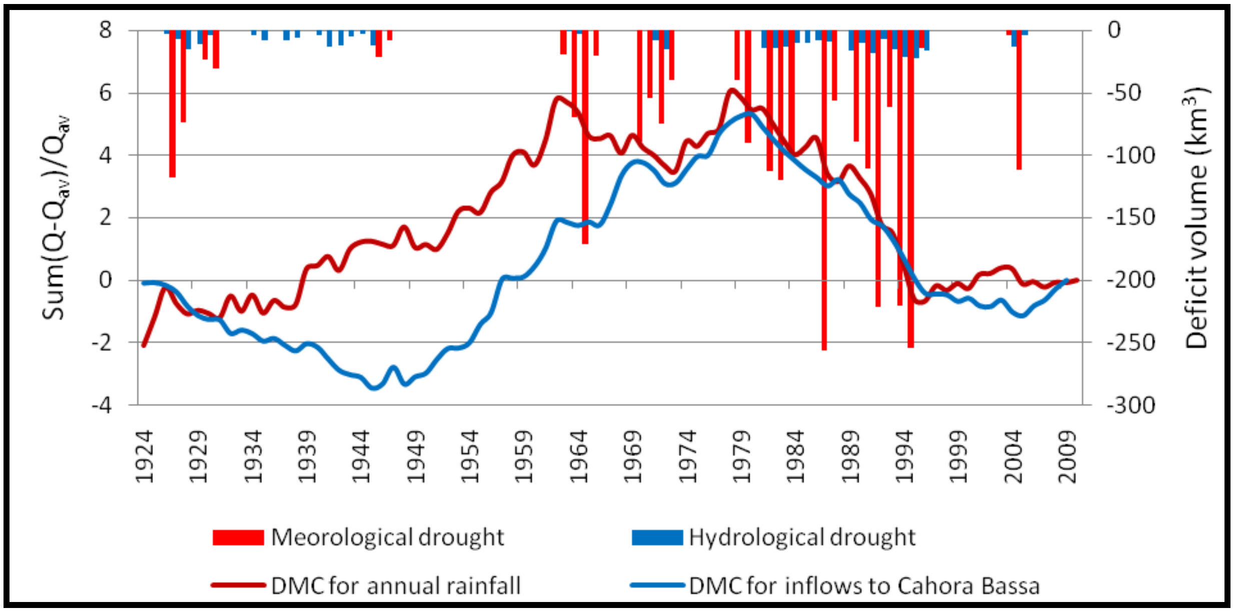

Figure 5.13: Hydrological droughts of the Zambezi at Victoria Falls superimposed on meteorological droughts of the middle Zambezi basin.

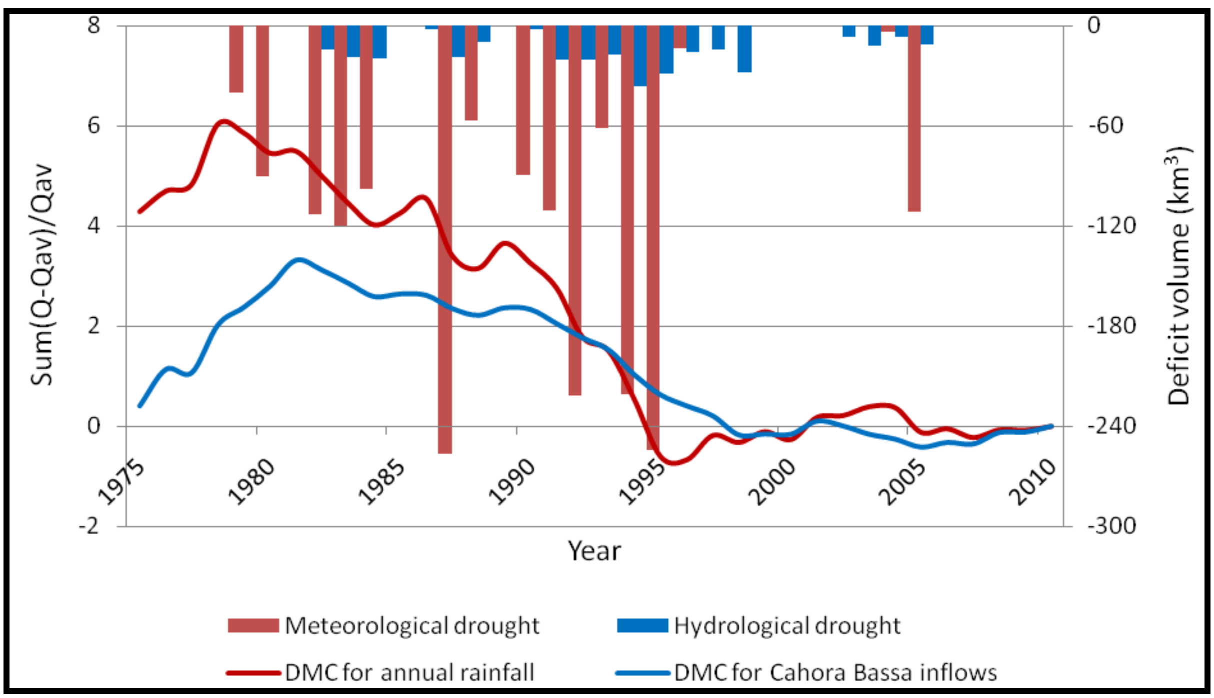

Figure 5.14: Hydrological drougth for the inflows at Cahora Bassa superimposed on meteorological droughts of the middle Zambezi

5.4 Contribution of Catchments in the occurrence of extreme hydrological events

As mentioned earlier; two approaches were used in an attempt to determine the influence of each tributary in the occurrence of floods and droughts. The first one, Pearson Correlation was used to determine the influence of each tributary on the Lake levels of Cahora Bassa. The second one, double mass analysis, was used to determine the contribution of each tributary in terms of magnitude and frequency.

5.4.1 Pearson Correlation results

There was no strong relationship between levels in Cahora Bassa and flows from the four tributaries of the middle Zambezi under study. Even though the confidence level at 95% showed that indeed relationship existed for inflows from Kariba, Kafue, Manyame, but not Luangwa, however, it was weak. The Pearson's correlation coefficients results are shown in table 5.1 below.

Table 5.1: Correlation results of tributaries with the level of Lake Cahora Bassa

Runoff source	Pearson Correlation (r)	Correlation classification (Cohen, 1988)
Kariba dam releases	0.27	Small
Kafue Gorge discharge	0.44	Medium
Manyame River	-0.15	Small
Luangwa River	-0.04	None
Combined flows	0.25	Small

These results summarized that the operation of Cahora Bassa was not considering input from only one tributary but considered the inflow from all the various tributaries as a unit, as supported by the correlation of total inflows into Cahora Bassa. The positive correlation with the two traibutaries may be associated with reservoir operations i.e. flood storage during peak season. On the other hand, the pattern of wet and dry years did not exactly follow the same trend for the tributaries supplying Lake Cahora Bassa thus leading to a weak relationship. The

Pearson's correlation is also susceptible to numerical instability depending on the number of sample and thus might have also contributed in making the correlation weaker (Rodgers and Nicewander, 1988).

5.4.2 Double Mass Analysis

The advantage of the double mass analysis is that, it does not only show the correlation between two samples but further helps in identifying a threshold at which the tributaries made a significant contribution in flooding. This in turn leads to identification of the percentage at which that threshold was exceeded in the corresponding tributary thus giving frequency of that flow. However, for the purpose of this study, the double mass analysis was used in order to obtain the thresholds at which the respective tributaries cause flooding, not the line of best fit. The highest and lowest monthly flows identified from a flow duration curve at Q_{20} and Q_{80} were 10 x 10^3 m^3/s and 3.5 x 10^3 m^3/s, respectively (Figure 5.15). In this method they were used as threshold to define a flood and a hydrological drought as applied by Shaw (2004) for floods and Awass (2009) for droughts. These were flows which were equaled or exceeded only 20% of the time for Q_{20}, and 80% of the time for Q_{80}, from 1975-2009.

