

# UNIVERSITY OF ZIMBABWE

# FACULTY OF ENGINEERING

# DEPARTMENT OF CIVIL ENGINEERING



# AN ANALYSIS OF THE CAHORA BASSA DAM WATER BALANCE AND RESERVOIR OPERATIONS AND THEIR FLOODING IMPACT

# **ON UPSTREAM SETTLEMENTS**

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M.Sc. Thesis in IWRM

Harare, July 2011

THE UNIVERSITY OF ZIMBABWE FACULTY OF ENGINEERING DEPARTMENT OF CIVIL ENGINEERING





In collaboration with

# AN ANALYSIS OF THE CAHORA BASSA DAM WATER BALANCE AND RESERVOIR OPERATIONS AND THEIR FLOODING IMPACT ON UPSTREAM SETTLEMENTS

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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 (IWRM)

July, 2011

I, **Mabvuto Phiri**, 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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# Table of contents

DECLARATION	· III
TABLE OF CONTENTS	IV
LIST OF TABLES	VI
LIST OF FIGURES	VII
LIST OF EQUATIONS	VIII
LIST OF SYMBOLS	IX
LIST OF APPENDICES	x
DEDICATION	XI
ACKNOWLEDGEMENTS	XII
ABSTRACT	XIII
CHAPTER 1: INTRODUCTION	1
1.1 BACKGROUND	1
1.2 PROBLEM STATEMENT	2
1.3 JUSTIFICATION	3
1.4 RESEARCH OBJECTIVES	3
1.4.1 Main Objective:	3
1.4.2 Specific Objectives:	
CHAPTER 2: LITERATURE REVIEW	5
2.1 Dams and River Flow Regime	5
2.2 FLOODING	
2.3 Water Balance	
2.3.1 Components of the Water Balance	
a) Areal Rainfall	8
b) Gauged Flows	9
c) Ungauged Flows	9
d) Outflows	10
e) Evaporation	10
f) Discharge and Change in Storage	
2.4 GIS AND REMOTE SENSING BASED RAINFALL-RUNOFF WIDDELLING	10
2.4.1 Drainage Basin Area Ratio Method	11
2.5 CATCHMENT PARAMETER COMPARISON	12
2.6 LAHORA BASSA DAM	12
2.6.1 Operational Objectives	12
2.6.2. Description of the Operating Rule	12
CHAPTER 3: MATERIALS AND METHODS	14
3.1 STUDY AREA	14
3.1.1 Types of floods affecting the study area	15
3.1.2 Effects of the Floods in the Study Area	16
3.1 3 Climate	17
3.2 METHODS USED FOR THE DIFFERENT SPECIFIC OBJECTIVES	17
3.2.1 The Water Balance Equation	17
3.2.2 Objective 1: Analyse flows into and out of the Cahora Bassa	17
	17
2 2 3 Objective 2: Determine the contribution from the unaquiand establishments	19 20
Rainfall-Runoff Modelling	20
HEC-HMS model	20 21
Gauging Ungauged Catchments	25
	-

3.2.4 Objective 3: Investigate link between the operation of the Cahora Bassa reserv	oir and flooding
frequency in the riparian areas	26
CHAPTER 4: RESULTS AND DISCUSSIONS	27
4.1 Extent of Ungauged Area	27
4.2 Water level and Lake Surface Area	28
4.3 Cahora Water Balance	30
4.3.1 Inflows	30
Gauged Inflows	30
Direct rainfall on Lake Surface	32
4.3.2 Volume of Outflows	33
Discharge	33
Evaporation	34
4.4 UNGAUGED FLOW CONTRIBUTION	34
4.4.1 HEC HMS Model Calibration and Validation	34
4.4.2 Catchments Comparison	38
4.4.3 Model Simulations	41
4.5 THE WATER BALANCE	43
4.6 RELATIONSHIP BETWEEN RESERVOIR OPERATIONS AND FLOODS IN STUDY AREA	44
CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS	51
REFERENCES	52
APPENDICES	56
APPENDIX B: RUNOFF ANALYSIS	59
APPENDIX C: CROSS SECTIONS AND RATING CURVES	61
APPENDIX D: HEC-HMS INPUTS AND OUTPUTS	63

TABLE 1: THE AVERAGE ANNUAL PERCENTAGE CONTRIBUTION FROM THE DIFFERENT GAUGED SOURCES	31
TABLE 2: SUMMARY OF KEY PHYSICAL CATCHMENT PARAMETERS USED FOR CATCHMENT COMPARISON	42
TABLE 2. THE REFINED SUBFACE WATER BALANCE OF THE CAHORA BASSA INCLUDING THE LINGALIGED FLOW	44
TABLE 5. THE REFINED SORFACE WATER BALANCE OF THE CATORA DASSA INCLODING THE ONGAOGED FLOW	

