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FACULTY OF ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

Hydrological analysis of the Middle Zambezi and impacts of the operation of hydropower dams on flow regime in the Mana Pools National Park

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In collaboration with

Hydrological analysis of the Middle Zambezi and impacts of the operation of hydropower dams on flow regime in the Mana Pools National Park

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

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DECLARATION

I, **Mikael Nekundi Ekandjo**, 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. It has not been submitted before for any degree of examination in any other University.

Date: ____________________

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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.

ABSTRACT

The Mana Pools flood plain along the Middle Zambezi River and part of a popular Mana Pools National Park of Zimbabwe is experiencing both ecological and morphological change since the construction of upstream hydropower reservoirs. It is against this background that hydrological analysis was done to investigate the hydro-dynamics from natural and human influenced flows, particularly at the Mana Pools floodplains upstream and downstream stations on each reservoir were indentified to represent what could be natural and modified flows respectively. Comparison of hydrographs and flow duration curves constructed from flow data recorded at each station was done to investigate the effects of each reservoir on the downstream flow regime. Descriptive statistics was used to assess the differences in flow regime upstream and downstream of hydropower reservoirs. A standard *t*-test (α=0.05) was done to compare the natural and modified mean annual flows. Monitoring of the effects of reservoirs operation to the Mana Pools flood plain was done by tracing contours from water levels recorded at Chirundu. A rainfall-runoff model, Soil Conservation Services utilizing a curve number system was used to estimate flows in six un-gauged catchments flowing towards the Mana Pools. Results indicated that, the presence of upstream reservoirs had reduced the high peak average monthly flows by 17 % and increased the average monthly low flows by 5 % at Mana Pools. However this effects observed at monthly level have not significantly affect the mean annual runoff. This was confirmed by a *t*-test at 95% confidence level. Although the presence of reservoirs upstream of Mana Pools reduced the peak flows, operation of sluice gates to release water can result in excess flooding at Mana Pools. The Mana Pools catchment contributes 7.2 % of the total flows at Mana Pools. From the findings of this study, In order to avoid unexpected flooding, operation of the sluice gates at Kariba Dam should be directly communicated to the communities residing in the low lying areas, downstream of the dam. With the establishment of a gauging station on the Rukomechi River, further studies that will make use of observed flow data from the same catchment are encouraged in order to support the findings of this study.

Key words: Curve Numbers, Flow Duration Curves, flow regime, Mana Pools, Middle Zambezi.

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LIST OF SYMBOLS AND ABBREVIATIONS

λ:	Initial abstraction coefficient
A:	Area
AMC:	Antecedent Moisture Condition
ASTER:	Advanced Spaceborne Thermal Emission and Reflection Radiometer
DEM:	Digital Elevation Model
ESA:	European Space Agency
F:	Cumulative infiltration
FAO:	Food and Agriculture Organisation
FDC:	Flow Duration Curves
HEC-HMS:	Hydrologic Engineering Centre-Hydrologic Modelling System
I:	Initial abstraction
ILWIS:	Integrated Land Water Information System
IWRM:	Integrated Water Resources Management
MW:	Mega Watts
n:	Manning roughness
P:	Precipitation
p:	Probability
Q:	Discharge
R:	The ratio of cross section area to its perimeter
RV_E:	Relative Volume Error
S:	Potential maximum water retention of the soil
SCS:	Soil Conservation System
SPLASH:	Simplified Precipitation Lumped Algorithms for Stream flow Hydrographs
SWAT:	Soil Water Assessment Tool
TOP MODEL:	Topography and Physical model
UCL:	Catholic University of Luvonia
USDA:	United State Department of Agriculture
WCD:	World Commission on Dams
WRB:	World Reference Base
ZINWA:	Zimbabwe National Water Authority
ZPWMA:	Zimbabwe Parks and Wildlife Management Authority
ZRA:	Zambezi River Authority
α:	Alpha

DEDICATION

To my parents Justina and Alfred Ekandjo

ACKNOWLEDGEMENTS

This study would have not been possible without the guidance and assistance from my supervisor Dr Hodson Makurira. You always made sure that you accommodated my concerns, despite your busy schedule. I also would like to thank Ms. Elenestina Mwelwa as my second supervisor for her guidance as well as for providing necessary data and information required in this study. I should also acknowledge the assistance rendered by Mr. Webster Gumindoga during the setup of a rainfall-runoff model used in this study. You have been of great assistance especially dealing with ILWIS in preparation of model inputs.

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CHAPTER 1

INTRODUCTION

Harnessing of rivers and streams affects their ability to support socially valued native species or sustain healthy ecosystems that provide important goods and services (Naiman *et al*., 1995). Reservoirs have caused substantial alterations to river flow regimes, especially on flood magnitude and monthly flow patterns (Batalla *et al*., 2004). The Middle Zambezi is one river reach where damming for hydropower purposes had occurred over the past 50 years, with the construction of Kariba Dam and Kafue (Ithezi-thezi and Kafue Gorge Dams) influencing the current flow through their operations. Kariba Dam, for example, was built (1958/59) during the time when environmental impact assessment was not a prerequisite developmental project (WCD, 2000), hence its environmental impacts were not predicted. Furthermore, its operations have been primarily for hydropower generation.

Changing the natural flow regimes through damming affects downstream river hydrology through changes in timing, magnitude and frequency of high and low flows (Attwell, 1970; Nugent, 1986). The river flow regime determines its physical form and its interaction with the riparian zone, for example, flooding of the floodplains. Hydropower reservoirs like Kariba Dam were established primarily for hydropower production purposes that require a high hydrologic head in order to maximize power production. Such kind of reservoir operation, impact negatively on the natural flow regime through reduced flooding of floodplains that serves as good habitat for various aquatic and terrestrial inhabitants (Tilmant *et al*., 2010a).

The Mana Pools flood plain along the Middle Zambezi River is said to have been affected by the changes in natural flow regime since the establishment of upstream hydropower reservoirs. Before construction of Kariba Dam this floodplain used to be flooded when the Zambezi River is at high flood. However, currently, the Mana Pools flood plain is sustained by rainfall and groundwater seepage, (Matiza and Crafter, 1994). Previous studies done on the Middle Zambezi River and the Mana Pools floodplain had already indicated changes in flow regime due to the presence of upstream hydropower reservoirs and their subsequent effect on the downstream environment, Attwell (1970), Nugent (1986), Timberlake (2000), Davies *et al*. (2000), Mumba and Thompson (2005), Ronco *et al*. (2010), and Tilmant *et al*. (2010a).

1. 1. Problem statement

Previous studies on flow dynamics in the Middle Zambezi River, (Matiza and Crafter, 1994; Nugent, 1986) have indicated that, the flood levels at Mana Pools have reduced. Matos *et al*. (2010) and Ncube (2011) have recommended for more studies to be done in order to better understand the relationship between natural flows and reservoir releases as well as their subsequent effects to the Mana Pools ecosystem. It is reported that, the Mana Pools floodplain, is currently maintained by local rainfall and ground water seepage (Matiza and Crafter, 1994).

The lack of flow gauging station in the Mana Pools lower catchment on the Zimbabwean side makes it difficult to quantify the flow contribution of this catchment to the Mana Pools floodplains. With the exception of Nugent (1986) who acknowledged the flow contribution of the lower catchment at Nyamuomba, just downstream of Kariba, little seems to have been documented about the flow contribution of the lower catchment to the Mana Pools floodplains. Therefore there is a need for more studies that can quantify the flow contribution of this catchment to the Mana Pools floodplain.

1. 2. Objectives

1.2.1. General objective

To analyse the hydro-dynamics from natural and human influenced flows, particularly in the Mana Pools floodplain.

1.2.2. Specific objectives

1) To analyse the middle Zambezi flow regime before and after the dams were constructed (1924-2009)
2) To investigate the effects of hydropower reservoirs operation on the Middle Zambezi River flow regime
3) To estimate flows in un-gauged catchments flowing towards the Mana Pools flood plain from the lower catchment area of Zimbabwe

1. 3. Justifications

The study helps to understand the impacts of reservoir operation on the Mana Pools ecosystem. Outcomes from this study will also provide guidance in policy formulation, which aims at restoring the flow regime in order to address environmental impacts. For example, Gadolfi *et al.* (1997) suggested that, it is beneficial to maintain the flooding pattern as close as possible to the natural regime in the Middle Zambezi River.

Estimation of flows in ungauged basins flowing towards the Mana area helps to understand the contribution of the lower catchment to the Mana Pools flood plains as compared to the Middle Zambezi River flows. The coincidence of a high flow from the lower catchment with the Kariba sluice gates opening may result in possible flooding of the Mana Pools area, including the Nyamepi Camp which is located near the Zambezi River banks. Given the amount of water that the Zimbabwean catchment contributes to the Mana Pools flood plains, and the number of floodgates to be opened at Kariba that season, this will help in the flood preparedness in the flood prone areas like Nyamepi and other low laying campsites within the Mana Pools area.

Link with Power2Flow Project

There are three MSc. Studies that have been going on in the Mana Pools area of which this is one of them. These studies are linked to the Power2Flow Project through PhD 2. Power2Flow is one of UNESCO-IHE in collaboration with Waternet and other stakeholders. The project is carried out within the Middle Zambezi Basin, aiming at improving reservoir operation sustainability through development of policy instrument which include; reservoir operation policies and cost sharing mechanism that balances environmental water use and for energy generation. The outcome of this research work will feed into the PhD 2, whose objective is to improve the understanding of flow variation, morphological evolution and vegetation interactions in response to regulated flow regimes. The PhD study will feed directly into the Power2Flow project. Figure 1.1 summarises the link between this research (MSc 1), and the Power2Flow project.

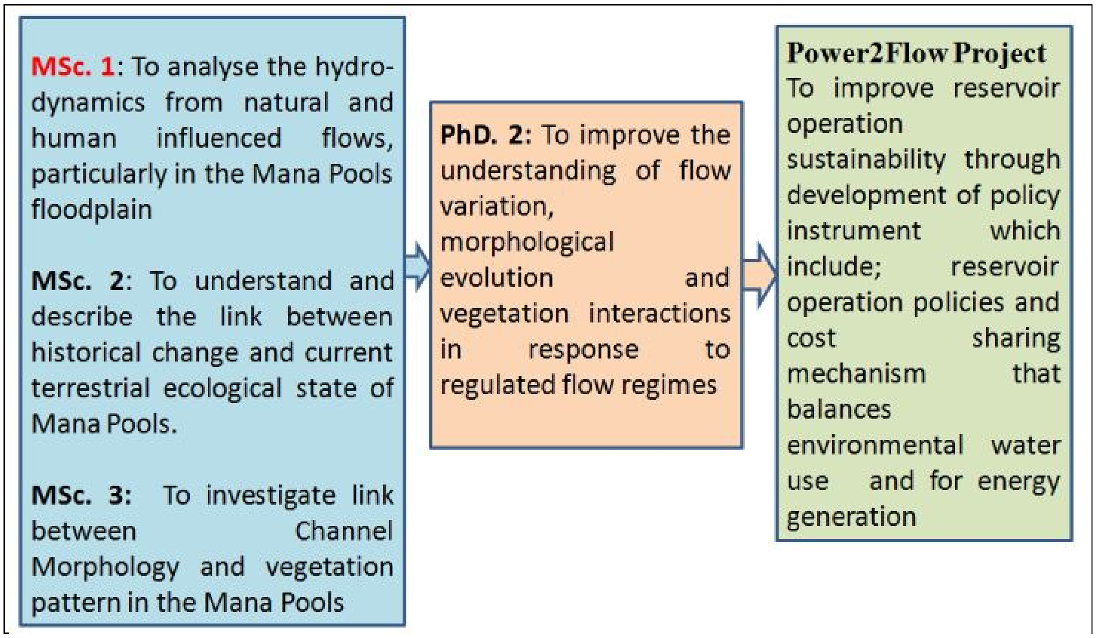

Figure 1.1: Link between the MSc research objectives and Power2Flow project

Scope of the study

The study is focussing on the Middle Zambezi River flow regime before and after the establishment of hydropower reservoirs. The focus area is the Mana Pools flood plain, downstream of the three reservoirs (Kariba, Itezhi-tezhi and Kafue Gorge Dam). This study investigated the effects of hydropower reservoirs on the natural flow regime at Mana Pools. The flow contribution of the lower catchment area, flowing towards the Mana Pools area is also estimated using a rainfall-runoff model.

CHAPTER 2

LITERATURE REVIEW

2. 1. Introduction

This chapter discusses reservoirs in general as well as their functions. This will further narrow down into hydropower reservoirs, their advantages and disadvantages as well as their environmental impacts. The chapter also look at the Middle Zambezi and hydropower reservoirs and how they impacted on the natural environment. The link between reservoirs and integrated water resources management (IWRM) is also discussed in this chapter. Lastly, this chapter will deal with the estimation of flows in ungauged basins.

2. 2. Reservoirs and their functions

Reservoirs in general are constructed to serve various functions that satisfy human needs. Among the functions, reservoirs are built to store water for direct use, (i.e. for domestic supply, irrigation agriculture and for industrial supply), hydropower generation, flood control and recreation. Other reservoirs functions include, balancing supply with demand, (that is storing water for use during peak demand, where supply may not match the demand) and provision of adequate hydraulic head in order to maintain pressure throughout the supply (Yeung, 2001). Some reservoirs may be constructed to serve multipurpose functions. For example a hydropower reservoir may serve for, recreation, fishery, domestic water supply and irrigation, instead of concentrating on the primary purpose which is hydropower generation.

2. 3. Hydropower reservoirs

Traditionally, hydropower is known to be the best renewable, non-polluting and environmental friendly source of energy (Ray and Sarma, 2010). One of the purposes of hydropower reservoirs is to store water at a desired hydraulic head, for the generation of required units of hydroelectricity. Storing water for future use allows utilities to meet the demand for electric power that varies considerably according to the time of day and the season (Olivares, 2008).

2.3.1. Advantages and disadvantages of hydropower reservoirs

Hydropower generation, provide benefits in addition to environmentally clean hydroelectricity. The hydropower reservoirs offers a variety of recreational opportunities, notably fishing, swimming, water sports and boating, among others. Most hydropower installations are required to provide some public access to the reservoir to allow the public to take advantage of these opportunities. Other benefits may include water supply and flood control.

Disadvantages of hydropower reservoirs includes loss of high quality agricultural land, displacement of people, changes to downstream flow patterns and impacts on fish migration (Jager and Smith, 2008). Fish populations can be impacted if fish cannot migrate upstream past impoundment dams to spawning grounds or if they cannot migrate downstream to the ocean. Upstream fish passage such as ladders or elevators, are mostly not provided for on many reservoirs.

Hydropower reservoirs impact on the local environment and may compete with other uses for the land. Humans, flora, and fauna may lose their natural habitat. Local cultures and historical sites may be impinged upon, (Olivares, 2008).

2.3.2. Environmental impact of hydropower dams

Hydropower reservoirs have resulted in ecological and social consequences, which were unexpected or deemed to have a lower societal importance than the design benefits (Goodwin *et al.*, 2006). Environmental effects of dams can be classified by subject themes or environmental components: examples include impacts on hydrology, morphology, fish, anthropology, etc. The impacts of hydropower reservoirs, on the flow regime, channel morphology and sediment transport has been recognized for several decades (Beilfuss and dos Santos, 2001). Typical responses of a river downstream of a reservoir include, reduction in channel bed slope, encroachment of the floodplains with terrestrial vegetation, changes in channel pattern or style (for example, from braided to meandering), and degradation of the river bed. Dams affect the riverine and floodplain vegetations, of which naturally being controlled by the dynamic interactions of flooding and sedimentation (McCartney, 2009).

The most obvious impact of storage reservoirs is the upstream inundation of terrestrial ecosystems (McCartney, 2009). The construction of a storage dam and subsequent inundation of the reservoir behind the dam kills terrestrial plants and displaces terrestrial animals. Emission of green house gases, from rotting flooded vegetation is another impact, challenging a perception that, hydropower produce only positive atmospheric effects (WCD, 2000).

2. 4. The Middle Zambezi River and hydropower dams

The Middle Zambezi River reach is one part of the Zambezi River that is impacted by the presence of reservoirs. There are three reservoirs present within the Middle Zambezi, with a fourth one just at the end of this river reach. Present reservoirs are Lake Kariba on the Zambezi and Itezhi-tezhi and Kafue gorge on the Kafue River. Cabora Bassa is just at the end of the Middle Zambezi.

2.4.1. Pre-impoundments Middle Zambezi flow regime

Hughes (1970) and Nugent (1986) had described the middle Zambezi flow pattern prior to Kariba Dam construction as characterised by two distinct high flow periods during its annual flooding. The lesser flood, with turbid water, locally known as *Gumbura*, occurs in February. *Gumbura* was presumed to be from the local rainfall recorded in the local catchment of Zimbabwe and Zambia. The second and higher flood occurred around April, this was characterised by clear water, locally known as *Murorwe*. This particular flood was presumed to be from the upper Zambezi catchment that had passed through Barotse and the Chobe/Caprivi flood plains. The two flow events were unlikely to coincide in many cases. The exceptional case was that of 1958 as pointed out by Nugent (1986). During the 1958/59 hydrologic year, the two flow events coincided, resulting in a high flood that year. Although in current years, with the presence of Kariba and Kafue reservoirs, the Upper Zambezi flood is attenuated by the presence of reservoirs, a coincidence may occur when the lower catchment flood coincide with the opening of the sluice gates at those upstream dams. Prior to the dam construction the middle Zambezi River's annual maximum flow used to range between 5000 m^3/s and 20000 m^3/s while minimum flows could drop as low as 200 m^3/s according to Gandolfi *et al*. (1997).

2.4.2. Post-impoundments Middle Zambezi flow regime

Hydropower reservoir operation has regularized the Middle Zambezi River flow regime, with increased low season flows and reduced peak flows (Gandolfi *et al*., 1997; Matos *et al*., 2010). According to Gandolfi *et al*. (1997), the presence of the Kariba and Kafue Gorge–Itezhi-tezhi reservoirs resulted in almost 90 % of the flow being regulated. After construction of hydropower reservoirs, the hydrology of the Middle Zambezi has changed, resulting in modified flooding regimes, which affect habitat and species composition (Timberlake, 2000). The defining river discharge includes both high and low flows, WCD (2000). These flow dynamics determine the river's physical foundation that ensures ecosystem integrity. The peak flow during the high flood period and the low flow pattern during the dry season, were significant flow events before the establishment of hydropower reservoirs. Various aquatic lives may have evolved as a result of those natural flow patterns. This had however been impacted on by almost averaged flows discharged through the turbines during hydropower generation.

On the Kafue River which is one of the major tributaries flowing into the Middle Zambezi River, a change in the natural flow regime was observed in the Kafue Flats after the construction of Kafue gorge and Itezhi-tezhi Dam in 1971 and 1976/77 respectively. Itezhi-tezhi reservoir was constructed with the purpose of maintaining a supply of a 120 m^3/s required at Kafue Gorge Dam for the generation of 450 MW (CEH., 2001; Mumba and Thompson, 2005). According to Mumba and Thompson (2005), the presence of

Itezhi-tezhi and Kafue Gorge reservoirs, had modified the hydrological regime of the Kafue Flats, of which part of the flood plains became permanently flooded as a result of year-round releases from Itezhi-tezhi and the backwater from Kafue Gorge. This permanent flooding of some portion in the Kafue flats had served as a favourable environment for the propagation and invasion of the area by the invasive species (Mumba and Thompson, 2005). Permanent flooding in the Kafue Flats may have reduced the flows downstream of Kafue Gorge Dam.