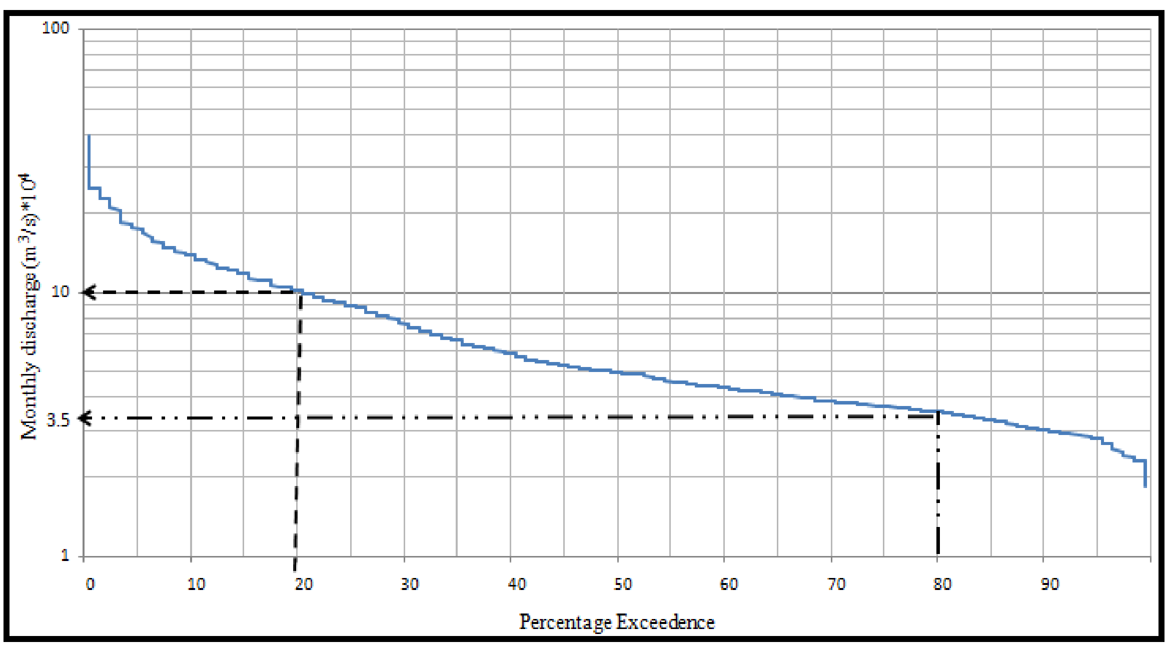

Figure 5.15: Flow duration curve of combined flows in Cahora Bassa (1975-2009)

Manyame Catchment

Manyame only contributed in the occurrence of floods but not droughts in the middle Zambezi. This was because, streamflow drought, were curtailed through the construction of the Kariba. As mentioned earlier, the lowest flows were increased and this curbed the effects of streamflow drought.

As the discharge increased, and as the trend-line crossed the threshold for flooding, the pattern became clear showing that the Manyame had a significant contribution in the occurrence of high flows. Keeping other factors constant, the Manyame made a significant contribution in flooding when its monthly flows exceeded 36 x 10^3 m^3/s (Figure 5.15) (Figure 5.16). The point at which the tributary start to make a significant contribution to flooding largely depends on the capacity of the river. By default, larger rivers contribute higher that smaller ones and they also have a potential to cause the highest increase in the combined discharge at *ceteris paribus.* .

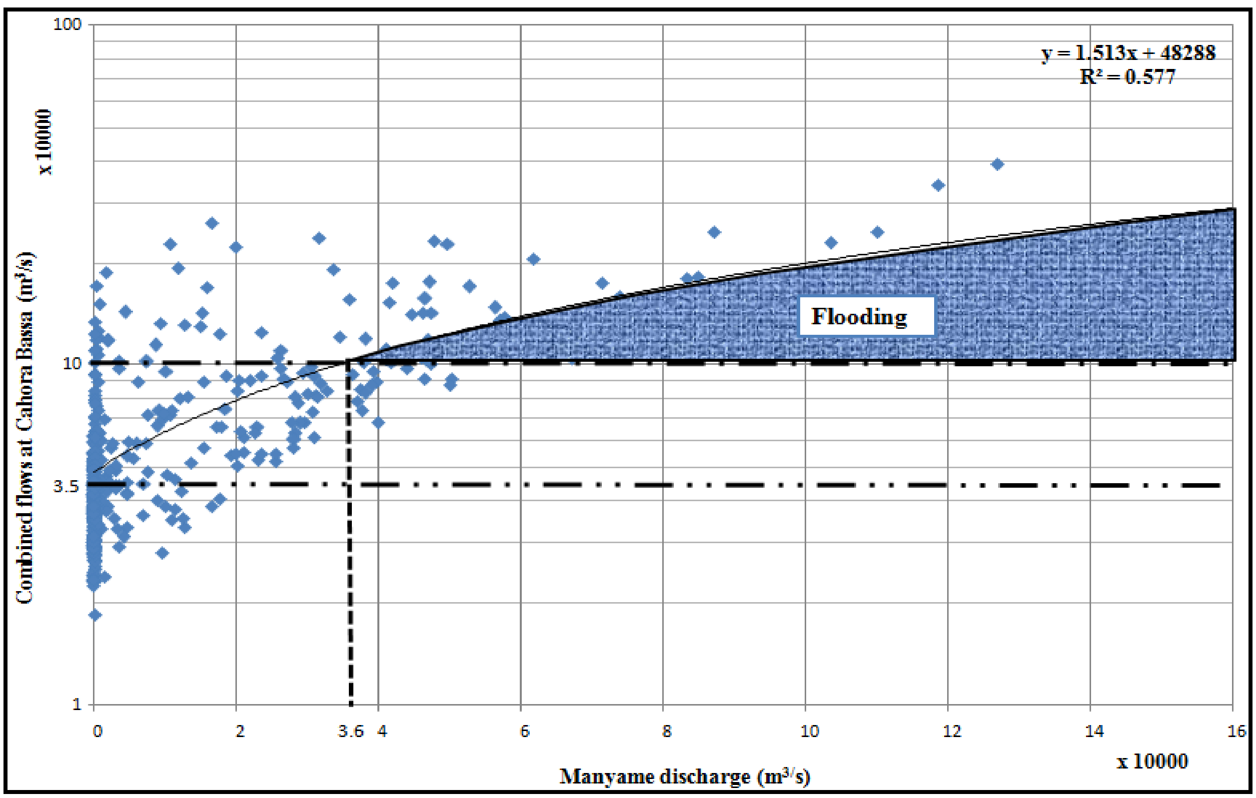

Figure 5.16: Threshold for Manyame to cause significant flooding in the middle Zambezi River basin

Kariba Reservoir

The releases from Kariba were a representative of flows from upstream Zambezi. Like all the other tributaries, most points were scattered between the high and low threshold values. Clear patterns were observed as the value of the abscissa increased (Figure 5.17). The threshold for monthly flows that defined the level at which Kariba significantly contributed to flooding was 50 x 10^3 m^3/s. From the graph, one can easily discern that indeed Kariba releases far exceeded the flow of Manyame River on average..