# List of Figures

FIGURE 1-1: A WOMAN ASSESSING HER MAIZE CROP FROM A FLOODED FIELD AT THE MANYAME-DANDE CONFLUENCE IN MBIR DISTRICT (28 JANUARY 2011)	E 2
FIGURE 2-1: CAHORA BASSA EXISTING OPERATIONAL RULE CURVE (ADAPTED FROM SADC. 2011)	13
FIGURE 2-2: CAHORA BASSA OPERATIONAL RULE CURVE WITH DIFFERENT RULES AT DIFFERENT WATER LEVELS.	13
FIGURE 3-1: STUDY AREA WITH MAJOR RIVERS AND GAUGING STATIONS	14
FIGURE 3-2: LAND COVER OF THE STUDY AREA (SOURCE: FAO 2009 GLOBAL LAND COVER MAP)	15
Figure 3-3: Kariba Dam old and new safety rule curves (Source: SADC. 2011)	16
FIGURE 3-4: RAINFALL PATTERN ON THE CAHORA BASSA LAKE USING DATA FROM LUANGWA. KANYEMBA AND MUZARABANI	
METEOROLOGY STATIONS	19
FIGURE 3-5: STUDY AREA SOIL MAP SHOWING THE DOMINANT SOIL TYPES	22
FIGURE 3-6: CROSS SECTION OF THE MANYAME RIVER AT MAPHOMA VILLAGE	25
FIGURE 3-7: CROSS SECTION OF THE MANYAME RIVER AT MAPOMHA VILLAGE WHERE A GAUGING STATION WAS INSTALLED AN	۱D
THE ACCOMPANYING RATING CURVE	26
FIGURE 4-1: A DIGITAL ELEVATION MODEL OF THE STUDY AREA OVERLAID WITH THE RIVER NETWORK SHOWING THE OLD AND I	NEW
GAUGING STATIONS	27
FIGURE 4-2: EXTENT OF THE UNGAUGED AREA	28
FIGURE 4-3: STAGE-AREA RELATIONSHIP OF THE CAHORA BASSA DAM (SOURCE: HIDRO ELECTRICA DE CAHORA BASSA)	29
FIGURE 4-4: THE LUANGWA WITH THE BLUE LINE SHOWING THE EXTENT OF FLOODS WHEN THE LUANGWA BREAKS ITS BANKS	
(Source: Google Earth)	29
FIGURE 4-5: FLOODED AREAS IN MUZARABANI, KANYEMBA AND LUANGWA SHOWN BY THE RED SHAPEFILE (SOURCE: GOOGLE	
Earth)	30
FIGURE 4-6: FLOWS FROM THE GAUGED RIVERS AND MANAGED DAM RELEASES	30
FIGURE 4-7: THE AVERAGE ANNUAL PERCENTAGE CONTRIBUTION FROM THE DIFFERENT GAUGED SOURCES	31
FIGURE 4-8: THIESSEN POLYGONS SHOWING THE RAINFALL PATTERN IN THE STUDY AREA	32
FIGURE 4-9: THIESSEN POLYGONS OF THE RAINFALL PATTERNS OVER THE LAKE SURFACE	33
FIGURE 4-10: RELATIONSHIP BETWEEN RAINFALL ON THE LAKE SURFACE AND THE AREA OF THE LAKE SURFACE DURING THE MOI	ΝΤΗ
OF JANUARY	33
FIGURE 4-11: THE RELATIONSHIP BETWEEN LAKE EVAPORATION AND LAKE SURFACE AREA MEASURED IN THE MONTH OF JANUA	ry 34
FIGURE 4-12: INITIAL MODEL PERFORMANCE	35
FIGURE 4-13: INITIAL MODEL PERFORMANCE FOR THE LUANGWA CATCHMENT	35
FIGURE 4-14: MODEL PERFORMANCE AFTER CALIBRATION	36
FIGURE 4-15: MODEL PERFORMANCE AFTER CALIBRATION AND PARAMETER OPTIMISATION FOR THE LUANGWA CATCHMENT.	36
FIGURE 4-16: MODEL PERFORMANCE DURING VALIDATION USING UPPER MUSENGEZI CATCHMENT	37
FIGURE 4-17: RESULTS OF MODEL VALIDATION FOR LUANGWA CATCHMENT	37
FIGURE 4-18: PERFORMANCE OF THE MODEL WHEN USED ON THE MANYAME CATCHMENT	38
FIGURE 4-19: SLOPE CLASS MAP FOR THE STUDY AREA	38
FIGURE 4-20: DIGITAL ELEVATION MODEL OF THE STUDY AREA SHOWING THE ELEVATION DIFFERENCES	39
FIGURE 4-21: SLOPE, ELEVATION AND SOIL MAPS OF THE LUANGWA CATCHMENT COMPARED WITH THE STUDY AREA	40
FIGURE 4-22: COMPARISON OF MONTHLY RAINFALL FOR THE SIX STATIONS IN THE STUDY AREA	41
FIGURE 4-23: AN OUTLINE OF THE CATCHMENTS IN THE STUDY AREA USED IN THE HEC-HMS MODEL. JUNCTION 4 IS THE FINAL	L
OUTLET FOR THE WHOLE AREA	43
FIGURE 4-24: HYDROGRAPH OF SIMULATED FLOWS FROM THE UNGAUGED CATCHMENT OVER A 7 YEARS PERIOD	43
FIGURE 4-25: A COMPARISON OF THE OPERATIONAL RULE CURVE WITH THE AVERAGE DAM WATER LEVEL IN DIFFERENT MONTI	HS OF
THE YEAR	45
FIGURE 4-26: COMPARISON OF INFLOWS AND CAHORA BASSA DISCHARGE	46
FIGURE 4-27: INFLOW-OUTFLOW RELATIONSHIP OF THE CAHORA BASSA DAM AND THE THREE MAJOR INFLOW SOURCES	46
FIGURE 4-28: SHOWS THE WATER LEVEL CHANGES IN DIFFERENT YEARS AND IN DIFFERENT MONTHS WHILE THE GREEN CIRCLES	
INDICATE THE OCCURRENCE OF NOTABLE FLOODS	47
FIGURE 4-29: DAM WATER LEVEL AND HOW OFTEN CRITICAL LEVELS HAVE BEEN EXCEEDED IN THE LAST TEN YEARS	48
FIGURE 4-30: WATER LEVEL CHANGES IN THE CAHORA BASSA DUE TO RELEASES FROM KARIBA AND KAFUE DAMS	48
FIGURE 4-31: INFLOW-OUTFLOW RELATIONSHIP OF THE CAHORA BASSA AND THE ASSOCIATED WATER LEVEL CHANGES	49
FIGURE 4-32: SHOWING HIGH FLOWS IN 1999, 2000 AND 2001 SOME OF THE YEARS OF FLOODS	49
FIGURE 4-33: SATELLITE IMAGE OF THE CAHORA BASSA SHOWING THE RIVERS (BLUE) AND HIGH WATER LEVEL CONTOUR (RED)	. The
black circles show areas in Muzarabani, Kanyemba and Luangwa that are flood prone	50