2. 5. Hydropower dams and Integrated Water Resources Management (IWRM)

Until the beginning of the 1980s, water resources developments have been done on a single objective basis (Medema and Jeffrey, 2005). Integrated water resources management (IWRM) which is a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (WGP-TAC, 2000) have been widely adopted in water resources development. Most of the reservoirs were constructed based on a single objective approach, being hydropower, irrigation or flood control. Other users especially downstream and the environment were not put into consideration during the establishment of those single purpose reservoirs. Establishment of reservoirs without considering other users, had resulted in relocation of communities against their will, flooding of habitats, as well as change in flow regime, as was the case with the Dirre Dam water supply project in Ethiopia (Tefera and Stroosnijder, 2007) and the Kariba Dam between Zambia and Zimbabwe (WCD, 2000). It is very important that an integrated approach be taken as a planning tool in water resources development.

2. 6. Effects of reservoirs on downstream flow in the region

In Tanzania, a study done by Mwamila *et al.* (2008) on the Pangani River downstream of Nyumba ya Mungu reservoir, found that after the construction of the reservoir, there was lack of natural flow variation, with the flows being maintained between 20-40m^3/s for most part of the year. In Insiza River of Zimbabwe, a study done on the effects of three dams on the flow of Insiza River had found that, the two upstream dams had reduced exceedance frequency of low flow (Kileshe-Onema *et al.*, 2006). In South Africa, Sukhmani *et al.* (2010)studied the ecological impacts of small dams in South Africa. He found that, the presence of small reservoirs had affected the natural flow of those rivers and consequently affecting the riverine ecology. The result from those studies supports the findings of similar studies carried out in the Middle Zambezi and Kafue Rivers.

2. 7. Estimation of flow in un-gauged catchments

In most countries there are plenty of rainfall records than the stream flows (Shaw, 2004). This is because stream flow measurement tends to be an expensive exercise. It is against this background that various rainfall-runoff models had been developed for the estimation of stream flows in un-gauged catchments.

During a storm event, the first drops of water are intercepted by the leaves and stems of the present vegetation; this is usually referred to as interception storage (de Groen and Savenije, 2006). As the rain storm continues, water reaching the ground surface infiltrates into the soil until it reaches a stage where the rate of rainfall (intensity) exceeds the infiltration capacity of the soil (Shaw, 2004). Thereafter, surface puddles, ditches, and other depressions are filled, after which storm water begins to flow over the surface

2. 8. Flow estimation using rainfall-runoff models

Several rainfall-runoff models have been employed in estimation of runoff in un-gauged catchments in the world. These include among others; SWAT, HEC-HMS, SPLAS model, TOPMODEL, Soil Conservation Services Curve Number System (SCS-CN) of the United State Department of Agriculture (USDA) among others. The SCS-CN has been widely used in estimation of storm flow with acceptable results comparable with other methods (Bwanali, 1999; Schulze *et al.*, 1992). In Zimbabwe, SCS have been applied in estimation of flow within the University of Zimbabwe's catchment (Gumbo *et al.*, 2001). Bwanali (1999) also used an improved SCS method in determination of runoff in ungauged small catchments of Zimbabwe.

2.8.1. Theoretical concept of SCS runoff estimation

The SCS-CN runoff model is based on the water balance equation (equation 2.1) with two hypotheses, given by equations 2.2 and 2.3. The model equations are based on field data recorded from a large number of gauged watersheds distributed throughout the United States (Tan *et al.*, 2002).

$Q = I_a+F+P$……………………………………………………………….Equation 2. 1

Where: Q = direct runoff (m^3/s)

I_a = the initial abstraction (mm)

F = cumulative infiltration (mm)

P= Precipitation (mm)

The first hypothesis (equation 2.2) indicates that, the ratio of the amount of actual soil water retention, F, to maximum potential watershed storage, S, is proportional to the ratio of actual direct runoff volume, Q, to the effective rainfall (total rainfall, P, minus initial abstraction I_a).

$\frac{F}{S} = \frac{Q}{(P - I_a)}$ ....…...Equation 2.2

Where: S = the maximum potential water retention of the soil (mm),

Other parameters are as stated in equation 2.1.

The second hypothesis states that,

$I_a = \lambda S$ ……………………………………………………………………....Equation 2.3

Where, λ the initial abstraction coefficient is given as equal to 20 % from field experiments.

The two equations (2.2 and 2.3) are combined to give the SCS storm flow equation for the estimation of storm flow in ungauged basins, (Schulze *et al*., 1992).

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{..........Equation 2.4}$$

Where; Q= runoff depth in mm

P = precipitation in mm

S = maximum potential soil water retention (mm)

For direct runoff estimation, equation 2.4 is based on the condition that, P > 0.2S. The value of maximum potential soil water retention, S is influenced by the hydrological soil properties, land cover and land use practices. The CN is determined from a combination of hydrological soil groups, land cover and antecedent moisture condition of the soil (AMC). Antecedent moisture condition is computed from the first five antecedent raining days of a given season, given as AMC I for dry, AMC II for average and AMC III for wet conditions, (Silveira *et al*., 2000; Tan *et al.*, 2002).

Limitations of SCS

The major limitation with the CN approach is the inability to account for rainfall intensity/duration in estimation of runoff depth (King *et al.*, 1999). Apart from lack of time factor with respect to rainfall distribution, SCS categorise the initial abstractions as one factor.

Summary

Reservoirs have both advantages and disadvantages. Hydropower reservoirs in particular benefit the community around them and the towns that benefit from electricity generated. However their constructions displace communities and affect the downstream ecosystem. Establishment of hydropower reservoirs within the Middle Zambezi is said to have affected the downstream environment such as the Mana Pools flood plains. This is because those reservoirs have been established with a single objective (hydropower), without considering their impacts on the downstream environment. The Soil Conservation Services estimate direct runoff from a storm event, using few inputs as compared to other models. It is based on empirical equations developed from various catchments in the United States of America. Its shortfall however, is the inability to account for rainfall intensity in estimation of runoff.

CHAPTER 3

MATERIALS AND METHODS

3. 1. Introduction

This chapter is divided into two parts, with part one focussing on description of study area and part two focusing on the methodology. Description of the study area starts with the broad overview of the Zambezi River, narrowing it down to the Middle Zambezi, and finally to the Mana Pools area. The methodology part of this chapter focuses on the methods used to achieve the objectives. This starts by looking on the pre and post impoundments Middle Zambezi flow regime, effects of hydropower reservoirs on Middle Zambezi flow regime and impacts of reservoir operations on the Mana Pools flood plains. This part also looks at the method used in estimation of flows in un-gauged lower catchment flowing to the Mana Pools area.

3. 2. Description of the study area

3.2.1. The Zambezi River

The Zambezi River is the fourth largest river in Africa after the Congo, Nile and Niger Rivers. It is the largest African river flowing into the Indian Ocean (Tumbare, 2010). The Zambezi River Basin is home to approximately 38.4 million people and it drains eight countries namely, Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe (Beilfuss and dos Santos, 2001).The river is divided into Upper Zambezi, Middle Zambezi and Lower Zambezi. The upper Zambezi starts from the head water originating from the Kalene Hills in the north-western part of Zambia and ends at Victoria Falls. The middle Zambezi begins from Victoria Falls up to Lake Cabora Bassa. The lower Zambezi is the portion from Cabora Bassa up to the Indian Ocean (Beilfuss and dos Santos, 2001).

3.2.2. Middle Zambezi River

The middle Zambezi River is part of the Zambezi River Basin between Victoria Falls and Cabora Bassa. It is the most developed part of the Zambezi River Basin, with three hydropower schemes, Kariba, Kafue and Cabora Bassa at the end (Timberlake, 2000). Kariba Dam across the Zambezi River was completed in 1959 and it is the largest of all four, with the storage capacity of 185 km^3 (Tumbare, 2010). On the Kafue River which is the major tributary joining the Middle Zambezi, the Kafue Gorge Dam and Itezhi-tezhi Dam were completed in 1971 and 1977 respectively (Mumba and Thompson, 2005). Itezhi-tezhi was constructed as a storage reservoir for hydropower generation at Kafue Gorge. Lake Cabora Bassa was completed in 1974 with a storage capacity of 64.2 km^3 (Beilfuss and dos Santos, 2001; Tilmant *et al*., 2010b) The storage and hydropower generation capacities of each reservoir are summarised in Table 2.1.

Table 3. 1: Middle Zambezi River reservoirs and their capacities

Reservoir	Year established	Storage capacity (km^3)	Generation capacity (MW)
Kariba	1959	185	1275
Kafue Gorge	1972	5.7	900
Itezhi-tezhi	1977	4.9	##
Cabora Bassa	1974	64.2	2073

Supply Kafue Gorge

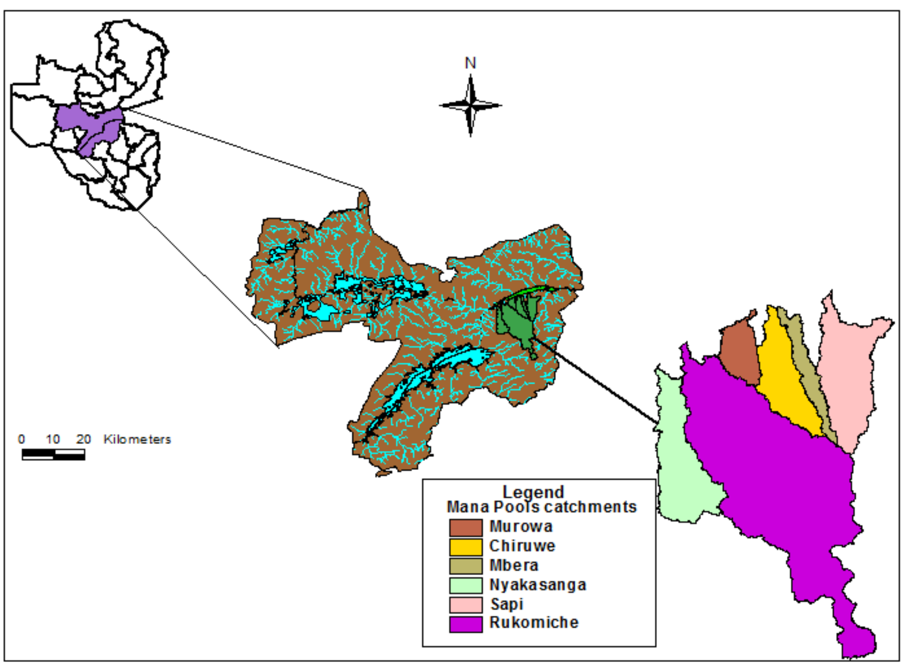

Figure 3. 1: Middle Zambezi Map and Mana Pools catchments

3.2.3. The Kariba Dam and Reservoir

The Kariba Dam was constructed between 1956 and 1960, creating Lake Kariba behind the dam wall. Its dam wall is about 128 m high, double-curved concrete arch. The lake extends for 280 km from Devils Gorge to Kariba Gorge and it is 32 km at its widest point. At full supply level, Lake Kariba has storage of 185 km^3 and it inundates an area of 5580 km^2 (Tumbare, 2010). Kariba Reservoir is the third largest manmade lake in Africa. Kariba Dam is a bi-national dam between Zambia and Zimbabwe, managed jointly by the Zambezi River Authority. Although Kariba Dam was established primarily for hydropower production, the lake supports a large Kapenta Fishery, serves as recreation area and supply water to the surrounding towns as well as for small scale irrigation (Magadza, 2006).

3.2.4. The Mana Pools

The Mana flood plains are located at 150 km downstream of the Kariba dam within the Mana Pools National Park in Zimbabwe. The Mana Pools National Park is about 2196 km^2 in size located between the Rukomechi and Sapi Rivers. The park is drained by ephemeral rivers that have their sources in the upland escarpment areas (Rukomechi and Chewore) as well as from the base of the escarpment, (Sapi, Chiruwe, Mbera and their associated tributaries (ZNPWMA, 2009).

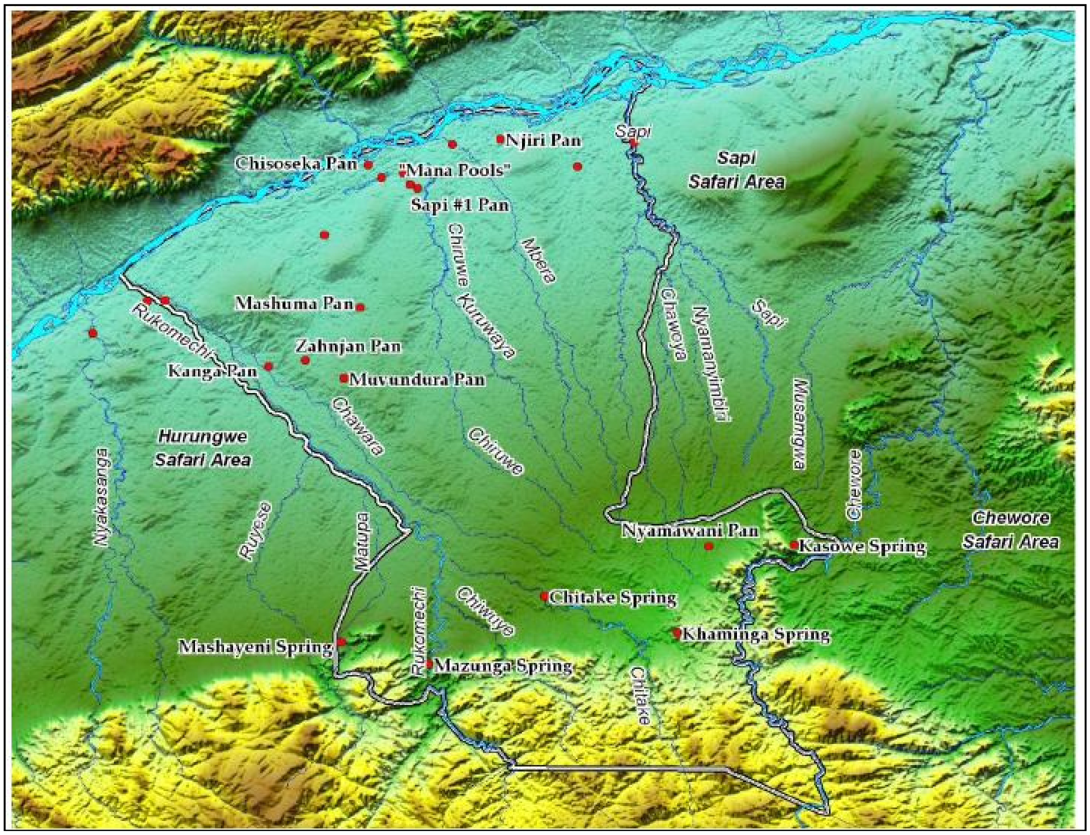

Figure 3. 2: Mana Pools National Park Google map (ZNPWMA, 2009)

The Mana Pools floodplain contains four Pools, which are likely remnants of former channels after the Zambezi shifted northwards (ZPWMA, 2009). The largest is the Long Pool. Larger pools such as Long Pool can hold water throughout the year. Ephemeral rivers such as Murowa, Chiruwe and Mbera, (Figure 3.2), sustain most of the pools in Mana Flood plains. Figure 3.3 shows a good flow from the ephemeral rivers into the Mana Pools floodplain during February 2011.

Figure 3. 3: Mana River flowing over the bridge to Nyamepi camp

Geology

The oldest rocks in the area are those of the Proterozoic Zambezi Metamorphic Belt forming the Zambezi Escarpment (Du Toit, 1982). The Mana flood plains were formed by the fertile alluvial deposits which are more pronounced along the Zambezi River banks, (Du Toit, 1982). The greater part of the Valley floor within the park is covered by Pebbly Arkoses and Forest Sandstone fluvial and Aeolian sequences of the Upper Karoo Group, that are of Triassic to Jurassic age, overlain by post- Karoo Red Beds close to the Escarpment foot (ZNPWMA, 2009). Adjacent to the Zambezi River is a belt of Pleistocene to Recent Kalahari-type beds, the Jesse Sands. Other deposits are riverine alluvium, the largest of which occurs along the Rukomechi River.

Soils

The soils of the Mana Pools National Park are of colluvial origins. Colluviums are soils that were deposited or built up at the bottom of the hill slope. The colluvium deposits of the Mana Pools area are deposits from the escarpment. The soils are deep, consisting of brown fine to medium grained sandy loam overlying sandy clay loam or sandy clay, (Henderson and Griffiths, 1981). The alluvial deposit of the Mana Pools is poorly structured and with relatively heavy textured surface that reduces rainfall infiltration and causing surface wetness (ZNPWMA, 2009).

Based on the Zimbabwean soil classification, most of the soils within Mana Pools catchment area, bellow the Zambezi escarpment, are classified as lithosols. This classification is based on depth of the soils. Lithosols are soils that are not more than 25 cm deep, (Nyamapfene, 1991). Under FAO classification these soils are classified as Leptosols. Adjacent to the Zambezi River, the soils are of the Kalahari Jesse sand, while the floodplains is characterised by alluvial deposits underlain by a layer of clay (ZNPWMA, 2009).

Rainfall

Over the period of 1967/68 to 2009/2010, the year 1977/78 recorded a high rainfall (1706 mm/annum) otherwise, there had not been many variations in annual rainfall as shown by a linear trend and a ten years moving average (Figure. 3.4).

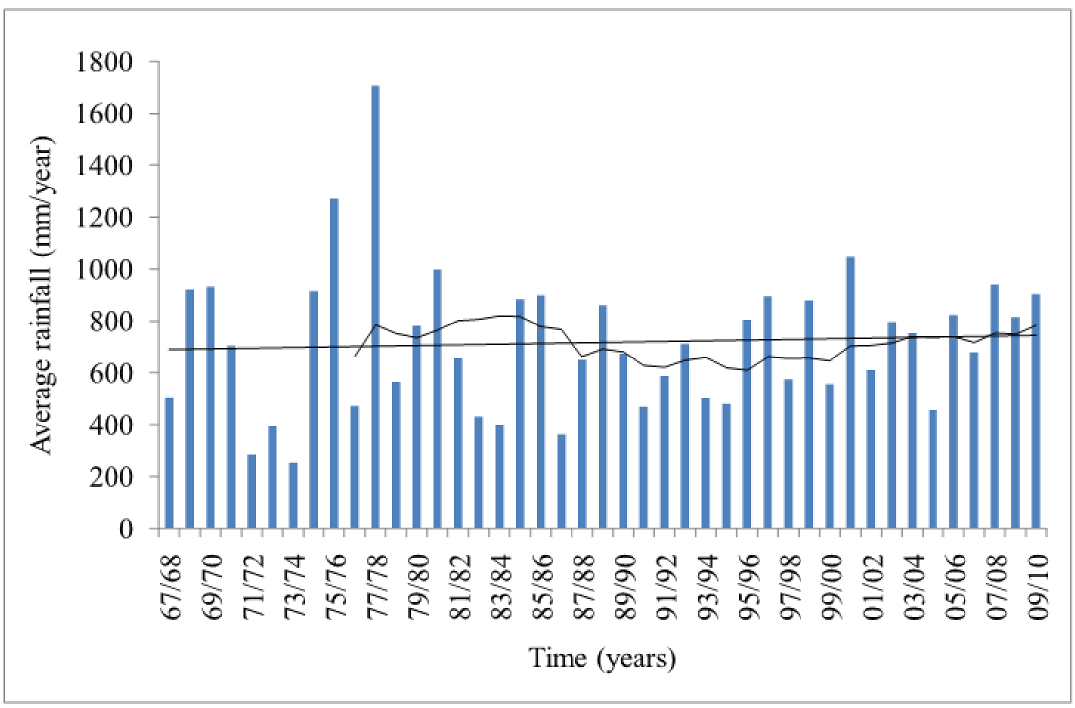

Figure 3. 4: Annual rainfall recorded at Nyamepi Camp, (1967-2010)

3. 3. Methods

3.3.1. Pre and post impoundments Middle Zambezi River flow regime

Using the historical data recorded at Victoria Falls' Big Tree station from 1924-2009, a differential mass curve was constructed. This was done in order to investigate the cyclic events that have taken place during the said period. Differential mass curve also helps in differentiating between the occurrence of natural phenomenon and the effects of reservoirs on downstream flows.