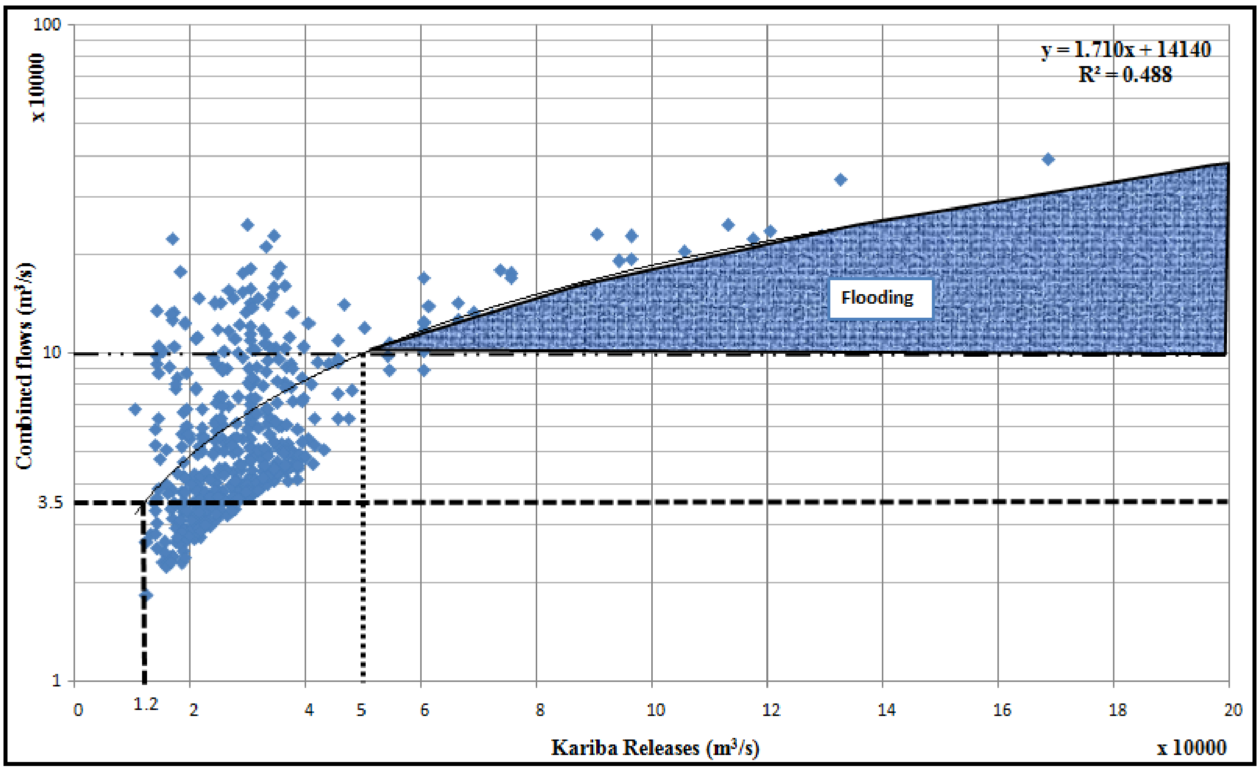

Figure 5.17: Threshold for Kariba release to cause significant flooding in the lower middle Zambezi River basin

Luangwa River

Effects of high flows were observed when the Luangwa contributed on average 28 x 10^3 m^3/s in a month (Figure 5.18). This was 22% less than that of Manyame. It must be noted that these figures can change if flows can be measured just before the confluence with the mainstream Zambezi and this also applies with all the other tributaries discussed in this study. However, because of poor gauging network within the middle Zambezi, these discussions are based on gauging stations located farther upstream which might not give the exact picture of the situation on the ground. Hence the results were as reliable as the data used.

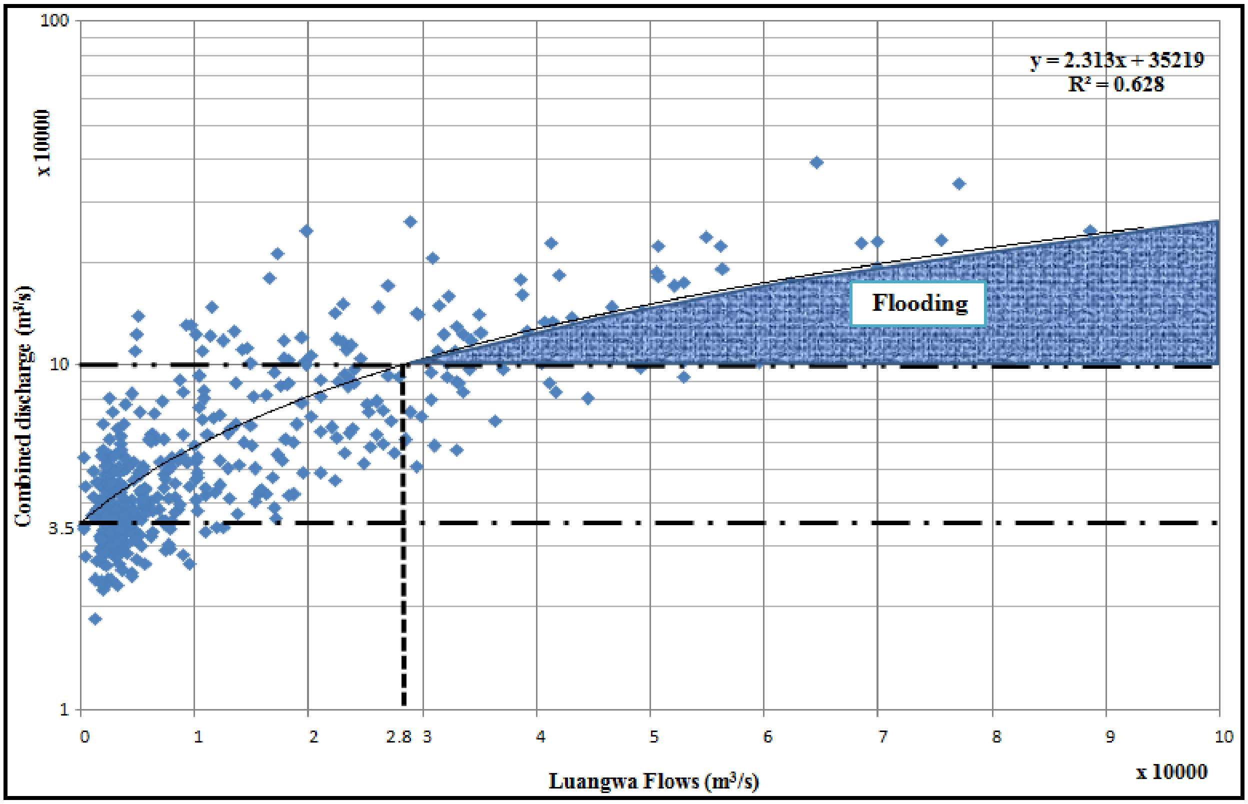

Figure 5.18: Threshold for Luangwa to cause significant flooding in the lower middle Zambezi River basin

Kafue River

Being the least in capacity (contributing about 11% of average runoff into Cahora Bassa), the Kafue River equally contributed the least as far as flooding was concerned. Figure 5.19 below showed that, on average, when the monthly discharge for Kafue at least reached, or exceeded, 17.5 x $10^3 m^3/s$ the Zambezi would have exceeded the threshold for flood, 10 x 10^3 m^3/s. Because of the size of the Kafue River downstream of the Kafue Gorge dam It could not influence the magnitude of the combined flow up to 20 x 10^3 m^3/s on average. The reason why Kafue is having a very low R^2=0.208 was that, the operations of the Kafue Gorge reservoir, and the Itezhi Tezhi, about 400 km upstream of Kafue Gorge, were such that, these reservoirs aimed at maintaining maximum storage levels for both reservoirs in order to maximise hydropower production (APFM, 2007). Average releases were made in the long run, thus removing the too high and too low values that would have made more impact on the increased discharge of the combined flows.