# List of Equations

EQUATION 1	
Equation 2	
EQUATION 3	
EQUATION 4	
EQUATION 5	
EQUATION 6	
EQUATION 7	
EQUATION 8	
EQUATION 9	

# List of Symbols

SYMBOL	MEANING	Units
92	Change in storage	(Mm <sup>3</sup> )
ðt	Change in time	(years)
Р	Precipitation	(mm/year)
Eo	Evaporation from lake surface	(mm/year)
Q <sub>gauged</sub>	Gauged flows	(Mm <sup>3</sup> /year)
Qungauged	Ungauged flows	(Mm <sup>3</sup> /year)
Q <sub>out</sub>	Managed releases from dam	(Mm³/year)
GWi	Inflows from ground water sources	(Mm <sup>3</sup> /year)
GWo	Outflow from the lake into the ground	(Mm <sup>3</sup> /year)
A <sub>ungauged</sub>	Catchment area of ungauged river	(Km²)
A <sub>gauged</sub>	Catchment area of gauged river	(Km²)
V	Discharge from dam outlet	(m³/s)
Q <sub>p</sub>	Peak discharge	(m <sup>3</sup> /s)
С	Runoff coefficient	
1	Rainfall intensity	(mm/hr)
t <sub>p</sub>	Basin lag time	(hours)
L	Length of longest channel from the divide to the outlet	(Km)
L <sub>c</sub>	Length of the main channel from the centroid to the outlet	(Km)
E	Nash-Sutcliffe model efficiency coefficient	
Q <sub>o</sub>	Observed discharge	(m³/s)
Q <sub>m</sub>	Modelled discharge	(m³/s)

# List of Appendices

APPENDIX A 1: KAROI ANNUAL RAINFALL	56
Appendix A 2: Guruve Annual Rainfall	56
Appendix A 3: Kanyemba Annual Rainfall	57
Appendix A 4: Luangwa Annual Rainfall	57
Appendix A 5: Muzarabani Annual Rainfall	58

Appendix B 1: Flows from the Chongwe and Musengezi rivers	59
Appendix B 2: Comparison of Cahora Bassa inflows and outflows	59
APPENDIX B 3: THE FLUCTUATIONS IN WATER LEVEL AT THE CONFLUENCE OF THE ZAMBEZI AND LUANGWA RIVERS	60
APPENDIX B 4: MEAN MONTHLY WATER LEVELS IN CAHORA BASSA	60

Appendix C 1: Manyame River Rating Curve at Manyame Bridge in Mushumbi	61
Appendix C 2: Angwa River Rating Curve at Angwa Bridge	61
Appendix C 3: Cross Section of the Angwa River at Angwa Bridge	62
Appendix C 4: Cross Section of the Manyame River at the Manyame Bridge in Mushumbi	62

Appendix D 1: Sub-catchments in the ungauged area used to model runoff	63
Appendix D 2: Simulated flows from the ungauged sub-catchments	64

# DEDICATION

To my mother

Margaret Phiri

The biggest and most positive influence in my life

Mum, I hope I made you proud

#### ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to my supervisors Dr. Eng. H. Makurira and Mr. W. Gumindoga for their constructive comments, close supervision and providing direction. Special thanks to Dr. Makurira for his open door policy enabling me to consult at some of the most inconvenient times and Mr. Gumindoga for ensuring that the HEC-HMS model "finally ran".

I am heavily indebted to my sponsors WaterNet for granting me the scholarship that enabled me to undertake this study and fulfil a long held dream of postgraduate study. My humble thanks and appreciation to all members of staff of the Department of Civil Engineering in the Faculty of Engineering, particularly Mai Sadazi, Mai Musiniwa and Mr Peter Chari who made the stay in Zimbabwe quite memorable.

To all my colleagues and friends in the IWRM class of 2010/11, it was a pleasure knowing you and you will all be sorely missed.

Finally, many thanks to my sister Sonile Phiri for taking care of my son, Marcus, in my absence. May God richly bless you for doing such a wonderful job.