To investigate the Middle Zambezi River flow regime before and after the construction of hydropower reservoirs, mean monthly flows for the period of 1961-2010 was used. The assumption made in this analysis is that; the pre-impoundments flow at Mana Pools is the sum of the Victoria Falls (Big tree) discharge and Hook Bridge discharge. Due to the absence of gauging stations immediately downstream of Kafue and Zambezi River confluence, the outflow from Kariba and Kafue Gorge Dam were assumed to be the post-impoundments flow at Mana Pools floodplain (Figure 3.5). Hydrograph drawn from mean monthly flows were used to compare the pre and post impoundments flow regime at Mana Pools. The two hydrographs were plotted against each other, in order to compare the difference between the two flow regimes.

Apart from the Kafue River, the assumptions made in this analysis did not consider other tributaries that are flowing into the Zambezi River between Victoria Falls and Mana Pools, from both Zimbabwe and Zambia.

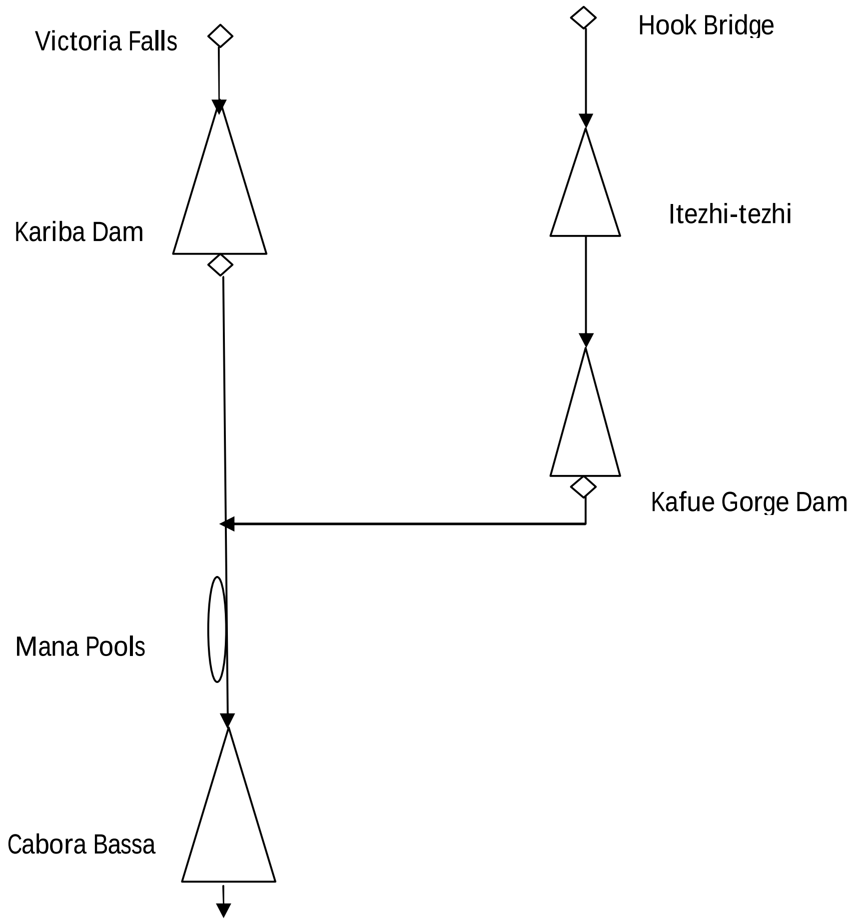

Figure 3.5: Schematic diagram of the Middle Zambezi Basin

Average monthly flows over the studied period were used to construct hydrographs that depict the Middle Zambezi flow regime, with and without the presence of hydropower reservoirs. Using the same twelve months mean monthly flows, descriptive statistics (mean, standard deviation and coefficient of variation), were used to describe the difference between the pre and post impoundments of the Middle Zambezi River flow regime at Mana Pools. The standard *t*-test was applied to test the hypothesis that there is no difference between upstream and downstream mean annual flows.

3.3.2. Effects of hydropower reservoirs operation on the Middle Zambezi River flow regime at Mana Pools

In order to investigate the effects of each reservoir on the Middle Zambezi natural flow regime, flow duration curves were used. A flow-duration curve (FDC) represents the relationship between the magnitude and frequency of daily, weekly, monthly or any time interval of streamflow, for a particular river basin, providing an estimate of the percentage of time that a given streamflow was equaled or exceeded over a historical period (Vogel and Fennessey, 1994). Mean monthly flow data recorded at each station were grouped into classes of equal intervals. The frequency of occurrence in each class was done, followed by cumulative frequency. Percentage of cumulative frequency was computed. Exceedance percentage was obtained by subtracting cumulative percentage from 100%. The exceedance percentages were plotted against the maximum class limit in each class.

The Victoria Falls flow duration curve was plotted against the Kariba flow duration curve in order to get the effects of Kariba Dam on the natural flow regime. Similarly, on the Kafue River, The Hook Bridge flow duration curve was compared with the Kafue Gorge flow duration curve in order to get the compounded effects of both Itezhi-tezhi and Kafue Gorge dams on the Kafue river flow regime.

The sum of Victoria Falls and Hook Bridge discharge were used to plot a flow duration curve that represented the natural flow in the Middle Zambezi. Similarly, Kariba Dam and Kafue Gorge discharges were used to plot a flow duration curve that represents the current flows in the Middle Zambezi. The two flow duration curves were then plotted against each other in order to investigate the effects of upstream reservoirs on the natural flows at the Mana Pools flood plains.

3.3.3. Monitoring of the impact of Kariba spillway releases at Chirundu

During the study period, the Zambezi River Authority (ZRA) fully opened four sluice gates at Kariba, between January and February 2011. This was done in order to release more water flowing in from the local catchment of Gwayi and Sanyati, and to make room for anticipated flood contributions from the upper Zambezi. The 2011 Kariba Dam daily release data were used to construct a hydrograph that shows the behaviour of Middle Zambezi flows when flood gates were opened. The Victoria Falls Flow Duration Curve (1924-2009) constructed from daily discharge was used to find out if the maximum discharge with four gates opened at Kariba could be exceeded without the presence of Kariba Dam. Another Flow Duration curve was constructed from Kariba releases (1993-2009) in order to establish whether such maximum discharge (with four flood gates opened) from the dam was exceeded before, downstream of Kariba dam during the said period. The 1993-2009 were the only daily releases available for this analysis.

The maximum elevation of the river after four gates were opened was recorded to be at 376 m. This was used to trace the contour in order to investigate the extent of flooding at Mana Pools floodplain. During peak flow period at Victoria Falls from the upper Zambezi flood in May, two sluice gates were again opened. The river level with two sluice gate opened at Kariba was recorded to be 367 m at Chirundu. This was also used to trace the contour in order to investigate the flooding extent at Mana Pools flood plain. The area flooded during the two events, was digitised in Arcview and converted to polygons in order to calculate the area. The difference in area flooded during the two events was calculated in order to get the magnitude of flood when sluice gates are opened at Kariba.

A cross section survey was done at the old Chirundu Bridge. At this point, the Zambezi River is narrower as compared to other areas around Chirundu. The cross-section was done by taking the depth of the river from the Old Chirundu Bridge top, at 20 m intervals, until the whole section was completed. This was done in order to compare the actual discharge released from Kariba Dam with the one calculated using the Slope Area Method.

The levels of the cross section were reduced from 386 m elevation at the middle of the bridge. Discharge was calculated using the slope area method, employing the Manning's equation. The 367 m water level with two sluice gates opened at Kariba Dam was used as a maximum level to construct the cross-section. Discharge was calculated using the Manning equation (Equation 3.1).

$$Q = \frac{A}{n} R^{2/3} S^{1/2} \qquad \text{Equation 3. 1}$$

Where: Q = Discharge (m^3/s)

A = Cross section area (m^2)

R = the ratio of cross section area to its perimeter

n = Manning roughness

S = Channel slope (m)

3.3.4. Estimation of flow in un-gauged catchments

Apart from the Zambezi River and the Kafue system, the Mana Pool flood plain receives flows from various major tributaries within Zimbabwe. This includes among others (from west to east): Nyakasanga, Rukomechi, Murowa, Chewore, Mbera and Sapi rivers. None of those tributaries are gauged, making it difficult to quantify the flows that those tributaries are contributing towards the Mana Pools flood plains. Therefore, runoff in those tributaries was estimated using the SCS CN method.

SCS CN method uses few inputs to estimate runoff, as compared to other methods. The model requires only precipitation, with the combination of catchment characteristics, making it suitable for this area where there is lack of both climatic and flow data.

Catchment extraction

Delineation of catchments was done using Integrated Land and Water Information System (ILWIS 3.3), through its hydro processing operation. A 90 meter resolution Digital Elevation Model (DEM), downloaded freely from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was used as primary data for catchment extraction. The DEM hydro processing with ILWIS that involves drainage network extraction, drainage network ordering and finally extraction of catchments around major tributaries was performed. The 1976, 1:250 000 map of the local Mana Pools area, obtained from the Surveyor General's Office in Harare, was used to identify major tributaries that flow toward the Mana Pools area. Six major tributaries were identified and the delineated catchments were named after them (Figure 3.6).

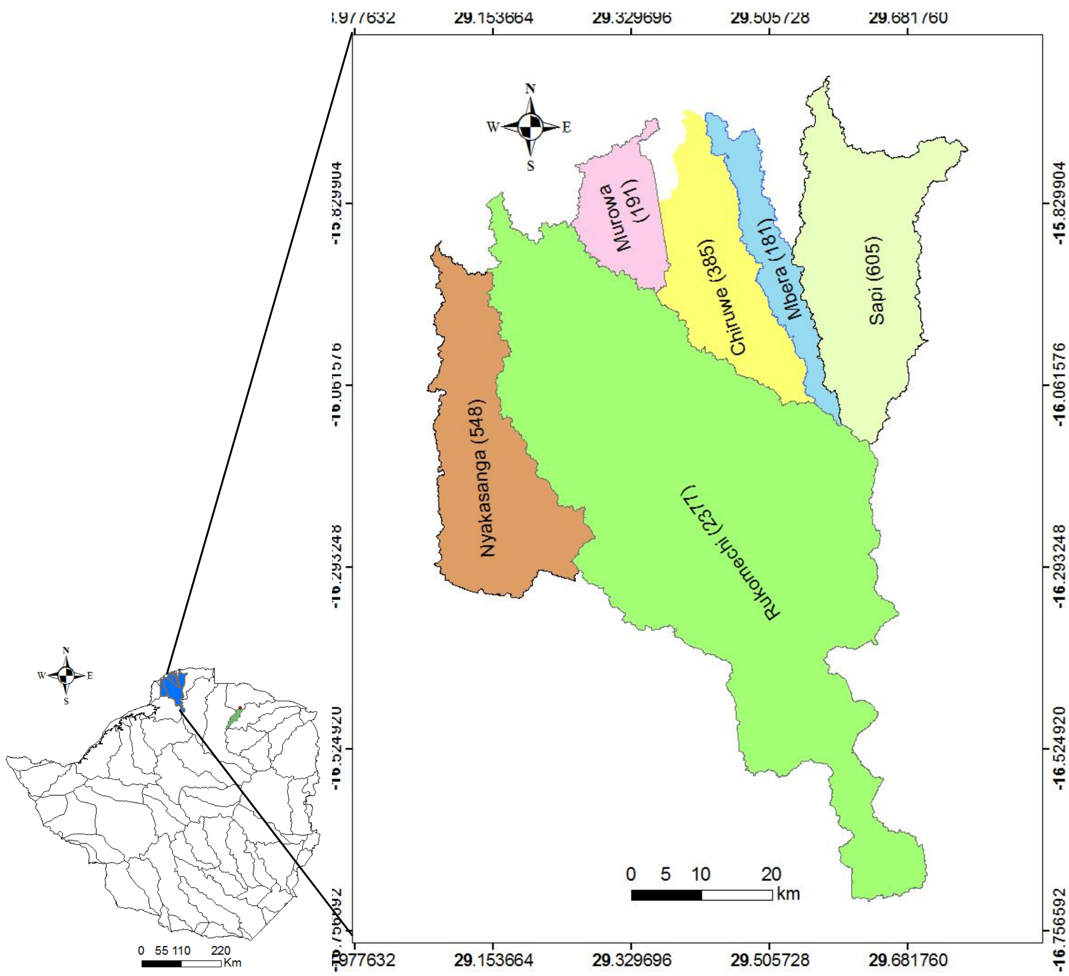

Figure 3. 6: A map showing the location of Mana Pools' lower catchments and area in km^2

Soil characteristics

The Food and Agriculture Organisation (FAO) soil map was used in this study. The FAO soil map is based on a combination of remote sensing and ground-truthing on various parts of the world, which was then extrapolated to the rest of the world (FAO, 2003). The FAO soil types in each catchment were reclassified into four hydrologic soil groups (A, B, C and D) based on their particulate characteristics as shown in Table 3.2 bellow. A total of eight soil samples were taken within Nyakasanga area and Chirundu.

Table 3. 2: Hydrologic soils characteristics

Hydrologic soil groups	Characteristics
A	Sand, loamy sand and sandy loam types of soils.
B	Silt, silt loam and loam soils.
C	Sandy clay loam soils.
D	Clay loam, silt clay loam, sandy clay, silt clay and clay soils.

A maximum of eight soil samples were taken within Nyakasanga Catchment. Sampling was only done within the first 30 cm layer of the soil. The top soil is underlain by a hard compacted layer. Sieve and hydrometer analyses were done at the soil Mechanics Laboratory of the Department of Civil Engineering. This was done in order to characterise the soil according to their particulate structure.

Land cover

The 300 meters resolution GlobCover2009 from ESA 2010 and UCLouvain was used to determine land cover type in all the studied catchments. Land covers were reclassified to suit the land cover types used by the model. All the predominantly forest land was reclassified as forest land, a combination of forest patches with shrubs and grasses was reclassified as rangeland, and water bodies were classified as water and all cropped area were classified as agricultural-land. Google Earth was used for verification, as some of the areas could not be accessed during the study period. A vegetation cover survey was done at 17 points along Marongora-Chirundu road, which is part of Nyakasanga catchment.

Rainfall

Average annual rainfall was derived from four rainfall stations, Nyamepi at Mana Pools, Rukomechi Research station, Marongora office and Karoi town (Figure 3.7). The mean annual rainfall was obtained through a Thiessen polygon method, using interpolation function of ILWIS 3.3. The influence of each rainfall station was computed and the mean annual precipitation in each catchment was obtained.

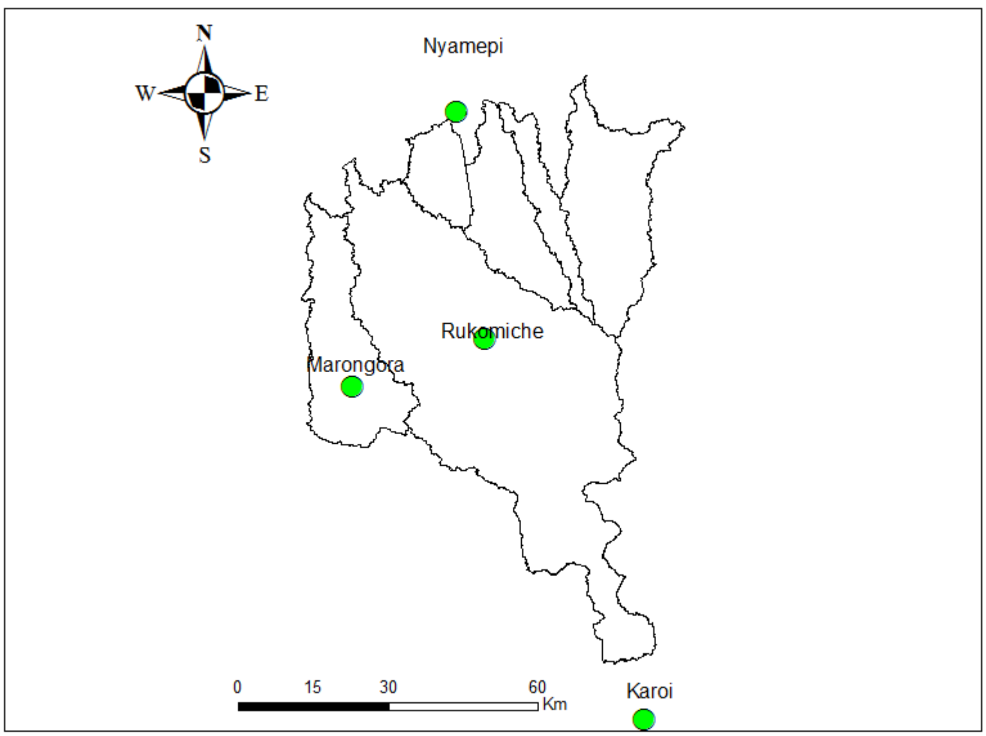

Figure 3. 6: Rainfall stations around Mana pools lower catchment area

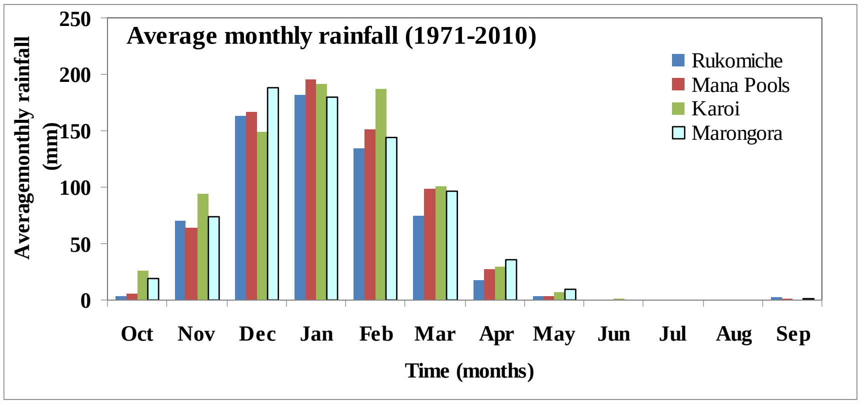

Figure 3.7: Average monthly rainfall from four stations around Mana pools catchment

The mean monthly rainfall from the four stations over the period of 1971-2010 (Figure 3.8) follow the same distribution pattern from October to May, with maximum rainfall being attained during December to January and the minimum rainfall observed during May.

Antecedent Moisture Condition (AMC)

Antecedent moisture condition of the soil was determined by taking the sum of five days antecedent rainfall recorded at the four rainfall stations. The SCS defines the antecedent moisture condition as an index of basin wetness (Silveira *et al.*, 2000). The five days antecedent rainfall was compared with the values in Table 3.3, to obtain the AMC for each catchment. The Zimbabwe rain season begins in October. Therefore the five days antecedent rainfall was compared to, the wet season values in Table 3.3. The AMC I, II and III, represent dry, average, and wet soil respectively.

Table 3. 2: Antecedent moisture condition of the soil, adopted from (Silveira *et al.*, 2000)

AMC	**Total 5-day antecedent rainfall (mm)**	
	Dormant season	Wet season
I	<13	<36
II	13-28	36-53
III	>28	>53

Selection of Curve Numbers

Using the land cover type, hydrological soil groups and wet conditions (AMC III), curve numbers (CN_i) were selected using Table 3.5.