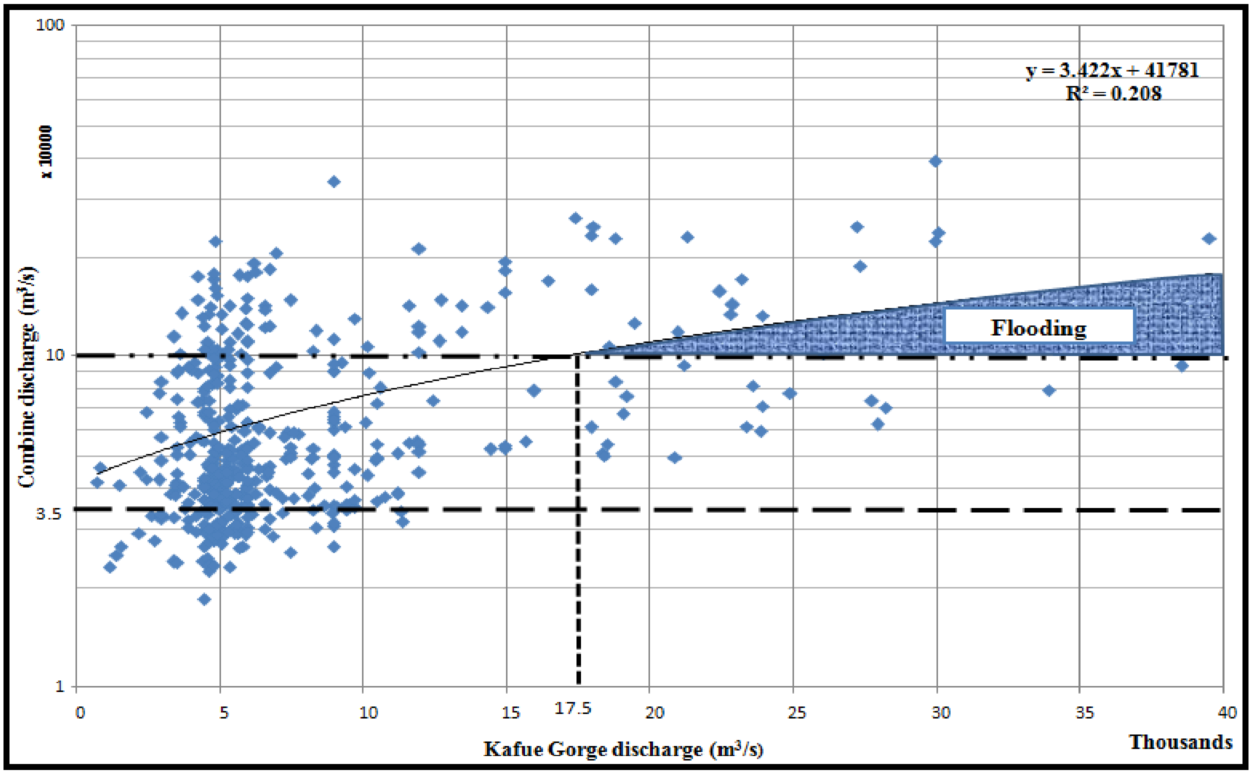

Figure 5.19: Threshold for Kafue Gorge releases to cause significant flooding in the lower middle Zambezi River basin

Conclusion of result for double mass analysis

The reason why most of the tributaries showed weak correlations were that, their sources were different, in terms of location as well as rainfall (which also depend largely on the wind source) making their correlations dissimilar from one another. This obviously leads to spatial and temporal variation in the down distribution of water as precipitation, and thus the peak discharge did not coincide, at least most of the time. This ties up with finding as detailed in APFM (2007) Furthermore, water management played a major role on the weakness of the correlation. This had more to do with whether the river was impounded or not because if impounded, releases happened anytime and the discharge was largely dependent on the demand for power. If demands are low, the releases would be equally lower making the relationship with the combined flows less stable and unpredictable. The complicating factors in the respective tributaries were resulting in the correlation being low. Some basins, like the Luangwa River responded well and quickly to flash floods compared with Kafue for example, since the latter had two dams in series and a wetland intermediate and thus translated, and attenuated the peak discharges of Kafue Gorge dam during period of high floods. The assumption being that the two experienced the same extreme rainfall event. This method may also require some improvements since it is new as far as flood analysis is concerned. There are discrepancies that can be improved.

From the threshold values of the respective tributaries (Zambezi discharge, Kafue discharge, Luangwa and Manyame), the equivalent percentage in which these values were exceeded in the duration of the period under study (1975-2010) were plotted in a flow duration curves of the respective tributaries to obtain the corresponding frequency(Figure 5.19)

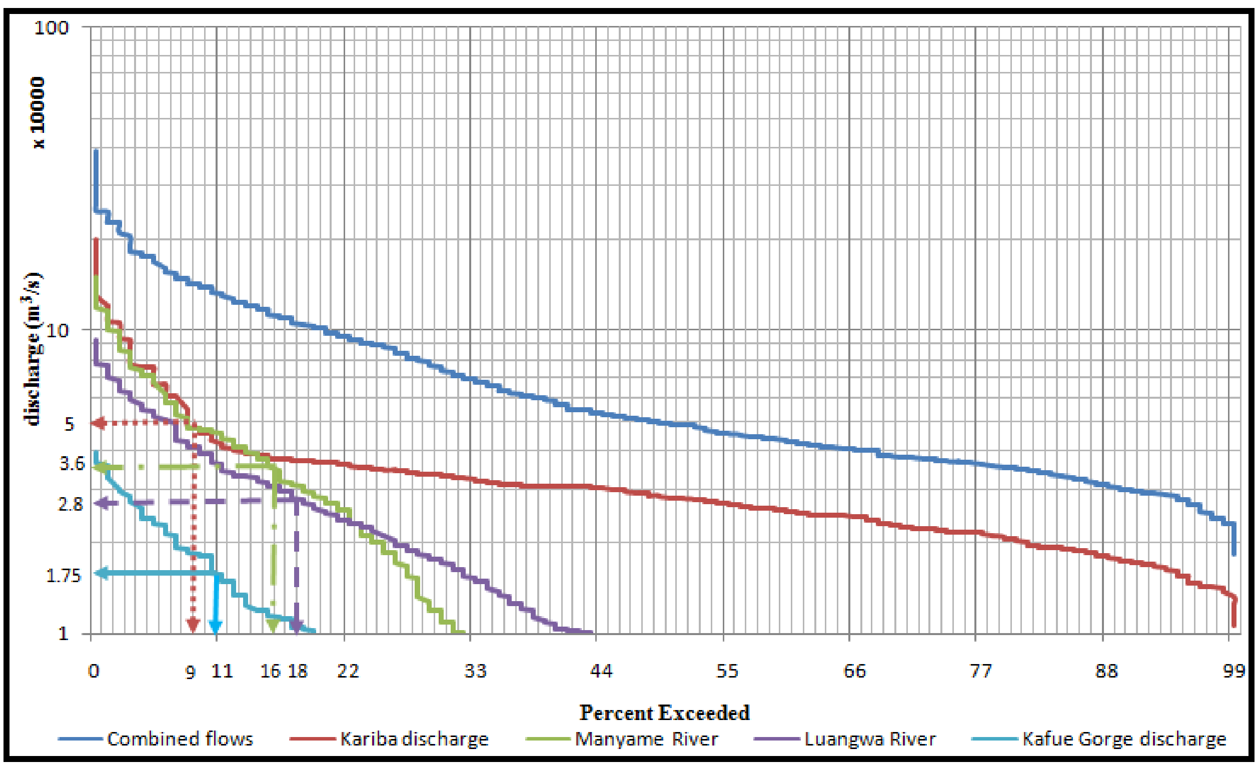

Figure 5.20: (zoomed in) FDC for the middle Zambezi River basin main tributaries and their corresponding percentage exceedence