The Lower Middle Zambezi catchment is sandwiched between three major dams; Kariba, Kafue (Itezhi-tezhi) and Cahora Bassa. The upstream dams have an impact on the inflows in the downstream Cahora Bassa Dam and, also, on the area inundated upstream of the Cahora Bassa. This study aimed at estimating the water balance of the Cahora Bassa using available meteorological and hydrological data sets such as rainfall, temperature and runoff for the period 1980 to 2010. The flow data analysed includes the discharge from the Kariba, Kafue and Cahora Bassa dams and river flows for Luangwa, Chongwe, Musengezi and Manyame.

Missing flow data was generated using regression and mean value infilling methods. GIS was used to calculate the isohyets for the average annual rainfall in the lake drainage basin using the nearest neighbour interpolation technique. GIS was further used to process the Digital Elevation Model (DEM) of the study area through the DEM hydroprocessing algorithm in ILWIS thus establishing the ungauged catchment area of the lake.

Two gauging stations were installed at Manyame Mapomha and Angwa Bridge on the Manyame and Angwa rivers, respectively, as part of the project's effort of moving from ungauged to gauged flow. The results from these stations were however too short to give any meaningful indications as to the discharge from the associated catchments. As a result, a hydrological model, the HEC-HMS, was then used to simulate runoff from the ungauged catchments which showed that these areas contribute about 12% of the total estimated inflows into the Cahora Bassa Dam. The average flow for one hydrological year revealed a total inflow of 71.73 x  $10^9$  m<sup>3</sup>/year, total outflows averaged 52.25 x  $10^9$  m<sup>3</sup>/year and a residual storage of 20 x  $10^9$  m<sup>3</sup>/year. While the high flood level for the Cahora Bassa Dam lies at the 329 masl contour line, which translates to an inundated area of 3,246 km<sup>2</sup>, the actual maximum water level for the period considered (1980 - 2010) reached only 328.18 m contour thus giving an inundated area of 2,920 km<sup>2</sup>.

Analysis of the river flow hydrographs and the associated lake water level indicates that there is a close link between reservoir operations and flood occurrence in Luangwa, Kanyemba and Muzarabani areas. The flooding effect of the reservoirs is only felt when the water level in the Cahora Bassa Dam is above 324.

The study concludes that the ungauged lower middle Zambezi contributes a significant amount which averages  $8.5 \times 10^9 \text{ m}^3$ /year, which is about 12 % of the total inflows into Cahora Bassa while the gauged flows from the Kariba, Kafue, Luangwa, Chongwe, Manyame and Musengezi contribute about 85 % of the total flows into the Cahora Bassa. The remaining 2.5 % comes from direct rainfall on the lake surface. Furthermore, the study showed that flooding is most likely when high water levels are accompanied by high flows in the associated rivers such as the Luangwa, the Mwanza Mtanda and the Musengezi.

## **CHAPTER 1: INTRODUCTION**

#### 1.1 BACKGROUND

The Zambezi river basin extends over 1,390,000 km<sup>2</sup> and drains eight southern African countries, namely, Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe (SADC, 2011). The basin has considerable water resources epitomised by the Zambezi and its tributaries such as the Kabompo, Luanginga, Kafue, Luangwa and Shire.

The last 60 years have seen a rapid growth in the human population worldwide leading to an increase in the pressure on natural resources such as water (Abernethy, 2000). The growth in population, coupled with economic development and improved living standards has increased the demand for water use (Abernethy, 2000). These increased water demands have led to the construction of dams to store excess flows that are then released during periods of low flows for hydropower generation, irrigation and other requirements.

These dams, however, may have positive or negative effects; such as an inland fishing industry, tourism and flooding of previously unflooded areas. While floods in the Zambezi basin are not a rare occurrence (Magadza, 2000), as evidenced by floods in the Barotse flood plains, Caprivi flood plains, Chobe flood plains and the Zambezi delta, floods in other parts of the basin may be human induced due to the construction and operation of dams. This could be the case with the lower middle Zambezi which stretches from the outlet of the Kariba Dam to the outlet of the Cahora Bassa Dam where the construction and operation of man-made water impoundment structures at Kariba, Kafue-Itezhi Tezhi and Cahora Bassa have changed the flow regime of the Zambezi River downstream of these hydraulic structures.

The impoundment of rivers to form man-made lakes has effects both upstream and downstream of the dam wall. Downstream, the most obvious effect is the change in flow regime. The effect of a dam on flow regime depends on the storage capacity of the reservoir relative to the volume of river flow, the main purpose of the dam and the way the dam is operated (Van Lanen *et al.*, 2008). The upstream, part of the basin is inundated creating a new ecosystem through loss of terrestrial riverine vegetation and reduction of fish species diversity (Reynolds *et al.*, 1999) resulting in the need to introduce new species in the established reservoirs (Magadza, 1996) such as introduced clupeid or sardine *Limnothrissa miodon* (Boulenger) from Lake Tanganyika in 1967–1968 into the Kariba.