Table 3. 3: Curve Numbers table (Tan *et al.*, 2002)

Hydrological soil groups	***A***			***B***			***C***			***D***		
AMC / Land-Cover	**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
Forestland	19	36	56	39	60	78	53	73	86	61	79	90
Wetland	100	100	100	100	100	100	100	100	100	100	100	100
Water	100	100	100	100	100	100	100	100	100	100	100	100
Barrenland	58	77	89	72	86	93	81	91	96	87	94	97
Urban	77	89	95	83	92	96	86	94	97	89	95	98

The soil map and land cover map were crossed in ILWIS 3.3, to obtain the area covered by a certain hydrologic soil group and land cover type. This was done in order to compute the weighted curve numbers (CN_j) useful in estimation of runoff from the whole catchment. The weighted curve number was computed using equation 3.2.

$$CN_j = \frac{1}{A}\sum CN_i \times A_i \text{ ……………………………………………………..Equation 3. 2}$$

Where; CN_j = Weighted curve number

A = the total catchment area, (km^2)

CN_i = the curve number for each soil group and land cover type

A_i = the area covered by land cover and hydrological soil group, (km^2)

Runoff depth from each catchment was estimated using equation 2.4

The maximum potential soil water retention S was determined using equation 3.3.

$$S = \frac{25400}{CN} - 254 \quad \text{......Equation 3. 3}$$

The cumulative flow from the six sub-catchments was compared to the Middle Zambezi flow at Mana Pools to obtain its total contribution. The SCS-CN model is summarised in Figure 4.1.

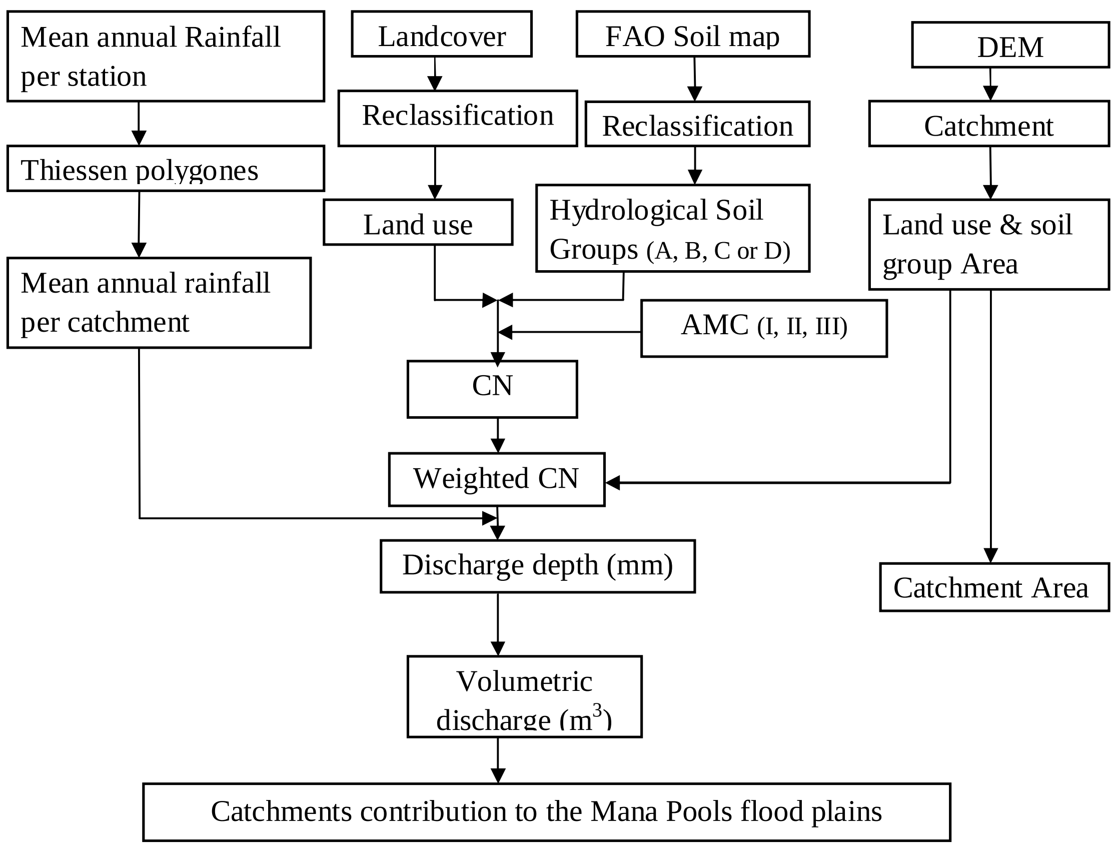

Figure 3.8: Flowchart of the CSC model applied in un-gauged catchments

3.3.5. SCS calibration and validation of the results

Due to lack of discharge data in the whole Mana Pools catchment within Zimbabwe, to calibrate and validate the model results, the model was applied to gauged catchment. Upper Musengezi sub-catchment upstream of C68 gauging station was used for the calibration and validation of the model results (Figure 4.2). The 1995 flow data from C68 and rainfall data from Muzarambani were used in both calibration and validation of the results. Although Upper Musengezi does not exactly poses the same characteristics as that of the Mana catchments, it was the nearest catchment and of almost the same size. The land use in the Mana catchment is Game Park while that of Musengezi is predominantly agriculture.

The parameters used during calibration were the FAO soil types. Since reclassification was done using literature information, wrong classification could happen. This was therefore an area considered to result in a high value of error. The leptosols which are characterised by gravel that forms crumbs can be wrongly classified as well drained soil, while when wet, it reduces infiltration. The same reclassification approach was applied in the classification of FAO soils in the Mana Pools catchments. Despite the difference in catchment characteristics, the method used in calibration does not cause the catchment used in calibration to influence the results in the ungauged catchments, since only classification approach was adopted but not the exact reclassification results.

The Relative Volume Error (RV_E) was used to test the accuracy of the model results.

$$RV_E = \sum \left(\frac{(Q_{estimated} - Q_{observed})}{Q_{observed}} \right) \times 100\% \quad \text{..Equation 3. 4}$$

Best results are obtained when RV_E, is between -10 and 10 (Janssen and Heuberger, 1995).

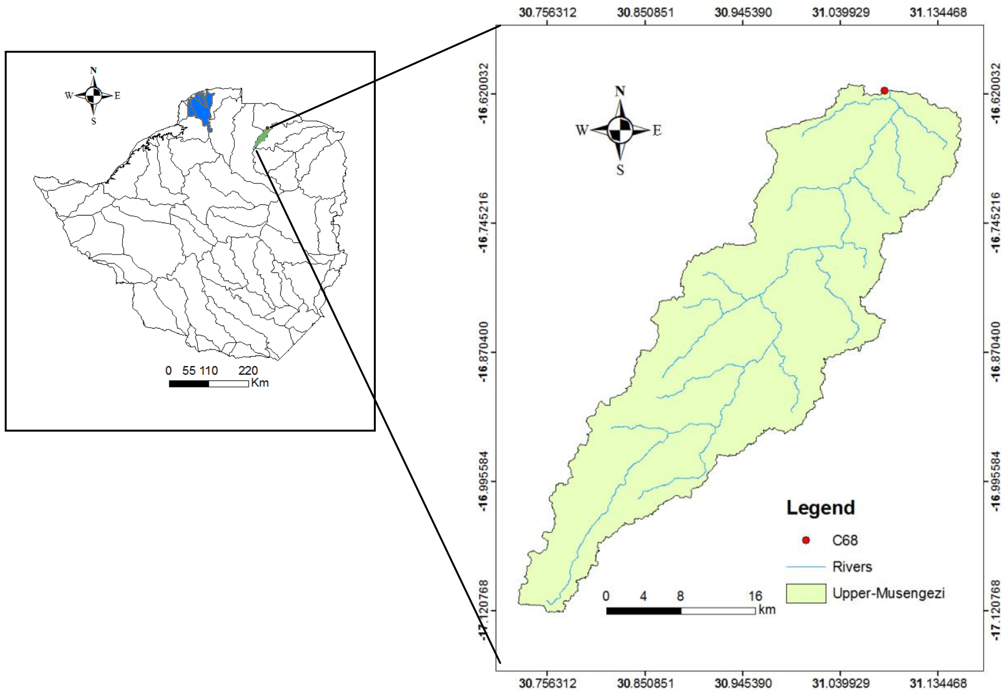

Figure 3. 9: A map showing the location of Upper Musengezi sub-catchment and C68 gauging

3.3.6. Installation of a Gauging station on the Rukomechi River

Modelling is considered as a last option in estimation of runoff in absence of measuring techniques in various catchments. In this study, the whole studied catchment did not have any gauging station for direct recording of flows. As a result, the Rukomechi River which is the largest river, flowing towards the Mana Pools, was selected for the installation of a gauging station. This was done in order to measure direct runoff as well as to use its data for the calibration of the rainfall-runoff model, to estimate discharge in adjacent catchments. The station was established next to the Rukomechi Research station. Site selection was done based on the suitability as well as accessibility for recording purposes. The presence of sand stone on one side of the river bank, extending from the bank to the river bed, made this site to be suitable for the installation of a gauging station. The rest of the river is underlined by alluvial sand as shown in Figures 3.10 and 3.11. The river at that section is straight for a distance of more than 100 m. Vegetation cover along the river is a mixture of evergreen thick bushes.

Figure 3. 10: Measuring the reduced levels as well as the distance using a Theodolite

A cross section survey was conducted to establish the cross section of the river (Figure 3.10). Three cross sections were done around that section. Based on the local knowledge on the maximum possible flow level at that point which was estimated to be about 1.5 m, two gauging plates with a maximum height of 2 m were installed at this station (Figure 3.11). The survey and installation of the gauging station was done with the assistance of Zimbabwe National Water Authority (ZINWA) staff. Installation of this gauging station was supposed to be done at the beginning of the rain season, in order to record discharge data which could be used for the calibration of a rainfall-runoff model.

Figure 3. 11: Installed gauging plates and the presence of rock materials at Rukomechi gauging station

3.3.7. Challenges

a. The delay in the installation of a gauging station on the Rukomechi River contributed to lack of flow data that led to calibration of the model to be done using a different catchment of slightly different characteristics.

b. Accessibility to some sub-catchment within the Mana Pools catchment area was one of the challenges. This is because, the study area falls under a national park, where road network connection is limited toward campsites.

c. Lack of monitoring stations at strategic sites such as Chirundu and immediately after the Kafue confluence with the Zambezi River, made it difficult to directly monitor the impacts of Kariba Dam operation as well as quantifying the actual Middle Zambezi flows that passes at Mana Pools.

CHAPTER 4

RESULTS AND DISCUSSION

Introduction

This chapter will present and discuss the results of this research. The results are presented and discussed in the following format: Firstly, the chapter will focus on pre and post impoundments Middle Zambezi River flow regime. The next section will deals with the effects of hydropower reservoirs on Middle Zambezi flow regime and impacts of reservoir operations on the Mana Pools flood plains and lastly, this chapter will discuss the results from SCS used in estimation of flows in un-gauged lower catchment flowing to the Mana Pools area.

4.1. Pre and post impoundments Middle Zambezi River flow regime

The Zambezi River discharge

The Victoria Falls differential mass curve (Figure 4.1) shows the cyclic events that had been taking place over the period 1924-2009. The falling curve indicates a dry period while the rising curve indicates the wet period. A wet period is shown as from 1950/51 to 1981/82. The year 1981/82 marked the beginning of a dry period.

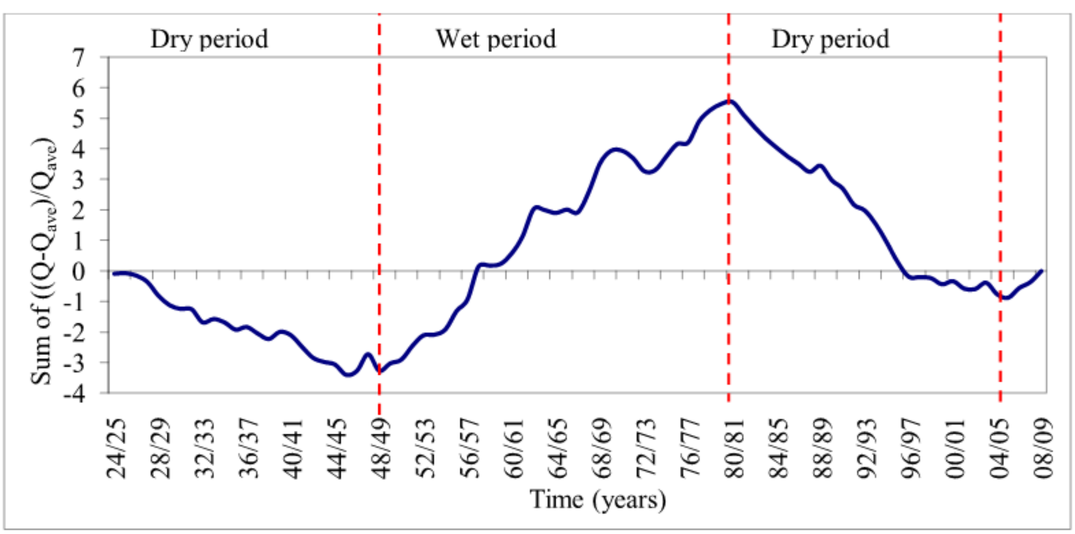

Figure 4. 1: Victoria Falls differential mass curve for the period of 1924-2009

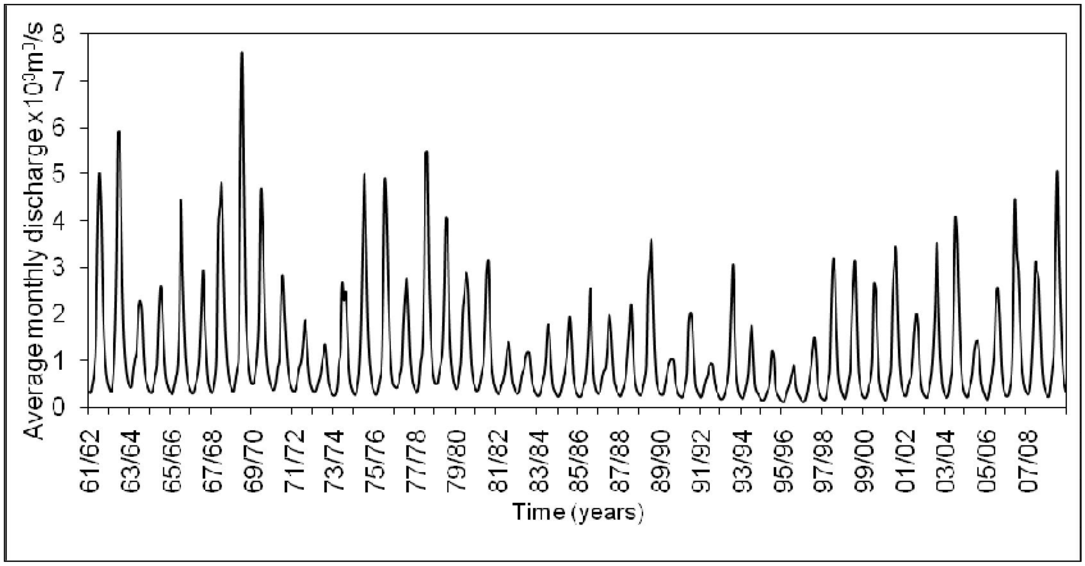

Figure 4. 2: Victoria Falls discharge for the period of 1961-2010

The Victoria Falls discharge for a period 1961-2010 shows a high peak flow in 1968/69, however the peak flows were lower in the 1980s (Figure 4.2). Peak flows started to pick up again as from 1997/98 onwards. This is supported by the Differential Mass Curve (Figure 4.1) which indicate that, there have been a wet season during the 1970s and a dry season starting in the early eighties (1981/82).

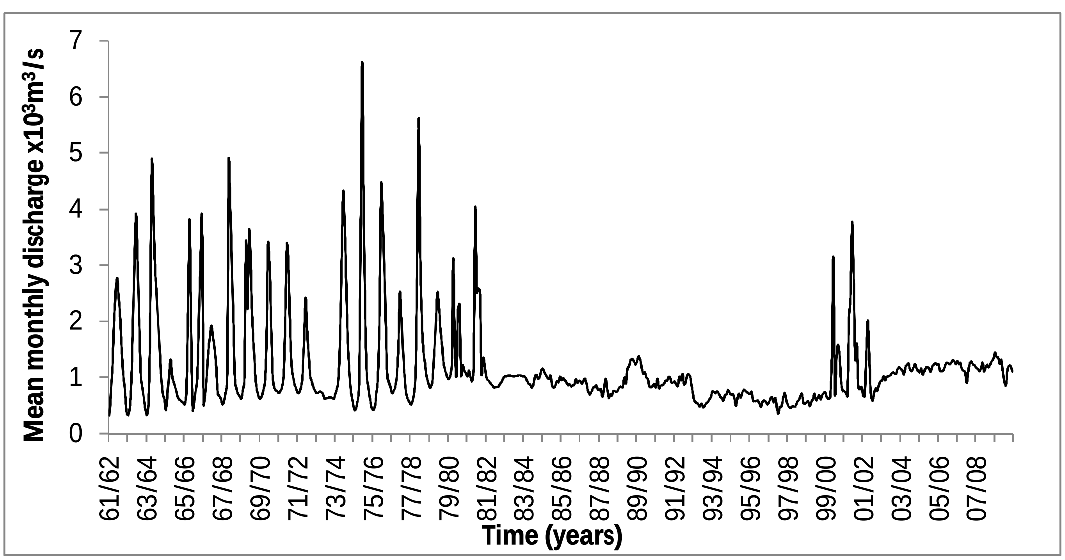

Figure 4. 3: Kariba outflows for the period of 1961-2009

The Kariba outflows curve became flattened as from 1981/82 which is the turning point from a wet period to dry period. This was maintained until the year 1999. Peak flows were only recorded between the years 1999/00-2001/02 when the sluice gates were opened (Figure 4.3). Three spillways were operated between February and July 2000 (ZRA, 2000). During the year 2001, three gates were also operated between January and June (ZRA, 2001).

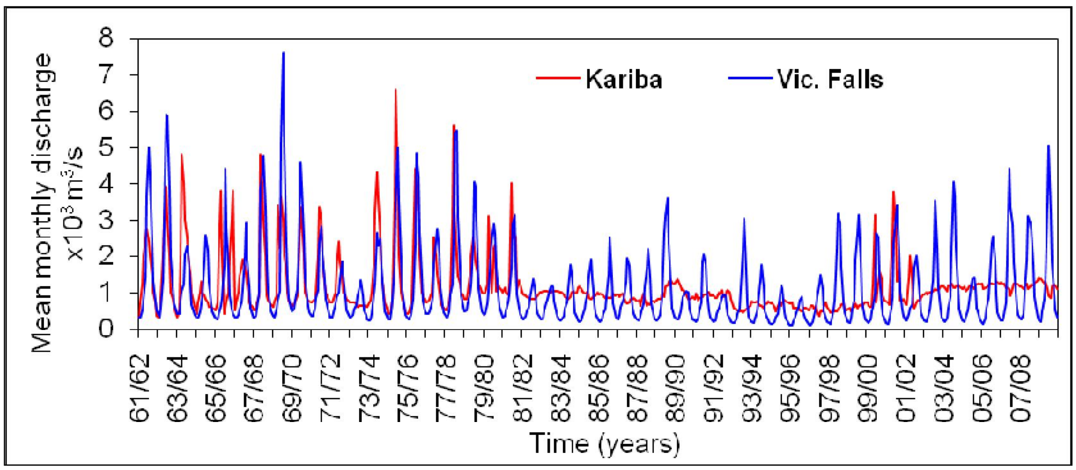

Figure 4. 4: Victoria Falls discharge and Kariba outflows (1961-2009)

The Comparison of Victoria Falls discharge and Kariba Dam releases (Figure 4.4) show a reduction in peak flows and more regularised flows from the Kariba Dam as compared to the Victoria Falls discharge. The Kariba releases become flattened as from the year 1981/82 which marked the transition from the wet to dry period. This increased the low flows that are usually recorded at Victoria Falls during October. The peak flows that are normally recorded at Victoria Falls were also reduced. Peak flows were only observed when the sluice gates were opened at Kariba, during 1999/00 and 2000/01 hydrological years. The Middle Zambezi Basin experienced Cyclone Eline in February 2000 and Cyclone Japhet in March 2003, (Madamobe, 2004). This may have caused the ZRA to release more water between 2000 and 2002.