Based on Figure 5.20 above, Luangwa River had the highest value of percentage exceedence (18%) followed by Manyame River, Kafue, and lastly the Kariba discharge with corresponding percentage exceedence of 16%, 11%, and 9%, respectively. This finally showed that the Luangwa had highest contribution on extreme events as far as frequency of occurrence was concerned. On the other hand, the Zambezi was the least, these differences were due to the fact that the Luangwa was unregulated and so it's a "free" tributary. The Manyame River was also amongst the highest and these showed that indeed the local catchment did contribute to flooding since the corresponding value was exceeded 16% of the time. These showed that the flow patterns of the high flows were more influenced by Luangwa as opposed to those Kariba. The variation among the percentage also showed that there were some interventions amongst these tributaries, apart from the fact that their sources were also different. Figure 5.21 shows the years at which the threshold were exceeded in the respective tributaries.

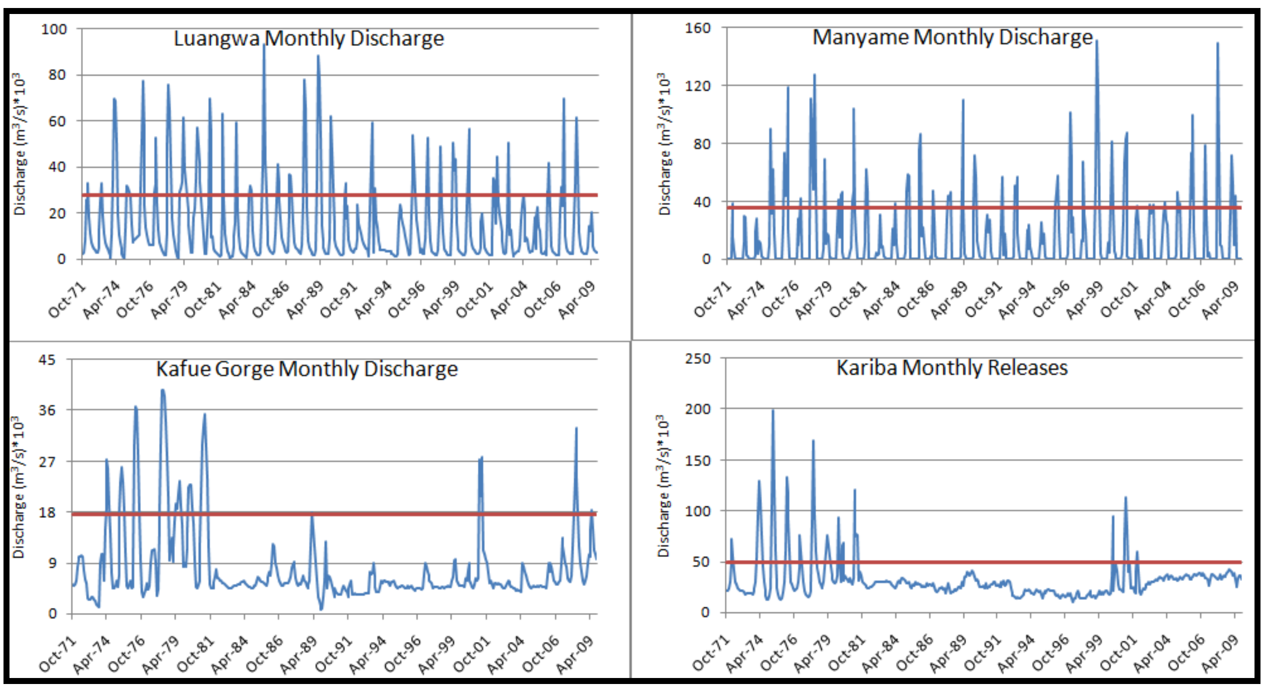

Figure 5.21: Hydrographs of the middle Zambezi tributaries showing the years when the thresholds were exceeded

5.5 Frequency Analysis of hydrological extreme events

5.5.1 Flood Frequency Analysis

Flood frequency was presented in a graphical form as shown if Figure 5.21 below. Most recurrent floods were those of a return period less than 10 years. These are floods which were observed in Victoria Falls.

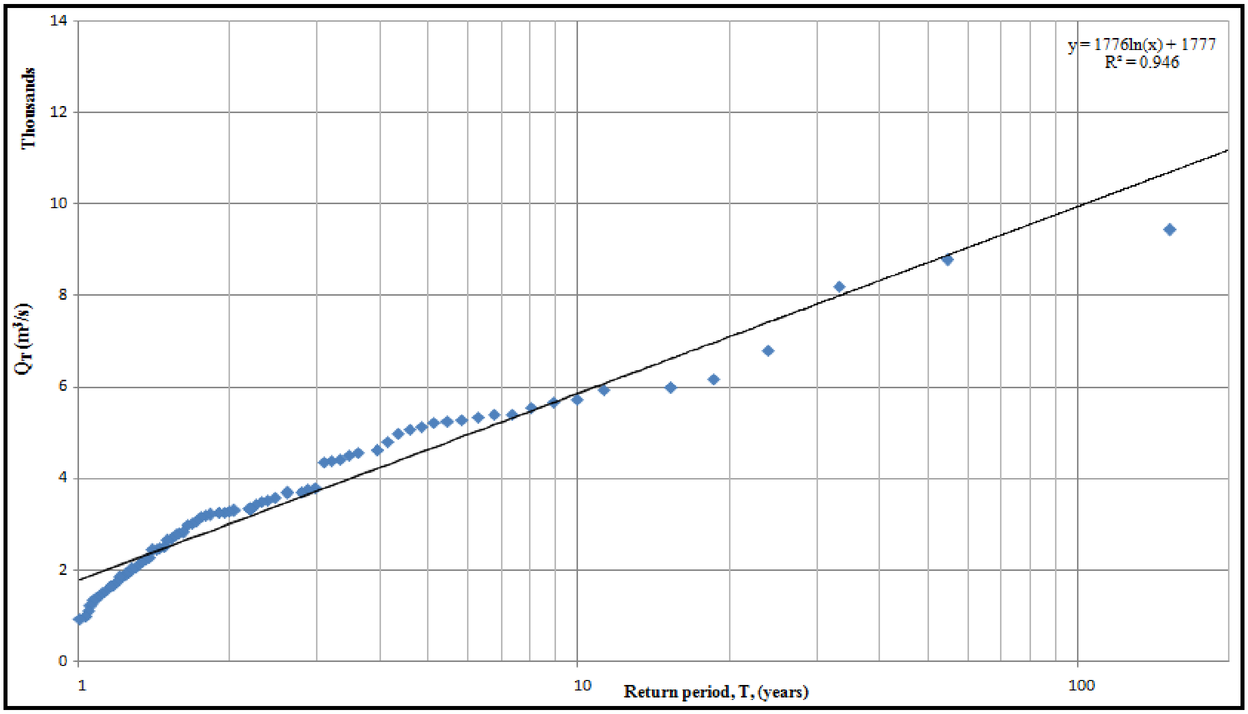

Figure 5.22: Frequency of occurrence of floods in the middle Zambezi as observed in Victoria Falls (1924-2010)

With respect to floods observed in the Cahora Bassa (1975-2010), the results were different from those of Victoria Falls. Even though frequent floods were those of less than 10 year return period, the highest largest one had a return period of 70 years. This was due to the fact that the length of the data used for the analysis of the two stations was different hence yielding different results. For example, Victoria Falls had a length of 86 years where Cahora Bassa was limited to 35 years.