Hydropower reservoirs like the Kariba, Kafue and Cahora Bassa that were constructed in the Zambezi Basin primarily for hydropower production purposes maintain a high hydraulic head in order to maximise power production. The middle Zambezi River watercourse system, which stretches from the Victoria Falls up to the Cahora Bassa dam wall (Reynolds, *et al.*, 1999), has currently three large hydroelectric dams namely; Kafue (Itezhi-Tezhi), Kariba and Cahora Bassa. Two of these, the Kariba and the Cahora Bassa, lie on the Zambezi while the third lies on the Kafue River, a major tributary of the Zambezi.

Prior to the construction of the dams, natural flooding played a central role in rural economies such as the Zambezi Delta, providing fertile agricultural land which supported a large human population (Beilfuss, 2001). The flood waters provided a breeding ground for large numbers of fish and brought essential moisture and nutrients to the soil for recession agriculture. As the flood waters recede, arable alluvial soils are exposed and crops are grown

(Acrernan, 1996). This is especially true in the large floodplain systems of Africa. During the rainy season, the fertile alluvium adjacent to river channels are planted with cereals, legumes, and gourds that are harvested just prior to the rivers' expected annual flood. Farmers plant a second alluvial crop after the floodwaters begin to recede, sowing seeds just behind the retreating water line and harvesting at the end of the dry season (*e.g.* Beilfuss 2001).

#### **1.2 PROBLEM STATEMENT**

Floods in the Zambezi basin are a fact of life. The floods may be natural due to high intensity and short duration rainfall or man-made due to the operation of the reservoirs in the basin. Parts of Mbire and Muzarabani districts (Zimbabwe) and Luangwa district (Zambia) extend into the low-lying Zambezi Valley. These areas are at an elevation of up to 400 m and may be prone to floods due to their low elevation.

Studies done in the lower middle Zambezi (e.g. Madamombe, 2004) suggest that the occurrence of these flood events in the study area is a function of the operations of the reservoirs upstream, the Cahora Bassa downstream and local rainfall events manifested in high flows in rivers such as the Luangwa, Mwanza Mutanda, Manyame and Musengezi. A high water level in the Cahora Bassa coupled with high flows in the Luangwa, Musengezi, Angwa, Manyame and Mwanza Mutanda results in a backwater effect leading to the inundation of land upstream of the dam seen as the floods of Kanyemba, Muzarabani and Luangwa. Since the soils of these areas are generally poor for agricultural activities as they are mostly sands with shallow depths and poor moisture retention (Du Toit, 1993), people seek out the fertile areas in the flood plains by practising stream bank and flood plain cultivation. This practise however, makes them vulnerable to floods resulting in their crop getting washed away (See Figure 1.1).



Figure 1-1: A woman assessing her maize crop from a flooded field at the Manyame-Dande confluence in Mbire District (28 January 2011)

This study sought to find out the contribution of the presence of reservoirs in the study area to the flooding that occurs there and also offer insight into the hydrological behaviour of the ungauged rivers feeding into the Cahora Bassa reservoir from the Luangwa and Mbire districts catchments through the development of a surface water balance of the dam. The operations of the Cahora Bassa Dam in response to the operations of the upstream reservoirs was also considered in order to come up with a holistic picture of how the reservoirs have changed the flow regime of the lower middle Zambezi flood plains resulting in floods upstream of the Cahora Bassa Dam.

#### **1.3 JUSTIFICATION**

As demand for water resources keeps increasing due to, among other factors, the increase in population and economic development, the number of dams constructed to meet any shortfall during low flow periods has gone up. The studies of the impacts of these dams have become a growing area of interest which is, however, mostly limited to environs downstream of the dam wall. Upstream, very little interest is taken as the impacts of these dams are less obvious here.

Muzarabani has experienced at least a flood almost every year since 2000 with the most notable ones being in 2000, 2003 and 2007 (IFRC, 2007). While the floods in the area occur mostly between January and March, the event in 2007 occurred in December following heavy storms (indicating input into floods from upstream rainfall) resulting in three reported deaths (IFRC, 2007) and destruction of property. Luangwa and Kanyemba have a lesser flood frequency with the most severe flood in Luangwa having been in 2003 when an estimated 30,000 people were affected (Madamombe, 2004, Times of Zambia, 2003; The Post Newspapers, 2003).

The frequency and intensity of these floods is a source of concern as the human and livestock population increases in these areas. This is coupled with the fact that the exact cause of these floods is not well known but speculated to be a result of the operations of the reservoirs at Kariba, Kafue and Cahora Bassa.

This study is therefore conducted to establish the contributing causes of floods in Mbire, Luangwa and Muzarabani districts and also to understand the extent of these floods.

#### **1.4 RESEARCH OBJECTIVES**

#### 1.4.1 Main Objective:

The main objective of this study is to produce a refined surface water balance of the Cahora Bassa Dam by including estimates of lake rainfall, gauged flows, lake evaporation, managed releases and flow from ungauged catchments and, hence, establish the flooding impact of the Cahora Bassa on upstream settlements.

This main objective was achieved through the following specific objectives:-

#### 1.4.2 Specific Objectives:

- 1. To analyse flows into and out of the Cahora Bassa and linking these with the resulting water level changes,
- 2. To determine the contribution from the ungauged catchments and so ascertain the significance of this flow,

3. To investigate how the operation of the Cahora Bassa reservoir affects flooding in the upstream areas in relation to the high flood level.