The Middle Zambezi flow regime

The Middle Zambezi flow regime, recorded at Victoria Falls attains a peak flow during April, with the low flows being recorded in October (Figure 4.5). The flow regime of the Middle Zambezi downstream the Kariba, attains its peak flow during March. The peak flow observed during March should be due to the operation of sluice gates that releases excess water coming from the local catchment area of Lake Kariba within Zimbabwe and Zambia. This is done in order to make room for possible floodwater coming from the upper Zambezi Basin.

The presence of Kariba Dam reduced the high peak flows recorded at Victoria Falls (2483 m^3/s) by 44% to 1552 m^3/s but increased the low flows in October (281 m^3/s) by 70 % to 782 m^3/s.

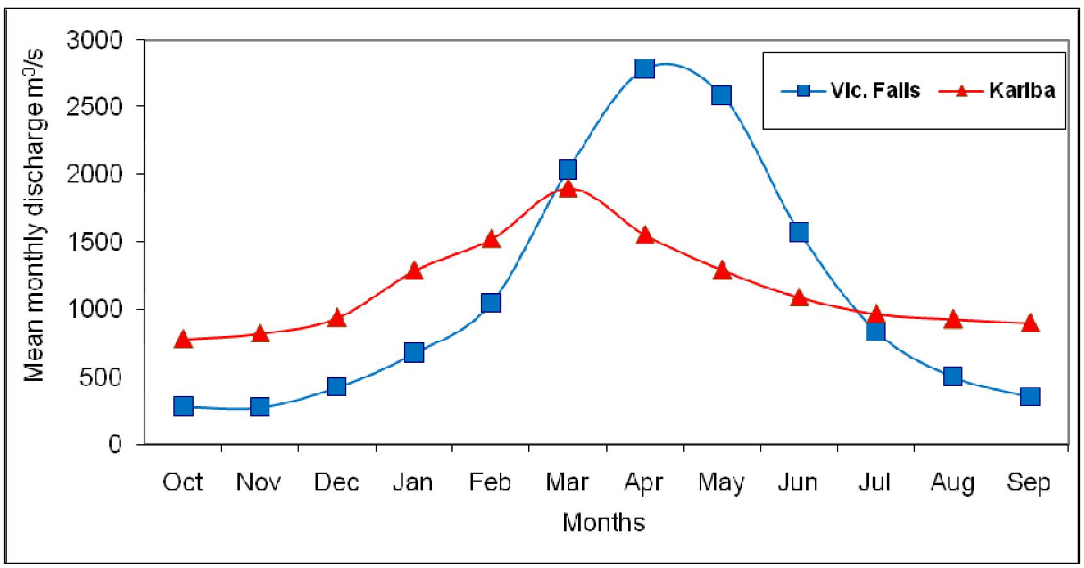

Figure 4. 5: Middle Zambezi river flow regime

Table 4. 1: Middle Zambezi River descriptive statistics

Parameters	Victoria Falls	Kariba Dam
Mean (m^3/s)	1025	1098
Standard Deviation (m^3/s)	837	256
Coefficient of Variation (%)	82	23

The Victoria Falls mean monthly flows for the period of 1973-2009, shows a high standard deviation of (837 m^3/s) and a high coefficient of variation of 82%, as compared to the Kariba outflows with both low standard deviation (256 m^3/s) and coefficient of variation (23 %) for the same duration (Table 4.1). The high standard deviation and coefficient of variation shown by the Victoria Falls mean monthly flows indicate a natural flow regime of the Zambezi River, while the low standard deviation and coefficient shown by the Kariba mean monthly outflows, indicate that, flows are more distributed around their mean with less pronounced variation in flows throughout the year. This is due to regularization of flows through the reservoirs operation that is more centered towards hydropower production.

The Kafue River discharge

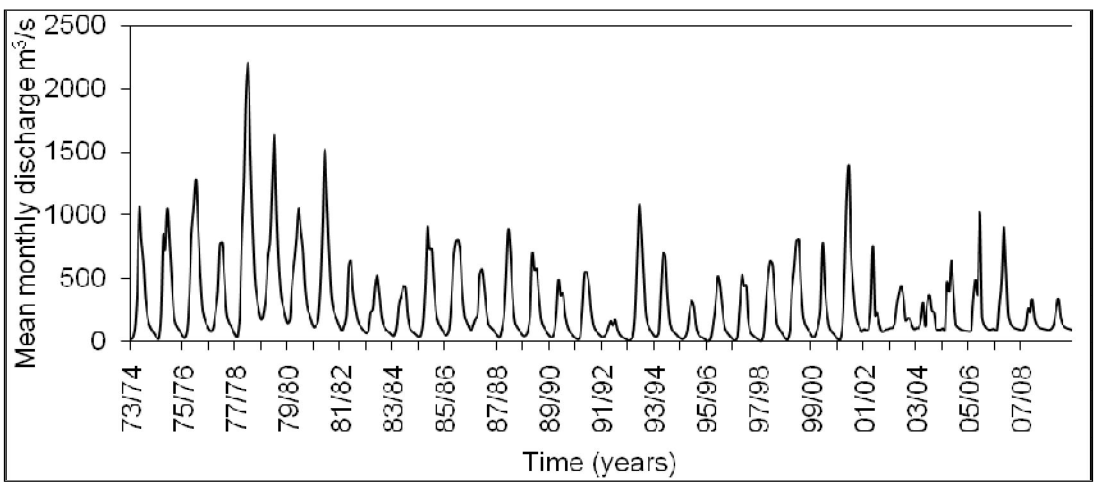

Figure 4. 6: Hook Bridge discharge for the period 1973-2010

The discharge at Hook Bridge shows a reduction I high peak flows as from the year 1981/82, with high peak flows only observed during 1992/93 and 200/01 hydrological years. The year 1981/82 marked the transition for the wet period to the dry period in the Kafue River system (Appendix 3), as observed in the Middle Zambezi River.

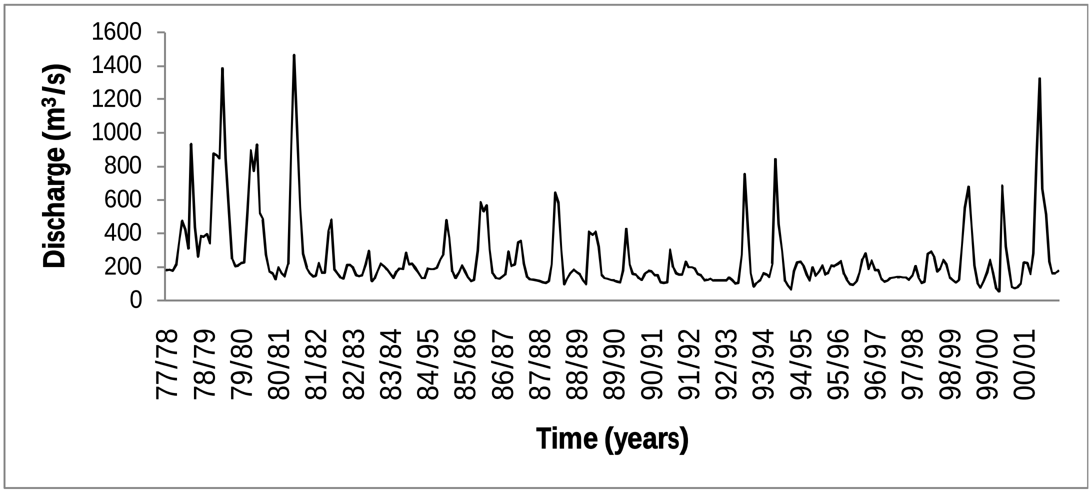

Figure 4. 7: Itezhi-tezhi discharge during the period, 1977-2001

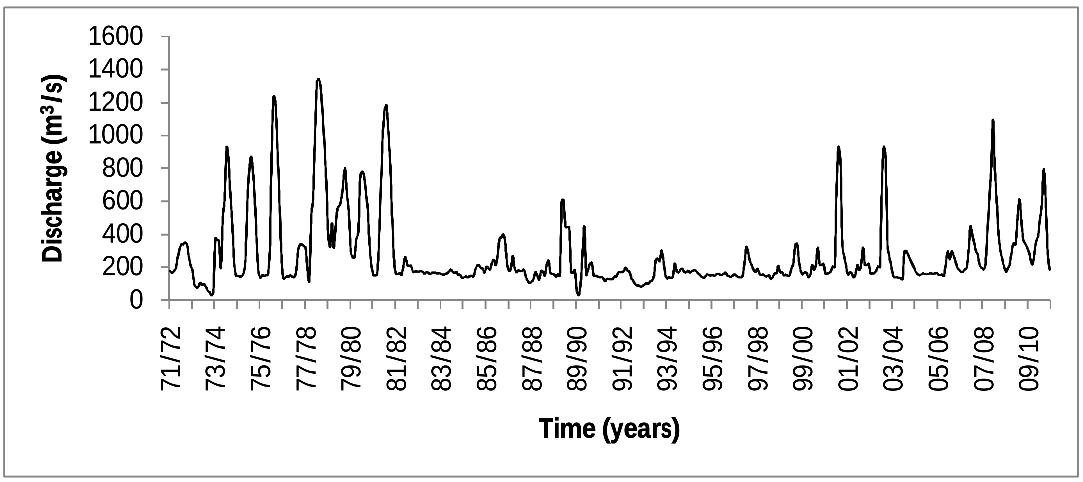

Figure 4. 8: Kafue Gorge discharge during the period, 1971-2010

The outflow from the Kafue Gorge Dam, also follow the same trend as that of Kariba, with more regularised flows being observed as from 1981/82 hydrological year (Figure 4.8). However for the Kafue Gorge, there are several peak flows observed, which may be due to the 300 m^3/s prescribed flows, released every March from Itezhi-tezhi for the maintenance of the Kafue flats ecosystem (Beilfuss and dos Santos, 2001). The peak flows were also observed in the Itezhi-tezhi hydrograph (Figure 4.7).

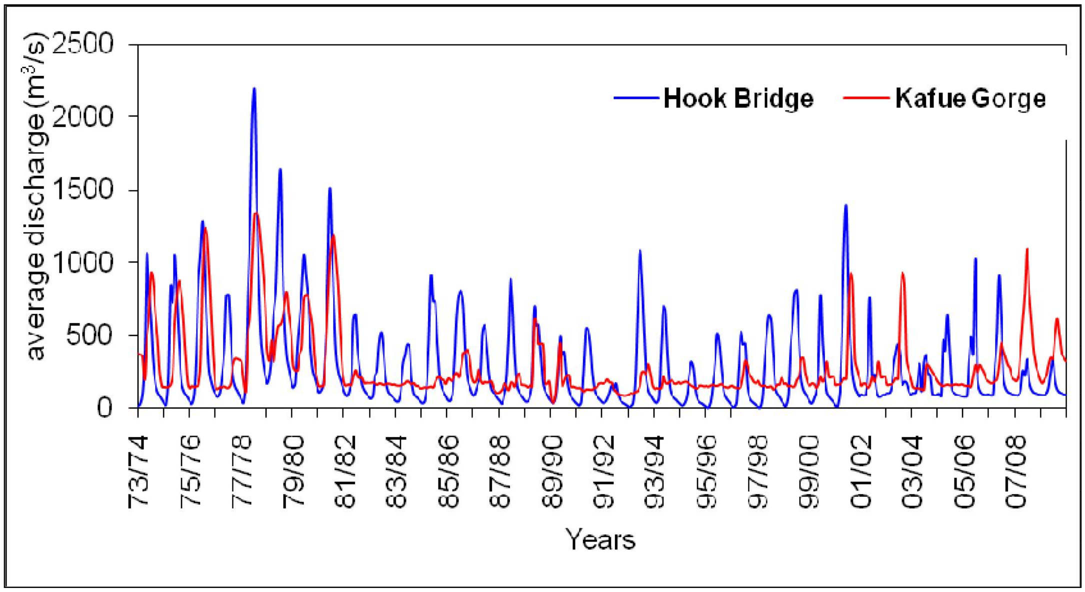

Figure 4. 9: Hook Bridge and Kafue Gorge discharge

The Kafue Gorge outflows shows a flattened curve after 1981/82 hydrological year, but with some peak flow events (Figure 4.9). Overally, from the year 1981/82, the low flow that normaly fell below 100 m^3/s at Hook Bridge could no longer reach such low levels downstream of Kafue Gorge, as the operation of the hydropower generation at Kafue Gorge requires a minimum flow of 120 m^3/s.

Kafue River flow regime

The flow regime at Hook bridge attain its peak during March, and low flows during October. The peak flow downstream of Kafue gorge is attenuated and translated to occur in May (Figure 4.10). The low flows are still observed in October as is observed at Hook Bridge. The presence of Itezhi-tezhi and Kafue Gorge Dams, had attenuated the Kafue River peak flows (723 m^3/s) by 57 % to 413 m^3/s in May. The low flows in October is increased by 64 % from 64 m^3/s to 180m^3/s.

Lack of flow data downstream of Kafue Gorge, prior to construction of the two dams, makes it difficult to isolate the effects of the Kafue Flats on the flow regime observed at Hook Bridge. As a largest flood plain, Kafue Flats may also contribute to the attenuation and translation of Kafue flows on its downstream.

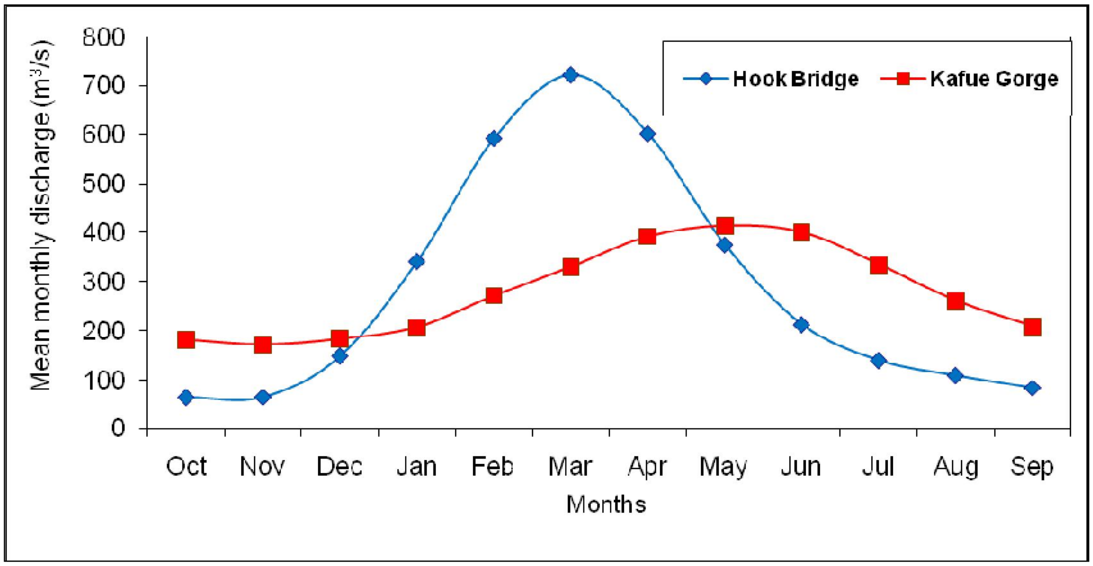

Figure 4. 10: Hook Bridge discharge and Kafue Gorge outflows 1973-2001

Table 4. 2: Kafue River descriptive statistics

Parameters	Hook Bridge	Kafue Gorge
Mean (m^3/s)	288	279
Standard Deviation (m^3/s)	236	92
Coefficient of Variation (%)	82	34

The Kafue Gorge discharge outflows shows a low stadard deviaton (92 m^3/s) and coefficient of variation (34 %) as compared to the upstream (Hook Bridge) with a standard deviation of 236 m^3/s and a coefficient of variation of 82 % (Table 4.2). This was done for the period of 1973-2010. The low standard deviation for Kafue gorge outflows imply that, the discharge from Kafue Gorge are more distributed around its mean, hence the variation among mean monthly flow is less pronounced. This is also supported by the low coefficient of variation. The high coefficient of variation shown by the upstream (Hook Bridge) flows indicate the natural flow pattern, with low flows and high peak flows.

The Middle Zambezi River flow at Mana Pools

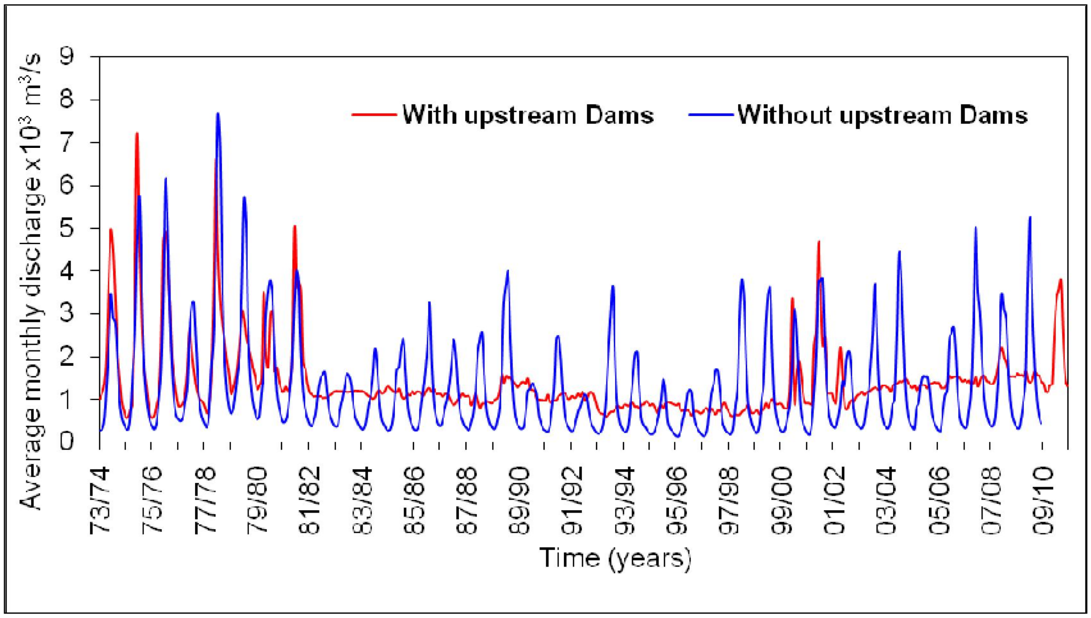

Figure 4. 11: Middle Zambezi flow at Mana Pools

Figure 4.11, Mana Pools flows with and without the presence of upstream dams, shows a reduction in peak flows and an increase in low flows as from 1982 until 2010. This flow pattern is more influenced by the releases from Kariba Dam which is the largest dam as compared to the other two on the Kafue River. Kariba Dam releases contributes about 80% of the total flows that passes at Mana Pools, while the Kafue system accounts for only 20%.