Figure 5.23: Frequency of occurrence of floods in the middle Zambezi as observed in Cahora Bassa (1971-2009)

5.5.2 Hydrological Drought Frequency Analysis

As mentioned early with the frequency of floods, similarly, the frequency of drought strongly depended on the length of data used. As a result, the one recorded in Victoria Falls had more frequencies than that of Cahora Bassa. In this study, only the frequency of the hydrological droughts which were experienced in Cahora Bassa would be presented (Table 5.2).. This is because, Cahora Bassa is the catchment outlet and hence a reflection of what is happening on the whole middle Zambezi sub-basin.

Table 5.2: Duration, magnitude, severity and frequency of hydrological droughts observed in Cahora Bassa (1975-2010)

Year	Duration (years)	Magnitude	Severity (km^3/y)	Rank	Probability	Return period (years)
1982-1984	3	52.9	17.1	2	0.05	20
1986-88	3	31.1	9.8	4	0.13	8
1990-98	9	184.8	20.0	1	0.03	33
2002-05	4	37.8	8.9	3	0.08	13

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

- Based on the research and findings of the study, hydrological extremes into Cahora Bassa are greatly influenced by runoff accumulated within the middle Zambezi since Lake Kariba curtails most of the floods and droughts which emanate from the upper Zambezi.
- Floods experienced in the middle Zambezi downstream of Kariba Dam are a combination of natural and human induced floods. However, there are more natural flood events compared with human induced flood events in the middle Zambezi River Basin. Droughts, on the other hand, are a result of natural extremes associated with shortfalls in rainfall as opposed to reservoir operations. The runoff into Cahora Bassa was strongly influenced by rainfall from the middle Zambezi River basin.
- Within the middle Zambezi, the Luangwa River contributed most in terms of frequency of occurrence of floods, whereas the releases from the Kariba Dam contributed most in terms of magnitude of the flood events.

6.2 Recommendations

Recommendations were divided into two categories namely; recommendations from the study and recommendations for further studies.

6.2.1 Recommendations from the study

- Based on the study, it is recommended that gauging stations be installed just before the confluence of any tributary with the Zambezi. This will enhance in proper assessment of magnitudes of floods and contribution from each catchment. This will also cater for the runoff accrued from the precipitation falling in the intermediate catchments, i.e. between the gauging station and the downstream points. Sufficient gauging stations with Manyame below the last dam since it has a significant contribution in the occurrence of floods.

- There should be a very good flow forecasting system for the whole Zambezi River basin in order to monitor flows within the basin so that early warnings for either drought or flood situations could be issued i.e. early release of water for storage of incoming floods, and also evacuation of people within the flood plains. The forecasting system should be able to pick out onset of extreme hydrological events such as droughts or cyclones.
- Data sharing protocols should be signed so that there will be ease of data exchange for studies, research, early warning and frequency analysis.
- The Zambezi River basin dams such as the Kariba, Kafue and Cahora Bassa should be conjunctively managed and operated in a synchronised manner.

6.2.2 Recommendation for further studies

Further studies are recommended on the contribution of the various streams between Kariba and the Cahora Bassa Dams since there is a lot of runoff accumulated in the intermediate part from rainfall.

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8 Appendices

FIGURES

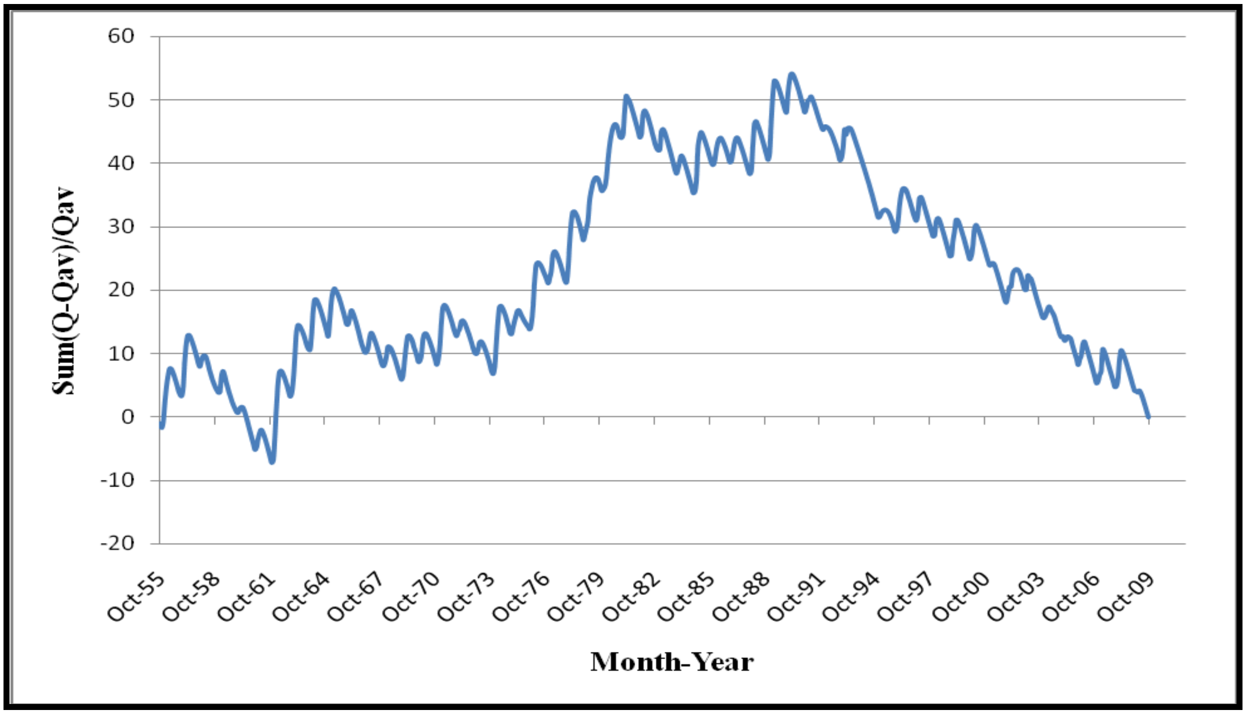

Figure 8.1: DMC of Luangwa Monthly Flows.