## **CHAPTER 2: LITERATURE REVIEW**

#### 2.1 DAMS AND RIVER FLOW REGIME

A river's flow regime (i.e. total discharge, flood flows, base flows, the shape of the seasonal and flood hydrographs, and inter-annual variability) controls many physical and ecological aspects of river form and processes (Batalla *et al.*, 2003). The presence of a hydraulic structure on a river affects the flow regime resulting in changes in these hydrologic and ecological processes of the river. Therefore, there exists a disagreement regarding the downstream impact of dams. One reason for this is the operational conflict between the main purpose of the reservoir, e.g. hydropower production, and its function in hazard mitigation or environmental regulation. The main purpose of the reservoir is commonly given priority over other considerations, and the nature of the downstream effects of reservoir operation is often debatable from an integrated water management viewpoint (Lopez-Moreno *et al.*, 2009).

Dams create a reservoir which drowns the river valley upstream from the dam wall, and replaces the natural cycle of floods and low flows with a more constant flow pattern related to electricity demand downstream (Acrernan, 1996). Reservoirs play an important role in flood management. They store flood water and reduce flood risks by attenuating the flood peaks and intensity of flooding in the downstream reaches. Within the context of Integrated Water Resources Management (IWRM), water storage by reservoirs is an important means of meeting needs of various activities when the natural supply is less than the demand. From both perspectives, reservoirs have been providing substantial benefits to human societies and their economic activities. Thus reservoirs result in alteration of the natural flow regime depending on the given purpose of storage of the water and the way the rule curves for their operation are established. Retention of water in the reservoir may affect its temperature, nutrient content and the quantity of sediment it transports. The way a reservoir is operated may alter the frequency, timing, and duration of the flood events downstream of the reservoir (McCartney *et al.*, 2001).

Cahora Bassa Reservoir operates to store and release water for hydropower generation. The characteristics of the reservoir are based on the design studies by Hidrotécnica Portuguesa with recent revisions provided by Hidroeléctrica de Cahora Bassa (Beilfuss, 2001). Inflows are based on the time series data for the Middle Zambezi catchment, including runoff from the Luangwa, Chongwe, Manyame, Angwa, Musengezi Rivers and some other smaller ungauged catchments. These flows are combined with Kariba and Kafue Gorge Reservoir releases to create the Cahora Bassa Reservoir inflow series. Depending on the operations of the Cahora Bassa Dam, the inflows result in a back water effect leading to the inundation of land upstream of the dam seen as the floods within the Kanyemba, Muzarabani and Luangwa communities.

Different statements about the effects of dams on river hydrology arise from various research, interest groups and government agencies (Romano *et al.*, 2009). These often contradicting statements may occur because changes in hydrology caused by dams are distinct for each dam and river watershed (Romano *et al.*, 2009). Researchers approach the challenge to quantify river hydrology in the floodplain using modelling wells, river gauges and Geographic Information Systems (GIS) estimating flooding variables such as flood frequency, duration and flow.

Floodplains are the preferred areas for human habitation since time immemorial for their various advantages. They support various kinds of socio-economic activities while the normal floods provide diversity of services to support these human activities. Many people depend for their livelihoods on the various services provided by the river and its corridor ecosystem. At the same time the floodplains are occasionally flooded thereby adversely impacting the economic activities and resulting in loss of property and life (WMO, 2008).

This study concentrated on the effects of river regulation at Cahora Bassa on flows in the lower middle Zambezi and how these impact on the extent, severity and frequency of flooding in the Dande Valley of Mbire and Muzarabani Districts of Zimbabwe and the Luangwa District of Zambia. The operation rules of the reservoir were taken into consideration to determine the extent to which managed releases cause the back water effect from the Cahora Bassa. The operation of the Cahora Bassa was used to determine the water level in the reservoir which was then related to the area inundated using the area capacity-curve of the dam.

#### 2.2 FLOODING

Different definitions of what constitutes a flood have been given by different authors but all these seem to converge to a single meaning that floods occur when water fills its natural channels and breaks its banks resulting in inundation of areas that are not normally flooded. Wilser and Brater (1949) defined a flood as an unusually high stage of a river at which the river channel becomes filled and above which it over flows its banks. Ward (1967), states that floods are unusually high rates of discharge often leading to inundation of land adjacent to the stream while Chow (1964) defines a flood as any relatively high flow that over tops the natural or artificial banks in any reach of the flood plain and coming into conflict with man. Flooding is defined by the United Nations Environment Programme, Division of Early Warning and Assessment (UNEP/DEWA, 2009), as the temporary inundation of normally dry land areas resulting from the overflowing of the natural or artificial confines of a river or other body of water.

Knowing the positive and negative effects associated with floods, it is important to be able to estimate the magnitude and frequency of flood occurrence. Several methods have been developed for the estimation of flood magnitude and Wilser and Brater (1949) suggests that these methods can be divided into three general classes. These classes include determination of flood flow by means of empirical formulae, determination of flood flow by unit hydrograph method and determination of flood flow by statistical probability methods. For this study, statistical methods will be used as this is a widely used and generally accepted method (Batalla *et al.*, 2003; Lopez-Moreno, 2009; Pegg *et al.*, 2003). This method is reliable in the determination of maximum flood expected on any stream with a given frequency provided there is sufficient data available and there are no important regime changes during or subsequent to the period of record (Wilser and Brater, 1949).