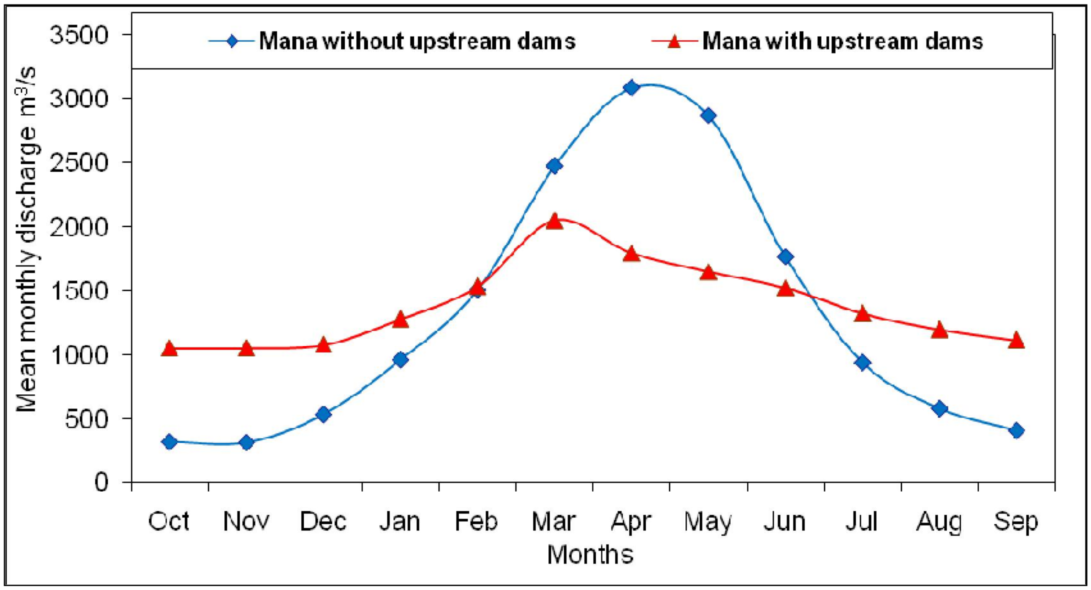

Figure 4. 12: Middle Zambezi flow regime at Mana Pools

The peak flow events at Mana Pools could be observed during the April month without the presence of upstream dams. However with the presence of upstream dams, the peak flow is observed a month earlier during March. This is a clear indication that, the flow regime at Mana Pools flood plains is no loger influenced by the Upper Zambezi flows but by the operation of the upstream reservoirs. This flow regime resembles that of the Kariba releases. Kariba Dam, needs to release water earlier during the rain season, to make room for the upper Zambezi flood. As shown in Figure 4.12, the presence of upstream Dams reduced the peak flows at Mana Pools (3085m^3/s) by 42 % to 1793 m^3/s and increased the low flows (320m^3/s) by 70 % to 1052 m^3/s.

Table 4. 3: Descriptive statistics for Mana Pools flow regime

Parameters	Man Pools without upstream dams	Man Pools with upstream dams
Mean(m^3/s)	1313	1388
Standard Deviation (m^3/s)	1015	324
Coefficient of Variation (%)	77	23

During the period of 1973-2010, the behaviour of what could be Mana Pools flow regime follows the flow pattern of both Victoria Falls and Hook Bridge, which are natural flows on Zambezi and Kafue Rivers respectively. Without the presence of upstream dams, the Middle Zambezi at Mana Pools shows a high standard deviation (1015 m^3/s) and high coefficient of variation (77 %) as shown in table 4.3. The Middle Zambezi flow regime at Mana Pools, with the presence of Kariba and the Kafue reservoirs, shows a low standard deviation (324 m^3/s) and coefficient of variation (23 %) among average monthly flows as shown in Table 4.3. The presence of upstream hydropower reservoirs (Kariba, Itezhi-tezhi and Kafue Gorge), affect the normal variation in average monthly flows at Mana Pools. This happens as a result of almost averaged flows released through turbines.

t-test statistics

Table 4. 4: t-test statistics between upstream and downstream stations' mean annual flows

Mean annual runoff	Calculated *t value*	*t*-critical (2-tails)	*P* value for *t*	Remarks
Victoria Falls and Kariba flows	-1.11	1.99	0.27	Not significant
Hook Bridge and Kafue Gorge flows	0.21	1.99	0.83	Not significant
Mana Pools with and without upstream dams	-0.29	2.00	0.77	Not significant

From Table 4.4, all the comparisons show high *t* critical as compared to the calculated *t* values. This means that, there is no significant difference in the mean annual runoff between upstream and downstream stations. This is shown by the *t*-test at 95% confidence level. Therefore, the variations observed at monthly level did not have any effect on the mean annual flows.

4.2. Effects of reservoirs operation on the Middle Zambezi flow regime at Mana Pools

Zambezi River Flow Duration Curves

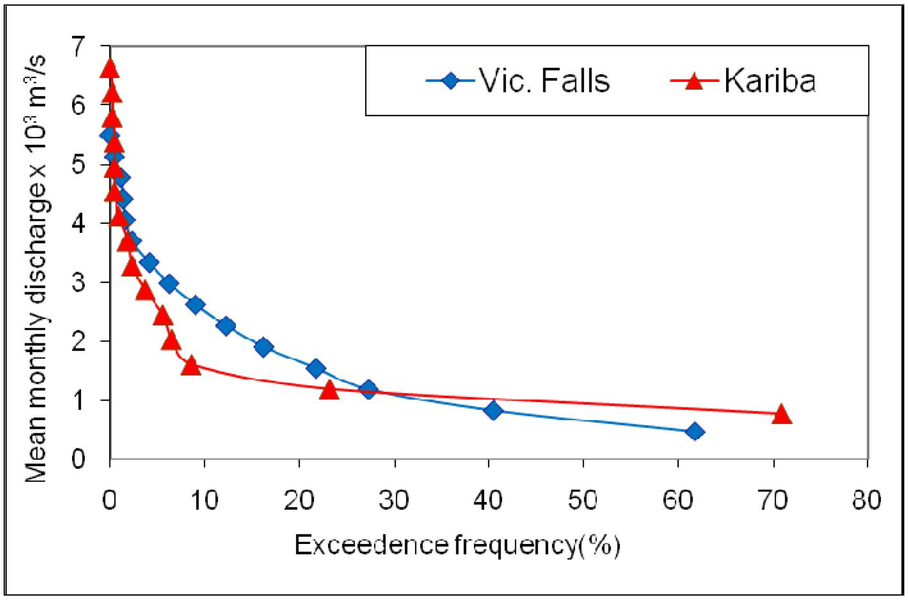

Figure 4. 13: Victoria Falls and Kariba discharge FDC

The presence of Kariba Dam resulted in increased exceedance frequencies for 38 % of mean monthly flow, by 9% and reduced the exceedance frequencies of 13% of the mean flow by 19% (Figure 4.13). The operation of Kariba hydropower scheme increased the exceedance frequency of low flows recorded at the upstream station (Victoria Falls). Kariba hydropower production requires a combined flow of 1300 m^3/s to generate electricity on both north and south banks (Shela, 2000).

Kafue River FDC

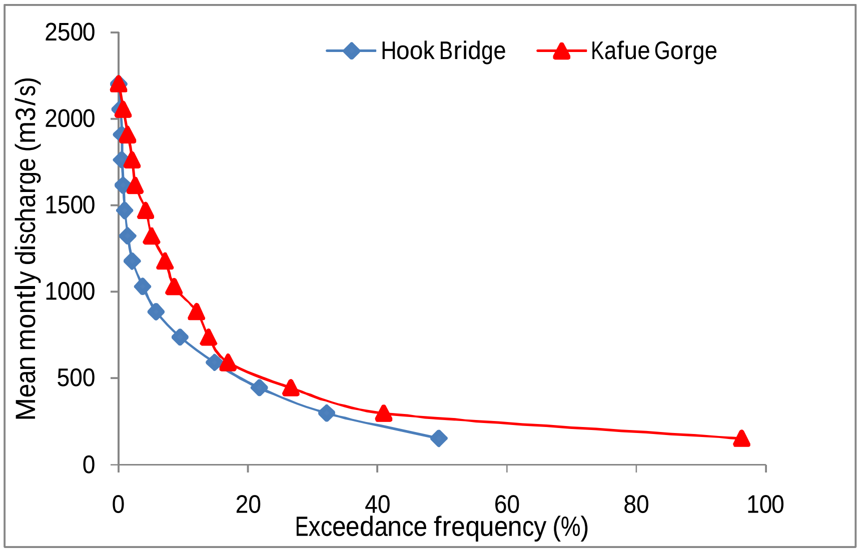

Figure 4. 14 Hook Bridge and Kafue Gorge FDC

The operation of Itezhi-tezhi and Kafue Gorge Dam shows an increase in exceedance frequencies for 50 % of the mean monthly flow by 48% (Figure 4.14). Itezhi-tezhi which was constructed to maintain the supply of 120 m^3/s, plus 300 m^3/s environmental flows for the Kafue Gorge and Kafue Flats respectively may have contributed to the reduction in exceedance frequency of low flows.

Mana Pools FDC

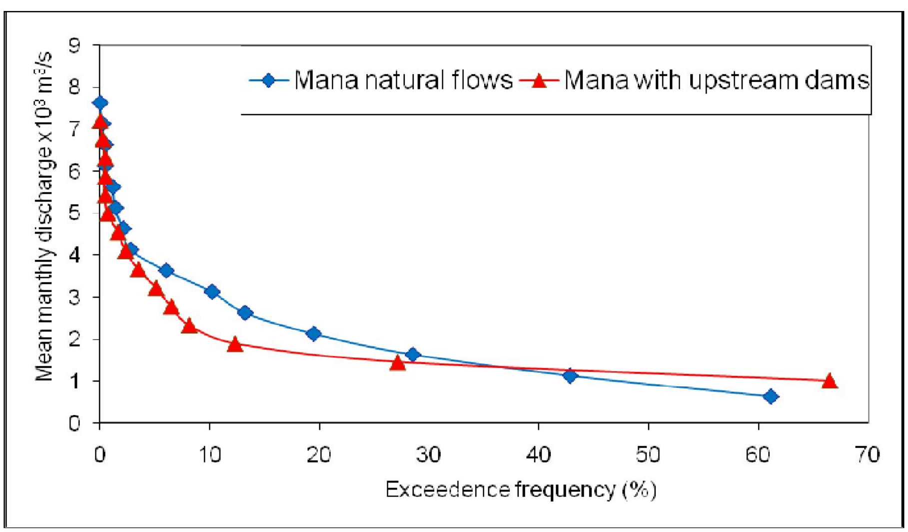

Figure 4. 15: Mana Pools FDC

Overall, the presence of upstream reservoirs, have resulted in increases of exceedance frequencies for 38% of mean monthly flows by 5% and a reduction in exceedance frequencies of 14% of the mean monthly flows by 17% as shown in Figure 4.15. The 38% of mean monthly flows is constituted mainly of low flows, while the 14% is a combination of medium to high flows.

Monitoring the impact of Kariba spillway releases at Chirundu

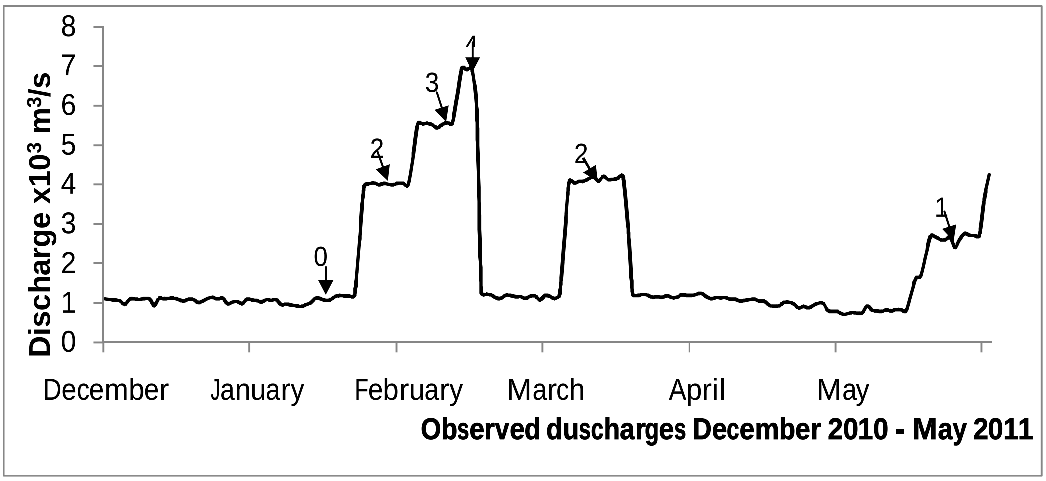

Figure 4. 16: Kariba releases 2010/2011 the numbers indicate the number of sluice gates opened

Figure 4.16 shows the daily flow behaviour when flood gates were operated at Kariba Dam during January to May 2011. The numbers indicate the number of flood gates opened at each stage. The maxim discharge with four flood gates opened was recorded to be 6951 m^3/s. This discharge has not been exceeded both upstream and downstream of Kariba Dam during 1993-2009, as shown by Figure 4.17.

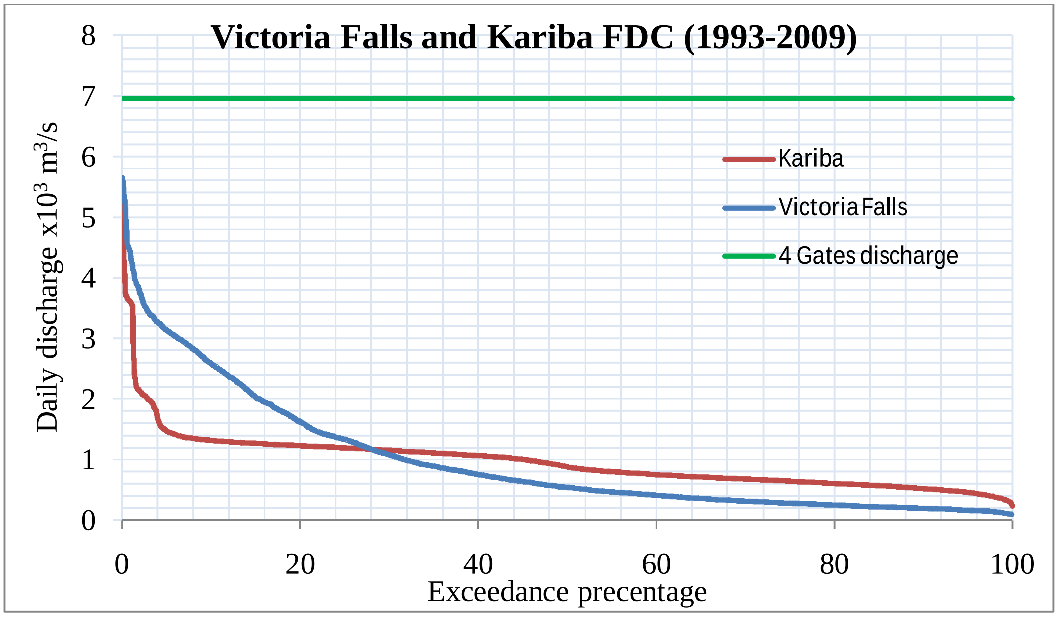

Figure 4. 17: Kariba FDC 1993-2009

However this discharge was exceeded 0.29 % of time at Victoria Falls between 1924 and 2009 (Appendix 9). This means that even without the Kariba Dam operation, such flow event could be observed at Mana Pools although with a very low probability of occurrence.

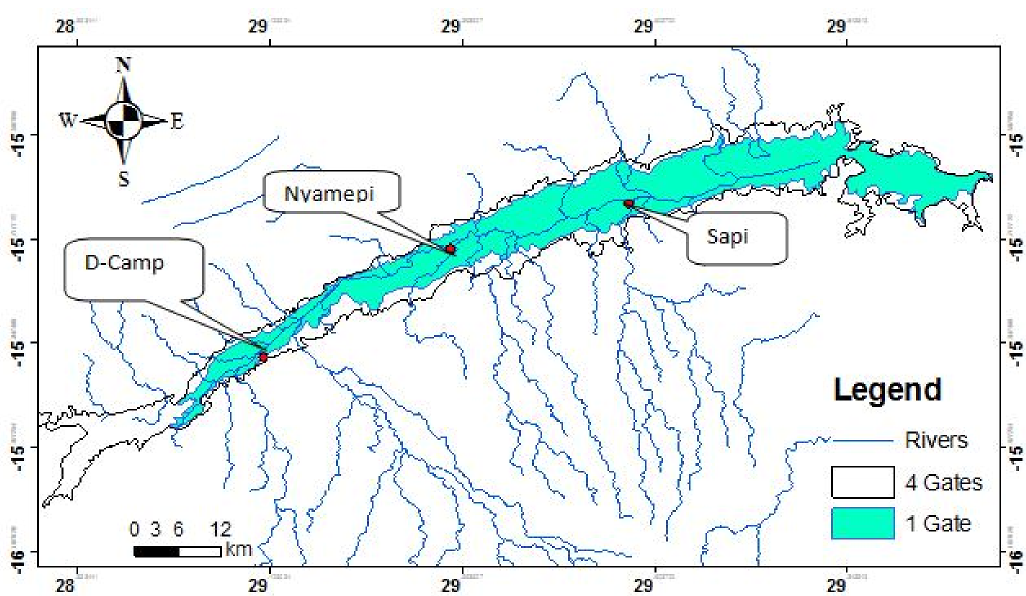

Figure 4. 18: Extent of flood mark after operation of flood gates at Kariba Dam (February - May 2011)

The flood mark of 376 m elevation recorded at Chirundu, with four Kariba sluice gates opened at Kariba Dam, translated to 9.07 km^2 of Mana Pools floodplain areas being flooded. The flood magnitude with one sluice gate opened at Kariba at 367 m water level, also recorded at Chirundu, translated to a flooded area of 5 km^2 of the Mana Pools flood plains.

In both scenarios, the Nyamepi and Sapi Camps in the Mana Pools area appear to be flooded (Figure 4.16). However this was only the case when four gates were opened at Kariba (corresponding to 6951 m^3/s). The seemingly flooded area around Nyamepi Camp may be due to the presence of several pools around it which may be filled by the Zambezi water and connect to form channels. Under normal circumstances the three campsites are safe (99 % of the time) from flooding, even without the presence of Kariba Dam.

Apart from campsites that got flooded, wildlife also fell victim to the flood events. Buffaloes that normally graze within the flood plains, found themselves being surrounded by flood water on some islands as shown in Figure 4.20.

Figure 4. 19: A group of buffaloes surrounded by water on an island after four flood gates were opened at Kariba

Zambezi River cross section at Chirundu

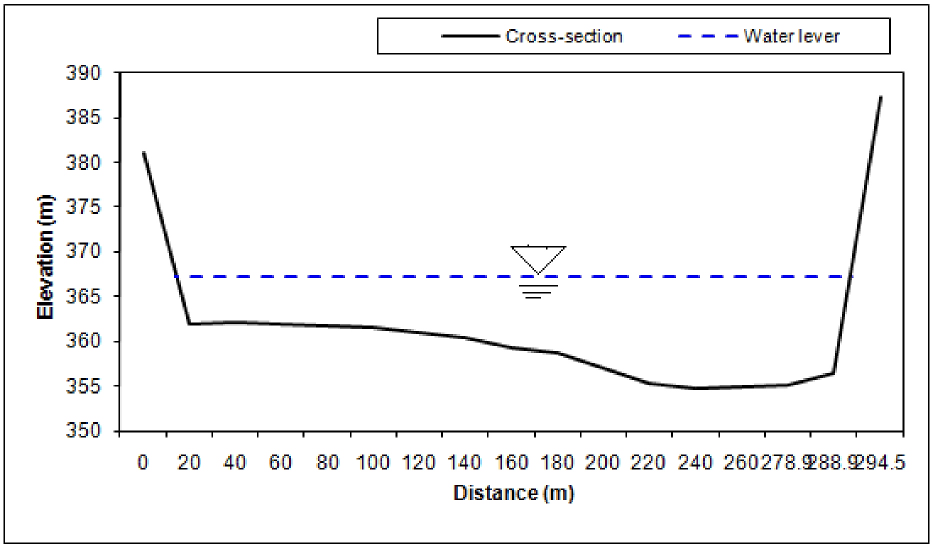

Figure 4. 20: Zambezi River cross section at Chirundu Bridge on 23/05/11

The Zambezi River cross section (Figure 4.20) was done at the old Chirundu Bridge. The water level of 367 m above sea level was recorded during the time when one sluice gate was opened at Kariba Dam. The slope area method using Manning Equation calculated the discharge at Chirudu Old Bridge to be equals to 2825 m^3/s. As compared to the actual discharge recorded at Kariba (2665 m^3/s) on the same day, the slope area method over estimated the discharge by 160 m^3/s which is about 6 % of the actual discharge at Kariba Dam. This difference may be due to inaccuracy in measuring the cross-section, since no proper survey was done or errors in the estimation of the hydraulic parameters.