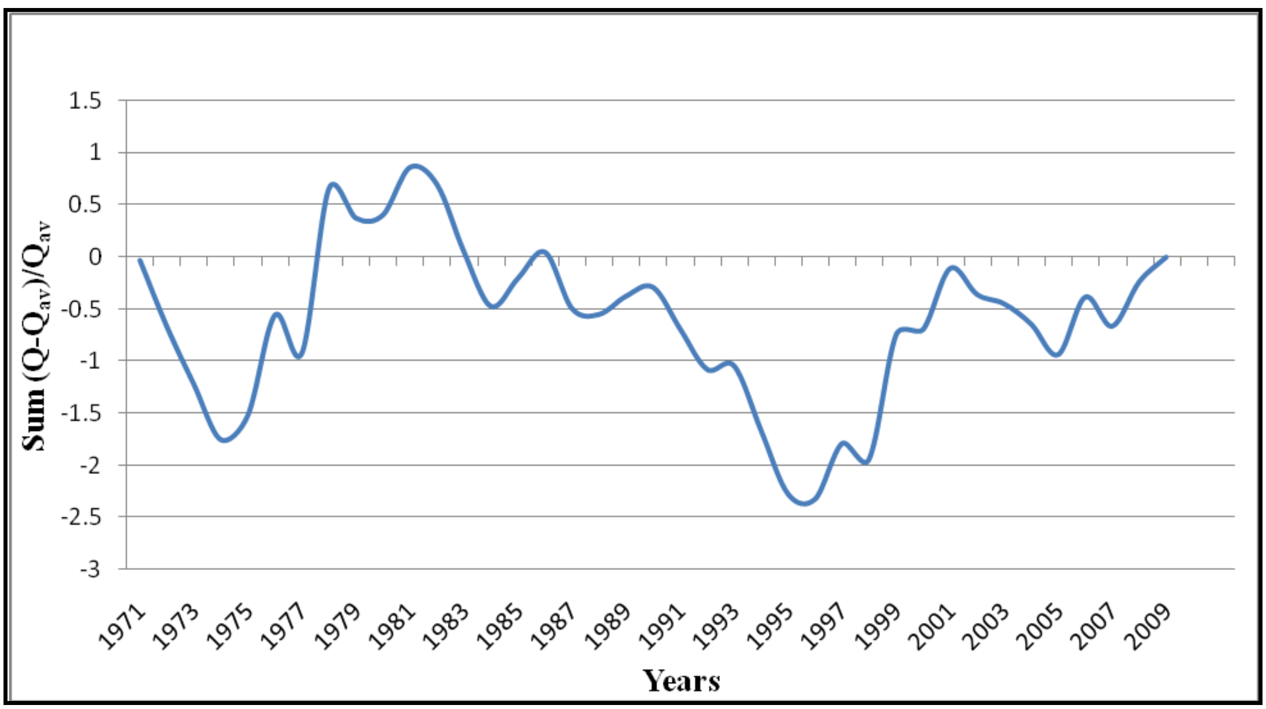

Figure 8.2: DMC for Manyame River in Cahora Bassa

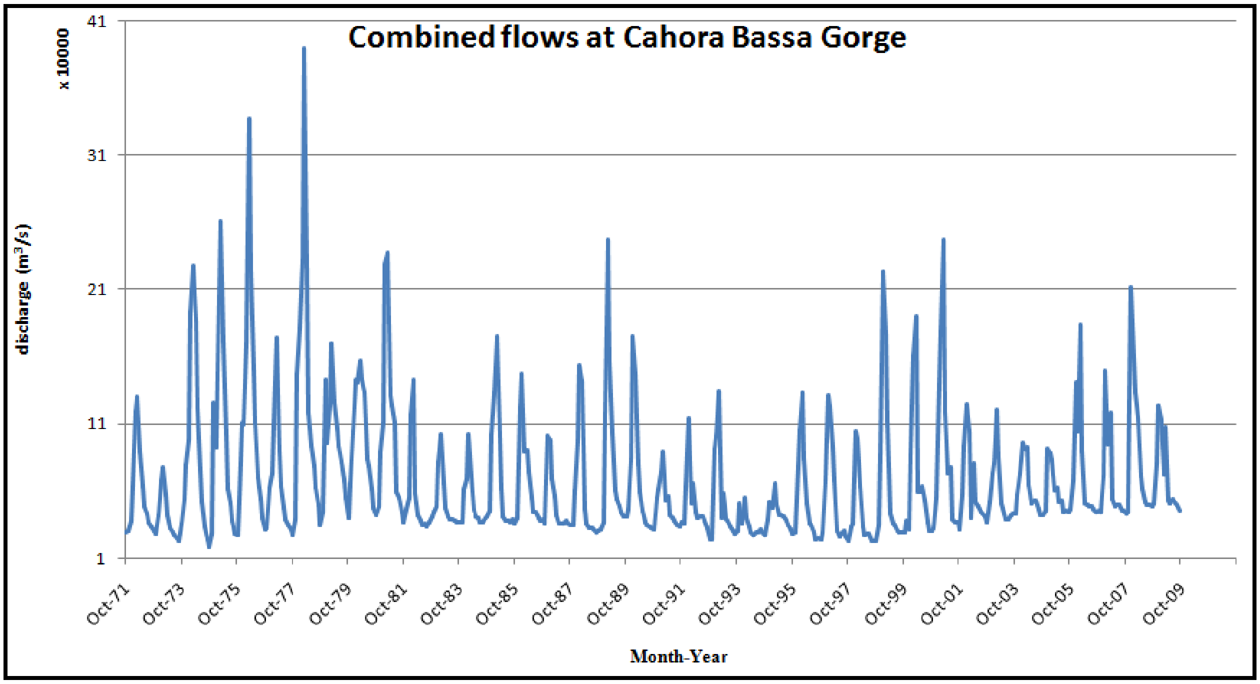

Figure 8.3: Combined flows of major tributaries of the middle Zambezi River Basin

TABLES

Table 8.1: Maximum monthly flows for Zambezi at Cahora Bassa (1971-2009)

Month	Discharge (m^3/s)	Rank	Return Period (Years)	Percentage Probability
Mar-78	389954	1	68	1
Mar-76	337300	2	24	4
Mar-75	261552	3	15	7
Mar-01	247349	4	11	9
Feb-89	246655	5	8	12
Mar-81	237110	6	7	15
Mar-74	227586	7	6	17
Jan-99	223328	8	5	20
Dec-07	211328	9	4	22
Mar-00	190659	10	4	25
Feb-06	183452	11	4	28
Feb-85	175349	12	3	30
Jan-90	174678	13	3	33
Mar-77	174650	14	3	36
Mar-79	169431	15	3	38
Mar-80	156857	16	2	41
Feb-88	153543	17	2	43
Jan-07	149803	18	2	46
Jan-86	147615	19	2	49
Feb-82	142659	20	2	51
Feb-93	134566	21	2	54
Feb-96	133550	22	2	57
Jan-97	131672	23	2	59
Mar-72	130252	24	2	62
Jan-02	125176	25	2	64
Dec-08	123715	26	1	67
Feb-03	120755	27	1	70
Jan-92	114383	28	1	72
Jan-98	104345	29	1	75
Feb-83	102277	30	1	78
Feb-84	101853	31	1	80

Dec-86	100631	32	1	83
Jan-04	95752	33	1	85
Dec-04	91205	34	1	88
Feb-91	89521	35	1	91
Feb-73	77573	36	1	93
Feb-95	65936	37	1	96
Jan-94	54640	38	1	99

Table 8.2: Frequency of occurrence of droughts in the middle Zambezi as recorded in Victoria Falls 1924-2009

Year	Duration (Years)	Magnitude (km^3)	Severity (km^3/year)	Rank	Probability	Return Period (Years)
1990-2000	11	136.2	12.4	1	0.01	86
1982-1988	7	80.4	11.5	2	0.02	43
1927-1933	7	56.5	8.1	3	0.03	29
1941-46	6	49.3	8.2	4	0.05	22
1972-73	2	23.5	11.7	5	0.06	17
1949	1	19.1	19.1	6	0.07	14
2005-2006	2	17.2	8.6	7	0.08	12
1938-39	2	13.9	6.9	8	0.09	11
1935-36	2	12.3	6.2	9	0.10	10
2002-2003	2	9.1	4.5	10	0.12	9
1964-65	2	4.6	2.3	11	0.13	8
1925	1	3.1	3.1	12	0.14	7
1967	1	3.1	3.1	13	0.15	7

Table 8.3: Reclassification of Land use land cover according to USGS Classification