Floods are most commonly described according to their magnitude, specifically in terms of whether an event has exceeded any known thresholds or historical record. The standard means of classifying an event is by return period, whereby a "1 in 100 year event" would be expected to occur once in every 100 years on average. Naturally, a 1 in 100 year event is less frequent and of higher magnitude than a 1 in 50 year event (Ward and Robinson, 2000).

One of the most important steps in the analysis of hydrological extremes is to decide the hydrological characteristics to be studied (Van Lanen *et al.*, 2008). Data availability,

climatic and regional features influence the hydrological characteristics to be studied. There is no single flood characteristic that is suitable to assess and describe hydrological extremes for any type of region (Van Lanen *et al.*, 2008).

Different ways of characterising extreme weather events can lead to different conclusions. When calculating flood characteristics, it is important to be aware of the processes underlying the generation of the hydrologic extreme e.g. floods can result from intense long lasting precipitation, flow obstruction (damming) or dam failure (Van Lanen *et al.*, 2008).

The exercise of estimating how often floods of a certain magnitude may occur based on long records using statistical methods is referred to as flood frequency analysis. The objective of flood frequency analysis is to estimate the magnitude of a flood corresponding to any return period (Roland and Stuckey, 2007). The accuracy of flood frequency analysis depends on the length of observations at the location of interest (WRC, 1981) while Linsley *et al.*, (1959) points out that problems with the results of frequency analysis come from short records.

The most common attribute of flow regulation is a decrease in the magnitude of the flood peaks and an increase in low flows. The resultant hydrological alterations caused by reservoirs may include changes in flood frequency and magnitude, reduction in overall flow, increased or decreased summer base flows, and altered timing of releases, with a resulting wide range of effects on riverine ecology (Petts, 1984; Ward and Stanford, 1995). Lopez-Moreno *et al.*, 2008 show that as a result of exploitation of the Alcántara reservoir in Spain and Portugal, (i) during periods of water scarcity, the releases in winter and spring are reduced dramatically and the magnitude and duration of summer low-flow show a slight increase; and (ii) the nature of hydrological droughts along the Tagus River basin downstream of the dam has shown severe changes since construction of the dam. Since the construction of the Alcántara dam, the Portuguese part of the basin has experienced more severe hydrological droughts than the upstream Spanish part, in terms of both magnitude and duration.

Yawson *et al.*, (2006), however showed that reservoirs can have an effect of artificially inducing a flood wave by increasing peak flows as was the case for Kidatu Dam in Tanzania, where pre and post dam peak flows of Kidatu dam were reported to be  $800 \text{ m}^3/\text{s}$  and  $1400\text{m}^3/\text{s}$ , respectively. The effects of a reservoir on flow regime depends on its capacity in comparison with river runoff, its purpose (e.g. irrigation diversions, hydro-electric generation, flood control), and its operating rules (Williams and Wolman, 1984). It is intuitive that the larger the reservoir capacity in relation to the natural flow of the river, the greater the hydrologic effect of the reservoir is likely to be.

Batalla *et al.*, (2003) proposed a simple ratio of reservoir capacity to (unimpaired) mean annual flow as the impounded runoff (IR) index. This ratio can be calculated using the total reservoir capacity or preferably the live storage capacity to better predict the effect of dams. The higher the IR index, the higher the effect of regulation in changing the flow regime.

#### 2.3 WATER BALANCE

The concept of the water balance has been successfully used to estimate the present and future water availability in different regions (Dominguez, 1997) and for water resources management (Neff and Killian, 2003). The term "water balance" is defined here as an accounting of the inflow to, outflow from, and storage in, a hydrologic unit, such as a reservoir (Langbein and Iseri, 1960). This is simplified as:

Inflows – Outflows = Change in Storage

The mathematical expression of a water balance for a lake may be written as:

Equation 1

$$\frac{\partial s}{\partial t} = (P + Q_{gauged} + Q_{ungauged} + GW_i) - (Q_{out} + E + GW_o)$$

Where:

$\partial s$	=	Change in storage (Mm <sup>3</sup> )
$\partial t$	=	Change in time (year)
Р	=	Lake's areal rainfall [Mm <sup>3</sup> /year],
E	=	Open water evaporation [Mm <sup>3</sup> /year],
Qgauged	=	Total gauged river inflow [Mm <sup>3</sup> /year],
Qungauged	=	Ungauged river inflow [Mm <sup>3</sup> /year] and
Q <sub>out</sub>	=	Managed releases outflow [Mm <sup>3</sup> /year].
$GW_i$	=	Groundwater inflow into the lake [Mm <sup>3</sup> /year]
$\mathrm{GW}_{\mathrm{o}}$	=	Groundwater outflow from the lake [Mm <sup>3</sup> /year]

Often, it is necessary to simulate the future behaviour of a dam in order to estimate the longterm benefits of different operating policies, the occurrence probabilities of deficits or surpluses the following year, or behaviour of the spillway when a flood of a certain probability occurs, (Dominguez, 1997). Dam characteristics such as elevation-volume relationships, elevation-area relationships, spillway dimensions, etc can be used for operational policies that determine outflow,  $Q_{out}$ , in Equation 1.

To estimate inflows, it is necessary to have historical information, which can be obtained principally in three ways: data measured at hydrometric stations near the reservoir; deducing inflows from the historical behaviour of the reservoir; and a combination of the above two options. The inflow components include river discharge, rainfall and groundwater.