4.3. Estimation of runoff from ungauged catchments

4.4. Nyakasanga soil analysis

Table 4. 5: Nyakasanga soil texture characteristics

Sample ID	Sand %	Silt %	Clay %	Soil type
35 (20cm)	72.7	14.7	12.5	Sandy loam
35 (30cm)	66	19	15	Sandy loam
38 (20cm)	78.8	10.6	10.6	Sandy loam
38 (30cm)	81.7	10.2	8.1	Sandy loam
42 (20cm)	83.6	8.2	8.2	Sandy loam
42 (30cm)	85.2	8.5	6.3	Sandy loam
44 (30cm)	87.2	6.4	6.4	Sandy loam
53 (30cm)	76.3	13	10.7	Sandy loam

The result from soil analysis shows that, the area sampled is predominantly sandy surface. Classification based on USDA soil triangle, classified this soil as sandy loam. This layer is however limited to a depth not more than 30 cm beyond that, there is a hard compact layer (Table 4.5). The Zimbabwean soil classification map also indicates that the soils around Nyakasanga are of Lithosol type, which is less than 25cm deep, overlaid by weathering rock or gravel. The FAO soil map classified the soils around Nyakasanga as predominantly Leptosols (see Appendix 6), which are the soils with high runoff potential. This corresponds well with the Zimbabwean soil classification.

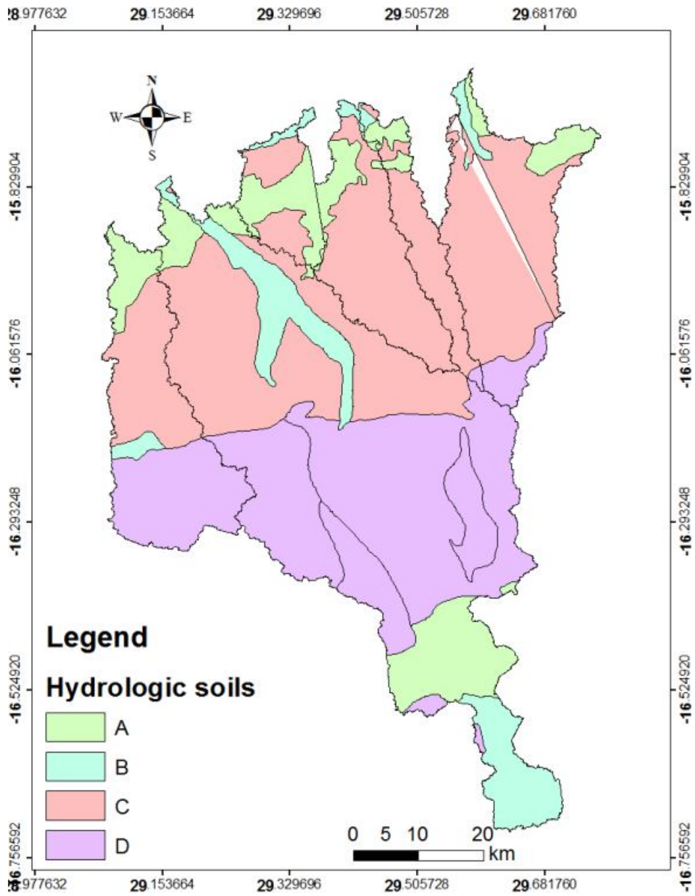

Figure 4. 21: Mana Pools Hydro-soils

Nyakasanga vegetation cover

The vegetation cover done on a section of Nyakasanga corespond well to the GlobCover map (Figure 4.23), with most part of the area beig covered by either encroached bushes and mixed with broadleaved trees. The survey concentrated along the road to Chirundu, only a small portion fall within the catchment boundaries. The landcover classification was confirmed to be correct at the sampled area as most of the points fall within the forestland, with only one point (Marongora) falling within the rangeland. Marongora office is located on the Zambezi escapement, a mountaineous area with sparced vegetation.

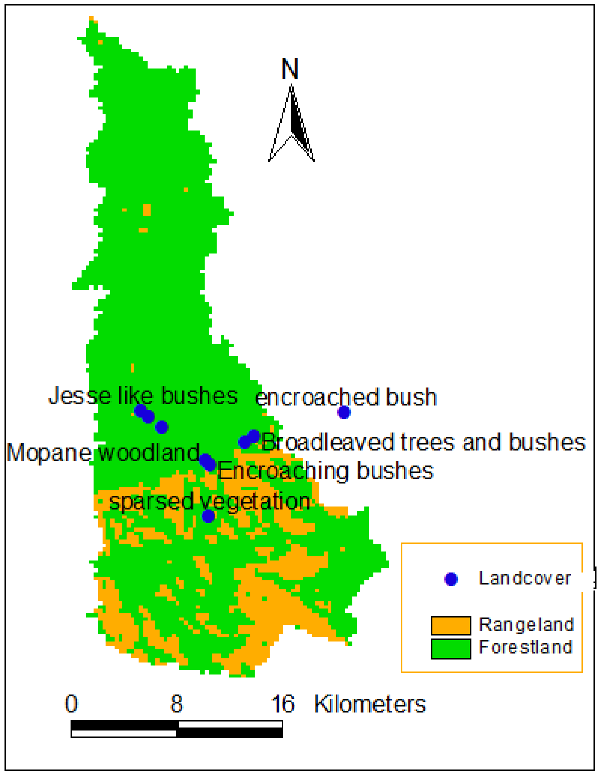

Figure 4. 22: Nyakasanga vegetation cover

4.5. Calibration and validation of SCS

After the first classification, the soil characteristics used gave the results shown in Figure 4.24. the relative volume error with the first reclassification was -16 which is outside the acceptable range. After another reclassification, the comparison between measured and computed discharge gave an error of -7 which is within the acceptable range of -10 % to 10% (Figure 4.25). This means that, this model under

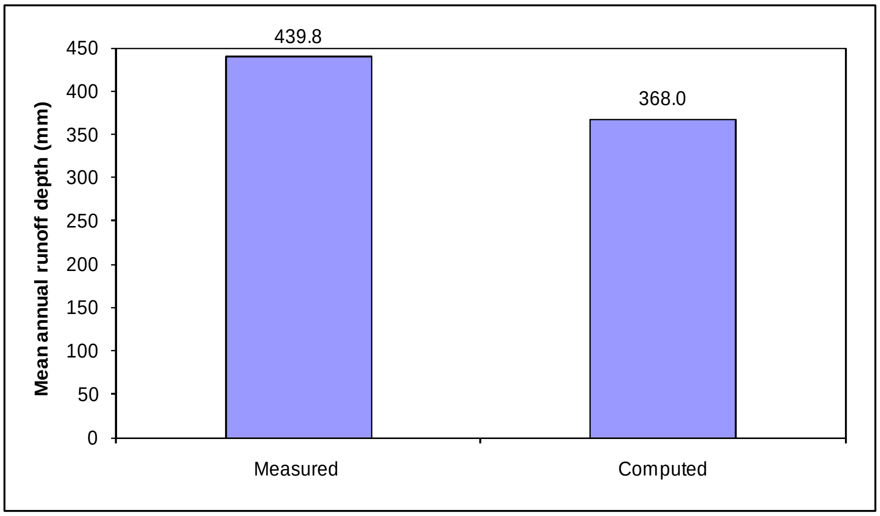

Figure 4. 23: Measured and computed Upper Musengezi flows before calibration

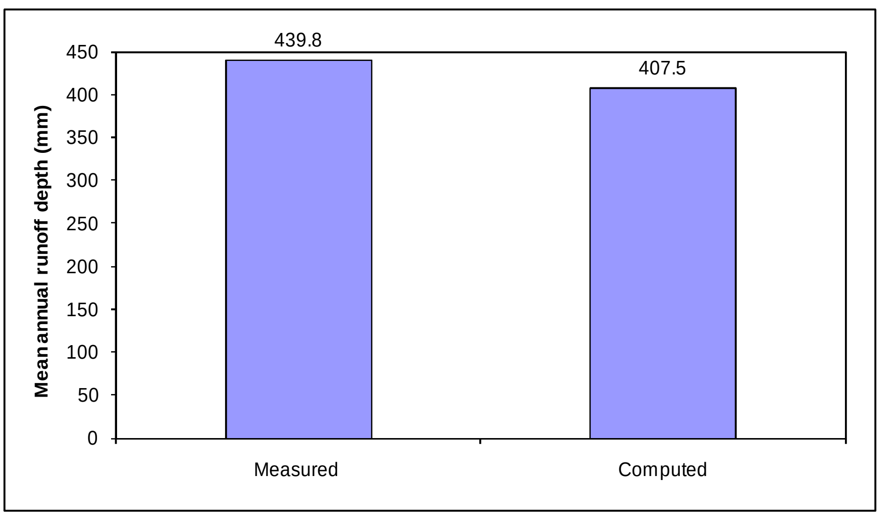

Figure 4.24: Measured and computed Upper Musengezi flows after calibration

1.2.3. SCS results

Table 4. 6: SCS direct runoff per catchment

Catchment	Area (km^2)	Weighted CN	S (mm)	Annual Precipitation (mm/year)	Runoff depth (mm)	Runoff Volume x 10^6 m^3/year
Chiruwe	385	81	58	672	607	234
Mbera	436	84	49	678	623	272
Murowa	191	70	109	715	599	115
Nyakasanga	548	83	51	729	671	368
Rukomiche	2377	83	53	662	602	1431
Sapi	605	82	57	673	609	368
Total contribution to the Mana Pools						**2787**

Nyakasanga catchment recorded the highest mean annual runoff depth (671 mm/year) followed by Mbera (623 mm/year), while Rukomechi is the lowest in terms of mean annual runoff depth producing 602 mm/year (Table 4.6). The results from SCS model shows that, the mean annual runoff depth is directly related to the amount of rainfall received in a catchment. Nyakasanga which shows a high runoff is also the highest in terms of mean annual rainfall as compared to the other five catchments. Rukomechi catchment on the other hand shows a low runoff potential as a result of low mean annual rainfall recorded.

In terms of runoff volume, Rukomechi contribute the highest mean annual runoff (1431 Mm^3/year) followed by Sapi (368 Mm^3/year). Murowa contribute the least mean annual runoff volume (115 Mm^3/year). Runoff volume is a product of catchment area and runoff depth, therefore Rukomechi which is largest catchment produces a high runoff volume. Although Mbera catchment is the smallest in terms size, it has a high runoff potential with a CN of 88 as compared to Murowa (CN of 73) which happened to contribute the least volume. The whole catchment, with a total area of 4286 km^2, contributes 2787 Mm^3 per year. This is 7.2 % of the total flow that passes at Mana Pools flood plain.

4.6. Gauging of Rukomechi River

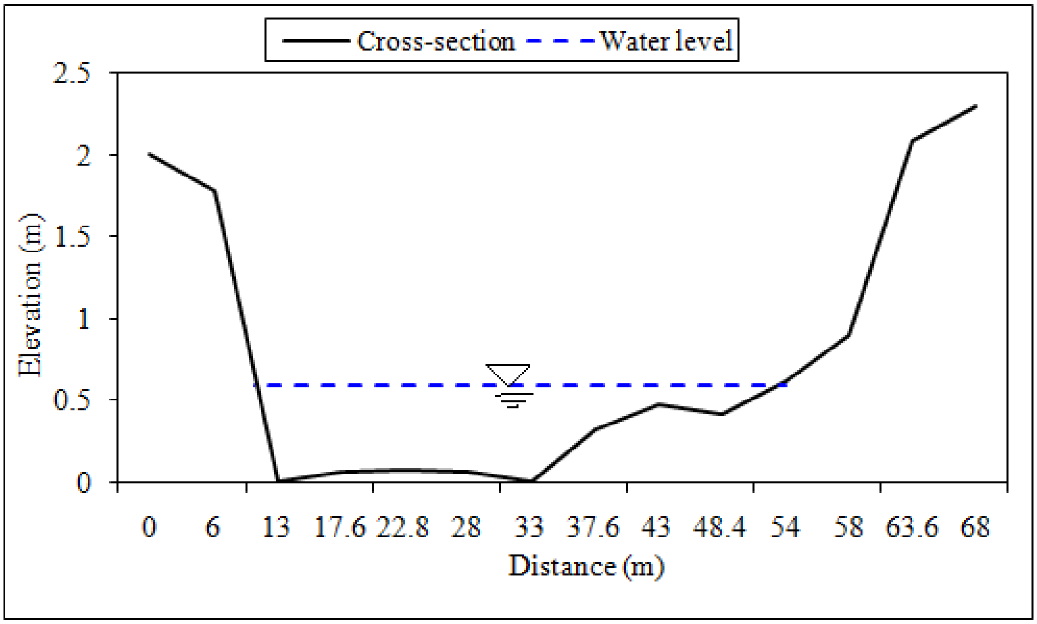

Figure 4. 25: Rukomechi River cross-section

The rating curve (Figure 4.26) was drawn using the mean annual runoff depth of 0.592m, estimated by SCS. The water level (Figure 4.19) also shows the same level that was estimated using the SCS, for an area upstream of the new gauging station. Discharge at 0.592 m water level is shown to be about 29 m^3/s.

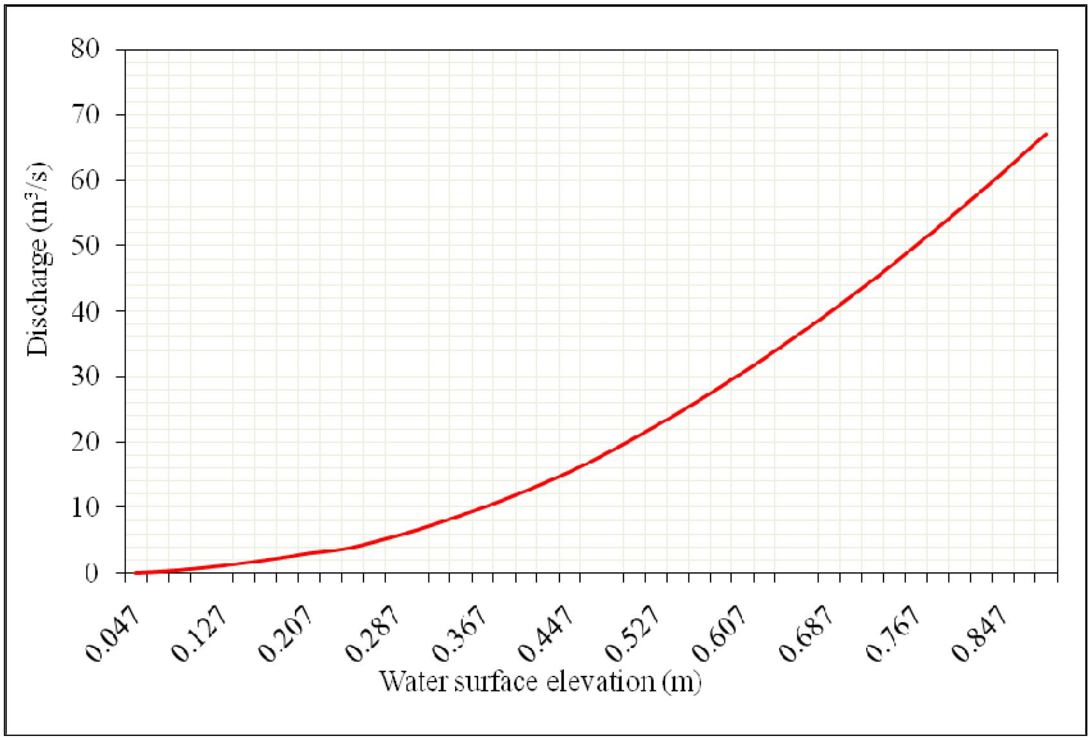

Figure 4. 26: Rukomechi River rating curve

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusion

a. The results from this study indicated that, the presence of upstream hydropower reservoirs, have altered the natural flow regime of the Middle Zambezi River and the Mana Pools flood plains. The high peak flows were reduced by 42 % and minimum flows were increased by 70 %. These changes in natural flow regime are more pronounced at a monthly level than at annual levels.

   The increase in high peak flows may be of an advantage to some aquatic organisms, while it may affect other organisms that had adapted to the natural dynamics of high and low flow periods prior the establishment of hydropower reservoirs.

b. The operation of upstream dams has reduced the exceedance frequency of high flows by 17 % while increasing the exceedance frequency of low flows by 5 %. Although the presence of upstream reservoirs reduced the peak flows in the Middle Zambezi, their operations may result in undesired flooding of downstream areas.

c. The ungauged Mana Pools catchment in Zimbabwe contributes 7.2 % of the Middle Zambezi River flow at Mana Pools floodplain.

Recommendations

a. Opening of flood gates at Kariba Dam should directly be communicated to the communities living in low lying areas well in advance, in order to prepare for any possible flood.

Further research work

i. There is a need for studies that focuses on the effects of changes in flow regime on specific vegetations or aquatic organisms, in order to suggest management measures that aim at improving the operation of hydropower reservoirs in order to release appropriate flows as per environmental requirement.

ii. Now with a newly installed gauging station on the Rukomechi River, further study should be done in the same area, utilising Rukomechi flows to calibrate the rainfall runoff model, in order to estimate flows in adjacent ungauged catchments.

iii. Due to the underlying sand bed in the Rukomechi River, there is a need to install piezometers at the station in order to support the rating curve by measuring the subsurface flow.

iv. A gauging station should also be installed at Chirudu Bridge in order to monitor the effects of Kariba Dam operation on the Mana Pools ecosystem.