Land use land cover name	Land Cover Class
Dry land cropland pasture	Agricultural land
Cropland/ grassland mosaic	Agricultural land
Cropland/woodland mosaic	Agricultural land
Grassland	Rangeland
Shrub land	Rangeland
Savanna	Rangeland
Deciduous broadleaf forest	Forest land
Evergreen broadleaf forest	Forest land
Water bodies	Water
Barren or sparsely vegetated	Barren land

Table 8.4: Soil type reclassification into hydrologic soil groups (Adapted from Murwira and Schmidt-Murwira, 2005)

Soil Type	Soil Group
Calcic Luvisols	C
Calcic Solonetz	C
Chromic Luvisols	C
Chromi-Cambisols	B
Chromi-Leptic Lixosols	C
Eutric Cambisols	B
Eutric Leptisols	D
Ferralic Cambisols	B
Ferralic-Hypoluvic Arenosols	A
Haplic Acrisols	C
Haplic Luvisols	C
Humi-mollic Fluvisols	C
Hyposodic-Calcaric Vertisols	D
Leptosols	D
Lithic Leptosols	D
Mollic Leptosols	D
Rhodic Ferralsols	D

Table 8.5: Proportion of area covered by rainfall and land cover-soil groups

Rainfall Station	Landuse/land cover type	Hydrologic Soil Group Class	Area (km^2)	Proportion of Total Area
Karoyi	Rangeland	C	339	0.01
Karoyi	Agricultural land	C	20	0.00063
Karoyi	Rangeland	B	722	0.023
Karoyi	Rangeland	D	1603	0.051
Karoyi	Agricultural land	D	1485	0.047
Karoyi	Agricultural land	B	667	0.021
Chinhoyi	Rangeland	C	411	0.013
Chinhoyi	Agricultural land	C	401	0.013
Chinhoyi	Rangeland	B	1059	0.033
Chinhoyi	Rangeland	D	475	0.015
Chinhoyi	Agricultural land	D	669	0.021
Chinhoyi	Agricultural land	B	791	0.025
Chinhoyi	Forest	D	20	0.00063
Mzarabani	Rangeland	A	1525	0.048
Mzarabani	Rangeland	C	7317	0.23
Mzarabani	Barren land	A	609	0.0192
Mzarabani	Water	A	63	0.002
Mzarabani	Agricultural land	A	82	0.0026
Mzarabani	Barren land	C	563	0.0178
Mzarabani	Forest	A	1	0.000032
Mzarabani	Agricultural land	C	530	0.017
Mzarabani	Barren land	B	30	0.000948
Mzarabani	Water	B	1	0.0000316
Mzarabani	Water	C	11	0.000348
Mzarabani	Rangeland	B	1446	0.0457
Mzarabani	Rangeland	D	2540	0.0803
Mzarabani	Agricultural land	D	258	0.00815
Mzarabani	Agricultural land	B	72	0.0023
Mzarabani	Forest	D	3	0.000095
Mushumbi	Rangeland	A	116	0.00367
Mushumbi	Rangeland	C	668	0.0211
Mushumbi	Agricultural land	A	27	0.00085
Mushumbi	Agricultural land	C	127	0.00401
Mushumbi	Rangeland	B	1409	0.0445
Mushumbi	Rangeland	D	3458	0.109

Mushumbi	Agricultural land	D	1296	0.041
Mushumbi	Agricultural land	B	72	0.00228
Kanyemba	Rangeland	A	370	0.0117
Kanyemba	Rangeland	C	43	0.0014
Kanyemba	Agricultural land	A	9	0.0028
Kanyemba	Barren land	C	4	0.00013
Kanyemba	Rangeland	D	280	0.0088
Kanyemba	Agricultural land	D	56	0.001
Total			31 648	1

Table 8.6: Average annual rainfall (1910-2010) for selected middle Zambezi rainfall stations.

Station ID	Station Name	Area of Influence (km^2)	Average annual Rainfall (mm/a)
1	The Range	4664	771.9
2	Victoria Falls	44929	699.6
3	Mvuma	4624	694.3
4	Hwange	15707	568.2
5	Inyati Police	5889	632.1
6	Kwekwe	10454	681.5
7	Gokwe	31965	791.8
8	Guruve	9741	795.5
9	Gwayi	16202	630.8
10	Gweru Thornhill	4932	680.2
11	Harare Belvedere	7632	834.5
12	Chegutu	12587	777.3
13	Chinhoyi	10792	832.6
14	Mana Pools	19974	928.9
15	Kanyemba	14929	764.2
16	Mushumbi	5025	556.2
17	Karoyi	19491	803.0
18	Mzarabani	25189	1094.8
19	Solwezi	20329	1338.5
20	Shiwa Ngandu	8476	1113
21	Mpika	22175	1085
22	Mumbwa	49300	877.8
23	Kasempa	29674	1099.2
24	Chipata	32399	1001.2
25	Chitambo	47552	1025.1
26	Chomo-Batoka	47579	778.4
27	Isoka	20015	1071.9
28	Kafironda	20926	1204.6
29	Kafue	22915	757.6
30	Kafulafuta	20060	1163.4
31	Broken Hill	30312	919.7
32	Chasefu	32640	899.6
33	Chikuni	14494	771.9

Table 8.7: Regression results and correlation coefficient for selected middle Zambezi rainfall stations

Station Name (X)	Station Name (Y)	Correlation Equation	R^2
Chegutu	Belvedere	y=0.918x + 110.0	0.823
Mana Pools	Brokenhill	y=0.516x + 515.5	0.813
Chipata	Chasefu	y=0.761x + 96.71	0.864
Gokwe	Chegutu	y=0.910x + 74.24	0.817
Kafue	Chikuni	y=0.1.089x – 52.10	0.869
Chegutu	Chinhoyi	y=0.663x + 340.0	0.805
Chitambo	Chipata	y=0.570x + 398.5	0.814
Broken Hill	Chitambo	y=0.680x + 408.2	0.804
Kafue	Chomo Batoka	y=0.887x + 106.2	0.742
Kwekwe	Gokwe	y=1.197x + 35.93	0.802
Chinhoyi	Guruve	y=1.118x – 112.2	0.802
Hwange	Gwayi	y=0.859x + 191.8	0.846
Inyati-Police	Gweru Thornhill	y=0.984x + 77.40	0.865
Victoria Falls	Hwange	y=0.587x + 118.8	0.823
Gwayi	Inyati Police	y=1.148x + 63.9	0.825
Shiwa Ngandu	Isoka	y=0.623x + 355.6	0.816
Kafulafuta	Kafironda	y=0.739x + 329.3	0.833
Mana Pools	Kafue	y=0.430x + 324.9	0.858
Broken Hill	Kafulafuta	y=0.739x + 481.0	0.751
Mana Pools	Kanyemba	y=0.566x + 206.9	0.838
Chinhoyi	Karoyi	y=0.790x + 145.3	0.877
Gweru-Thornhill	Kwekwe	y=0.783x + 142.0	0.826
Chipata	Mpika	y=0.933x + 148.7	0.920
Chikuni	Mumbwa	y=0.712x + 289.3	0.749
Kanyemba	Mushumbi	y=0.854x – 80.00	0.799
Gweru Thornhill	Mvuma	y=1.005x + 1.103	0.839
Mushumbi	Mzarabani	y=0.2.182x – 69.10	0.997
Mpika	Shiwa Ngandu	y=0.901x + 110.7	0.930
Kafironda	Solwezi	y=0.932x + 144.0	0.810
Mvuma	The Range	y=1.138x + 6.548	0.809
Chomo Batoka	Victoria Falls	y=0.800 + 110.0	0.821