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APPENDICES

Appendix 1: Flow frequencies tables used to construct flow duration curves

Victoria Falls

Classes	Min	Max	Frequency	Cumulative	Non exceedance %	Exceedance %
class 1	118.5	475.5	165	165	38.19	61.81
class 2	476.5	833.5	92	257	59.49	40.51
class 3	834.5	1191.5	57	314	72.69	27.31
class 4	1192.5	1549.6	24	338	78.24	21.76
class 5	1550.6	1907.6	24	362	83.80	16.20
class 6	1908.6	2265.6	17	379	87.73	12.27
class 7	2266.6	2623.6	14	393	90.97	9.03
class 8	2624.6	2981.7	12	405	93.75	6.25
class 9	2982.7	3339.7	9	414	95.83	4.17
class 10	3340.7	3697.7	8	422	97.69	2.31
class 11	3698.7	4055.7	3	425	98.38	1.62
class 12	4056.7	4413.8	1	426	98.61	1.39
class 13	4414.8	4771.8	1	427	98.84	1.16
class 14	4772.8	5129.8	3	430	99.54	0.46
class 15	5130.8	5487.8	2	432	100.00	0.00

Kariba

Classes	Min	Max	Frequency	Cumulative	Non-exceedance %	Exceedance %
class 1	354.0	771.6	126	126	29.17	70.83
class 2	772.6	1190.2	206	332	76.85	23.15
class 3	1191.2	1608.7	63	395	91.44	8.56
class 4	1609.7	2027.3	9	404	93.52	6.48
class 5	2028.3	2445.9	4	408	94.44	5.56
class 6	2446.9	2864.5	8	416	96.30	3.70
class 7	2865.5	3283.1	6	422	97.69	2.31
class 8	3284.1	3701.7	2	424	98.15	1.85
class 9	3702.7	4120.2	4	428	99.07	0.93
class 10	4121.2	4538.8	2	430	99.54	0.46
class 11	4539.8	4957.4	0	430	99.54	0.46
class 12	4958.4	5376.0	0	430	99.54	0.46
class 13	5377.0	5794.6	1	431	99.77	0.23
class 14	5795.6	6213.1	0	431	99.77	0.23
class 15	6214.1	6631.7	1	432	100.00	0.00

Hook Bridge

Classes	Min	Max	Frequency	Cumulative frequency	Non-exceedance%	exceedance%
class 1	30.0	123.8	30	30	8.33	91.67
class 2	124.8	218.5	211	241	66.94	33.06
class 3	219.5	313.3	35	276	76.67	23.33
class 4	314.3	408.0	28	304	84.44	15.56
class 5	409.0	502.8	10	314	87.22	12.78
class 6	503.8	597.5	6	320	88.89	11.11
class 7	598.5	692.3	11	331	91.94	8.06
class 8	693.3	787.0	7	338	93.89	6.11
class 9	788.0	881.8	6	344	95.56	4.44
class 10	882.8	976.5	5	349	96.94	3.06
class 11	977.5	1071.3	3	352	97.78	2.22
class 12	1072.3	1166.0	2	354	98.33	1.67
class 13	1167.0	1260.8	3	357	99.17	0.83
class 14	1261.8	1355.5	3	360	100.00	0.00

Kafue Gorge

Classes	Min	Max	Frequency	Cumulative frequency	non exceedance%	%exceeded
Class 1	6.5	162.2	165	165	49.11	50.89
Class 2	163.2	318.9	55	220	65.48	34.52
Class 3	319.9	475.6	38	258	76.79	23.21
Class 4	476.6	632.4	24	282	83.93	16.07
Class 5	633.4	789.1	21	303	90.18	9.82
Class 6	790.1	945.8	16	319	94.94	5.06
Class 7	946.8	1102.5	8	327	97.32	2.68
Class 8	1103.5	1259.2	2	329	97.92	2.08
Class 9	1260.2	1415.9	2	331	98.51	1.49
Class 10	1416.9	1572.6	2	333	99.11	0.89
Class 11	1573.6	1729.4	1	334	99.40	0.60
Class 12	1730.4	1886.1	0	334	99.40	0.60
Class 13	1887.1	2042.8	1	335	99.70	0.30
Class 14	2043.8	2199.5	1	336	100.00	0.00

Mana Pools without upstream dams

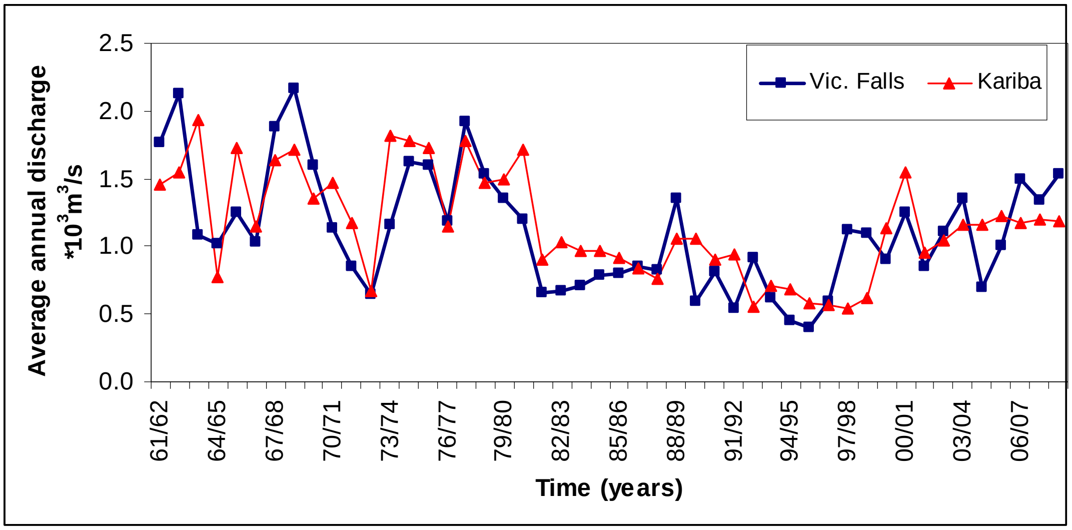
Classes	Min	Max	Frequency	Cumulative	Non-exceedance %	Exceedance %
Class1	127.2	626.6	168	168	38.89	61.11
Class2	627.6	1127.1	79	247	57.18	42.82
Class3	1128.1	1627.6	62	309	71.53	28.47
Class4	1628.6	2128.1	39	348	80.56	19.44
Class5	2129.1	2628.6	27	375	86.81	13.19
Class6	2629.6	3129.0	13	388	89.81	10.19
Class7	3130.0	3629.5	18	406	93.98	6.02
Class8	3630.5	4130.0	14	420	97.22	2.78
Class9	4131.0	4630.5	3	423	97.92	2.08
Class10	4631.5	5131.0	3	426	98.61	1.39
Class11	5132.0	5631.5	1	427	98.84	1.16
Class12	5632.5	6131.9	3	430	99.54	0.46
Class13	6132.9	6632.4	0	430	99.54	0.46
Class14	6633.4	7132.9	1	431	99.77	0.23
Class15	7133.9	7633.4	1	432	100.00	0.00

Mana Pools with upstream dams

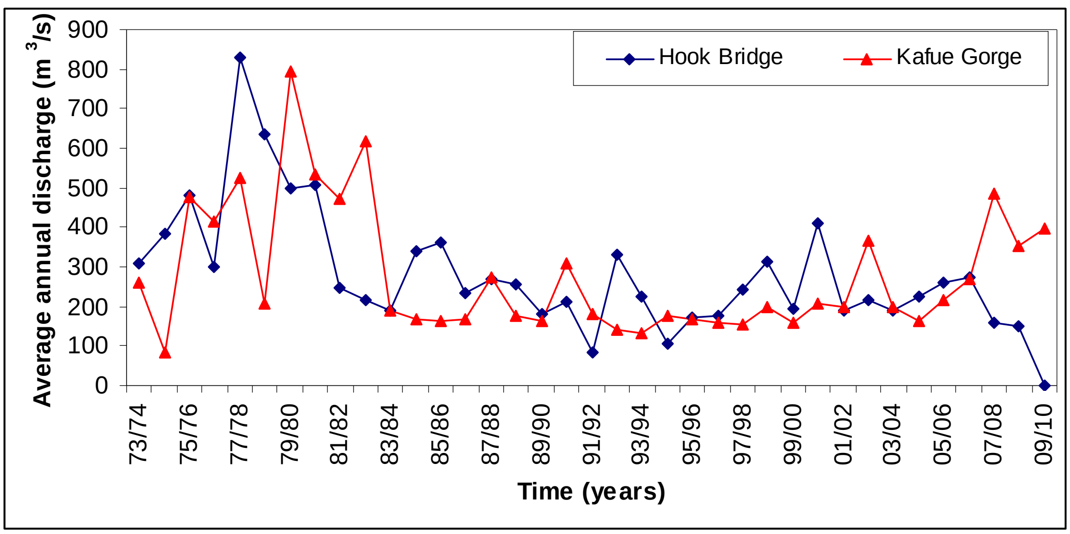
Classes	Min	Max	Frequency	Cumulative	Non-exceedance %	Exceedance %
Class1	567.3	1009.4	144	144	33.33	66.67
Class2	1010.4	1452.5	182	326	75.46	24.54
Class3	1453.5	1895.6	56	382	88.43	11.57
Class4	1896.6	2338.7	15	397	91.90	8.10
Class5	2339.7	2781.8	7	404	93.52	6.48
Class6	2782.8	3224.9	6	410	94.91	5.09
Class7	3225.9	3668.0	7	417	96.53	3.47
Class8	3669.0	4111.1	4	421	97.45	2.55
Class9	4112.1	4554.2	3	424	98.15	1.85
Class10	4555.2	4997.3	5	429	99.31	0.69
Class11	4998.3	5440.4	1	430	99.54	0.46
Class12	5441.4	5883.5	0	430	99.54	0.46
Class13	5884.5	6326.7	0	430	99.54	0.46
Class14	6327.7	6769.8	1	431	99.77	0.23
Class15	6770.8	7212.9	1	432	100.00	0.00

Appendix 2: Average annual runoff

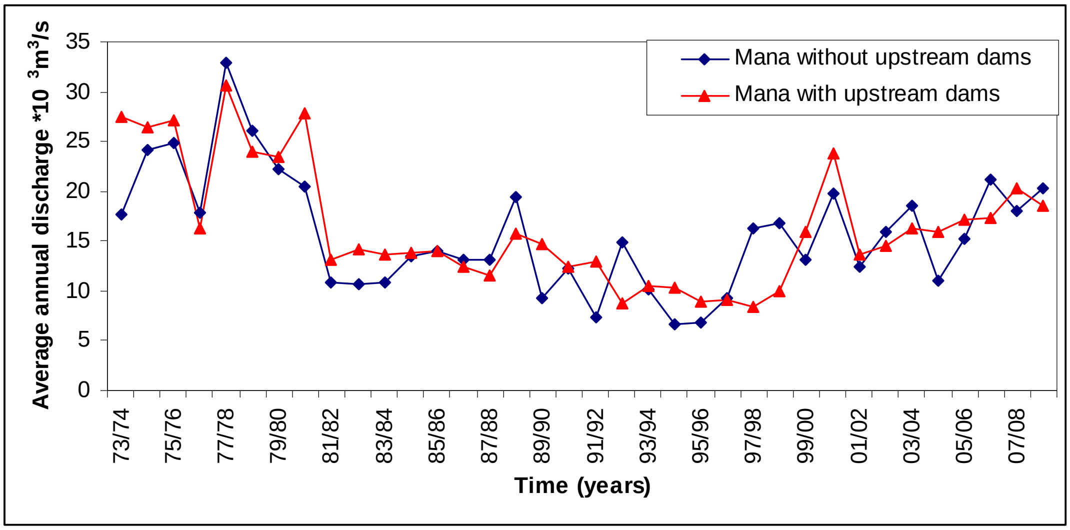
Victoria Falls and Kariba



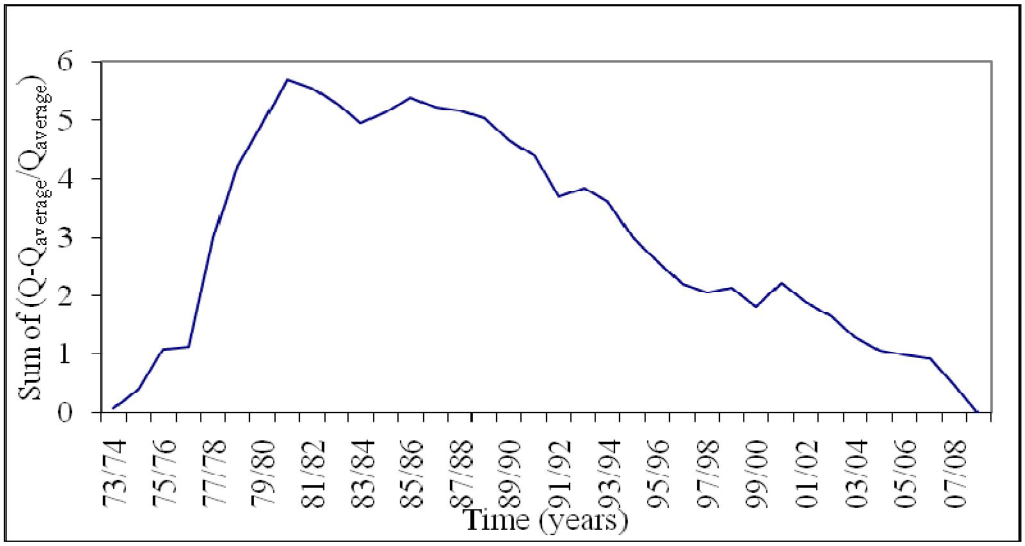
Hook Bridge and Kafue Gorge



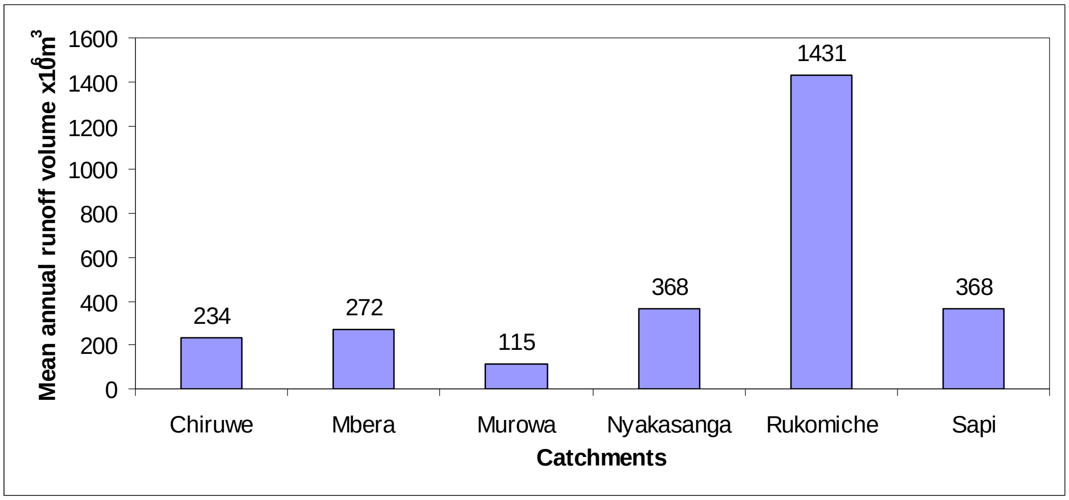
Mana Pools with and without upstream dams



Appendix 3: Hook Bridge FDC 1973-2009



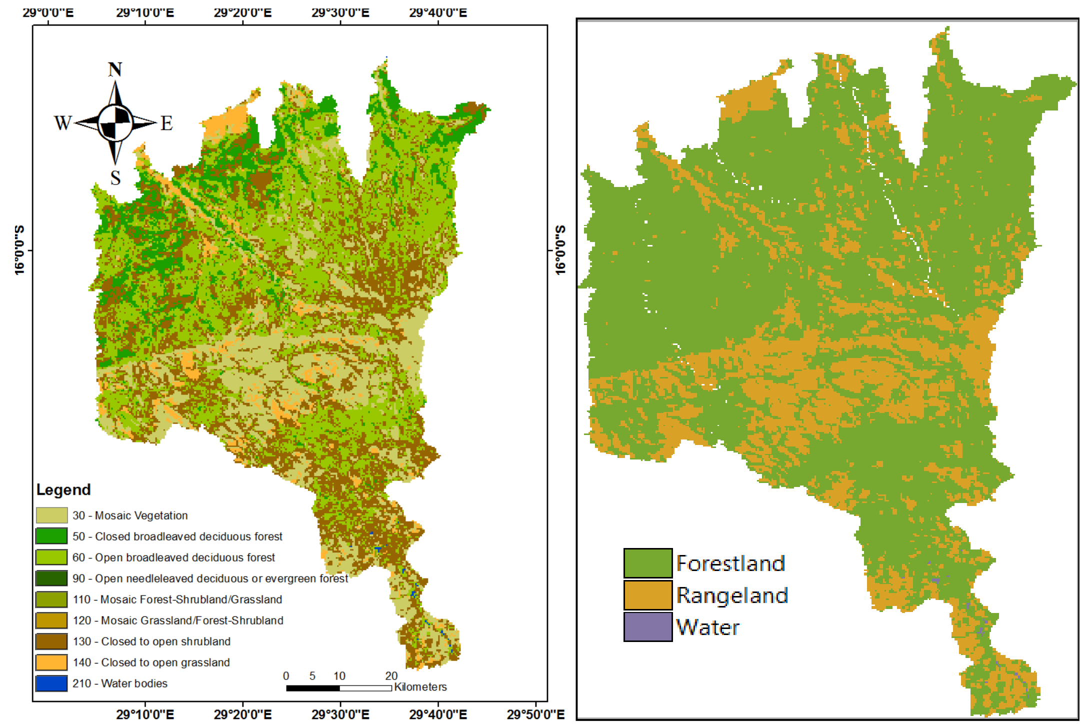
Appendix 4: SCS results for all six catchments



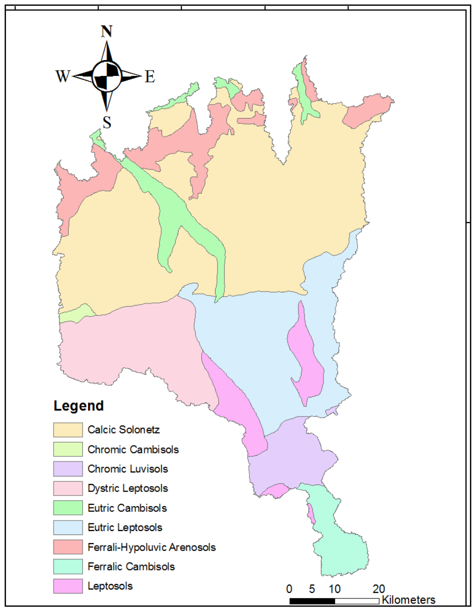
Appendix 5: Rukomechi River channel parameters

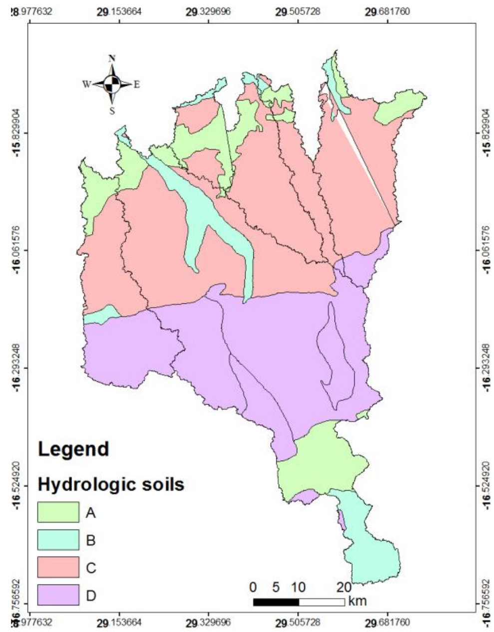
Channel characteristics	
Wetted Manning Coefficient	0.025
Discharge (m^3/s)	29.0307
Flow Area (m^2)	23.073
Wetted Perimeter (m)	53.014
Top Width (m)	52.954
Height (m)	0.592
Critical Depth (m)	0.464
Critical Slope (m/m)	0.00897
Velocity (m/s)	1.258
Velocity Head (m)	0.081
Specific Energy (m)	0.673

Appendix 6: Land cover map used in the SCS before and after reclassification



Appendix 7: FAO soil map for the study area before and after reclassification





Appendix 8: FAO soil classes and their characteristics

FAO soil class	Characteristics	Hydrologic soil group
Calsic solonetz	Hard when dry and swell to a sticky mass of very low permeability when wet. Sodic soils, sand silt and clay	C
Eutric cambisols	Loamy to clay	B
Ferrali-hypoluvic Arenosols	Loamy, sandy	A
Chromic luvisols	Well drained soil, Loamy sand or coarser	A
Eutric leptosols	Gravelly	D
Leptosols	Well developed crumbs or granular structures, gravelly materials	D
Euthic Leptosols	Gravelly or stony	D
Sodic solonchanks	Sticky (clay), powdery fine sand or silt	D
Dystric leptosols	gravelly materials	D
Ferrali cambisols	Clay loamy	C

Appendix 9: Victoria Falls FDC 1924-2009