## 2.3.1 Components of the Water Balance

The terms of the water balance as indicated in equation 1 are the gauged inflows, the ungauged inflows, lake areal rainfall, groundwater inflow, evaporation, groundwater outflow and releases from the lake.

## a) Areal Rainfall

Over-lake precipitation can make a significant contribution to inflows depending on the surface area of a reservoir and the amount of rainfall received. In the great lakes region of North America, over-lake precipitation is a very large component of the Great Lakes water balance, larger than either runoff or evaporation (Neff and Nicholas, 2005). This component of inflows depends on the amount of rainfall received and the surface area of the lake. The rainfall received is based on rainfall records from stations around the lake and these are then

interpolated to determine the areal rainfall. Direct over-lake precipitation is counted directly as a major input into the water balance. Over-land precipitation can be used indirectly to estimate runoff in areas where stream gauging is incomplete. Precipitation data may be generated in multiple ways. Conventional weather stations measure precipitation directly at one point. Data from multiple stations may be combined using various methods to calculate estimates of precipitation falling over a large area. All over-lake precipitation estimates used in the water balance are modelled estimates based on near-shore data (Croley *et al.*, 2001).

Areal precipitation data can also be obtained from satellite based rainfall estimation (Winsemius, 2009) such as the Tropical Rainfall Measuring Mission (TRMM) and the Famine Early Warning System (FEWS). Other methods for obtaining areal rainfall include Thiessen polygons, Inverse distance interpolation (Wale *et al.*, 2009). Accurate estimation of the spatial distribution of rainfall and extrapolation of point measurements over large areas is complicated. This is especially true in mountainous areas, where in addition to the stochastic nature of rainfall, the precipitation pattern may be influenced by the irregular topography (Wale, 2008).

#### b) Gauged Flows

Stream flow is generally not continuously measured; instead, a stage-discharge or velocitydischarge relation is established to estimate stream flow on a continuous basis (Neff and Nicholas, 2005). In these methods, stream flow is measured directly at many stream stages or velocities. These data are used to develop a regression relation that mathematically relates the stage or velocity of a stream and its discharge. Some degree of uncertainty exists in these stage-discharge and velocity-discharge relations. Uncertainty may result from improperly measuring stream flow or from not recording the stage or velocity of the stream accurately.

Special hydrologic conditions can affect the uncertainty of stream flow estimation. For example, floods present a special problem to estimating discharge. If a stream overflows its banks, the accuracy with which stream flow can be estimated decreases significantly. Compounding the problem is the fact that flood stream flows may be many times greater than the normal flow of the stream. So, the inaccuracies during a relatively short flood event (hours to weeks) may amplify the total uncertainty in longer-term runoff estimates significantly (Neff and Nicholas, 2005)

Runoff into a reservoir includes all water entering the lake through rivers, streams, and direct overland flow. Runoff from rivers and streams is calculated by considering runoff from gauged and ungauged portions of the basin (Neff and Killian, 2003). Direct overland flow into the reservoir is considered to be an insignificant input to the water balance and therefore few attempts have been made to estimate the amount (Neff and Killian, 2003). Runoff from gauged portions of the basin is calculated using stage data collected at gauging stations located throughout the basin. These stage data are compared to stage-discharge relationships developed and maintained for each station and stream flow is thus estimated.

#### c) Ungauged Flows

However, much of the middle Zambezi basin remains ungauged (Winsemius, 2009), necessitating the estimation of runoff from these areas. Records of stream flow in the Zambezi Basin are spatially incomplete for two reasons. First, gauging stations are usually several kilometres upstream rather than at stream mouths, leaving spatial gaps in data to describe stream flow in areas near the lake. Several different methods have been used to estimate runoff from ungauged catchments such as (i) linear extrapolation of the average

stream flow-to-drainage-area ratio observed throughout the basin (Neff and Killian, 2003), (ii) transfer parameters from neighbouring or nearby catchments to ungauged catchments to allow for runoff simulation, (iii) parameter sets of gauged catchments are transferred to ungauged catchments by simple comparison of catchment size (Wale *et al.*, 2009).

Direct discharge of ground water to the reservoir is generally ignored in water balance calculations (Neff and Killian, 2003). This is likely due to the relative magnitude of direct ground-water seepage is a minor component of the water balance.

#### d) Outflows

The outflow components of the water balance include managed releases from the dam, groundwater seepage and evaporation. In some cases, consumptive use, if in significant quantities is included. Records of discharge readings for outflows, changes in water level and estimated potential evaporation are used to quantify the outflows.

#### e) Evaporation

Evaporation is a large component of the water balance (Neff and Killian, 2003). Evaporation rates are difficult to estimate accurately and reliable estimation relies heavily on extensive data availability. Furthermore, no single method of determining evaporation is considered to be the best for all situations. Winter *et al.*, 1995 indicates that more than 11 equations have been proposed for determining evaporation. These included pan evaporation methods, a heat budget method and models using global solar radiation. While there is good agreement in total evaporation, comparisons between the monthly figures were poor. Although the Penman combination equation is the most widely used method (Wale *et al.*, 2009; Piper *et al.*, 1986), Ahmed and Bastiaanssen (2000) used the landsat thematic mapper to estimate evaporation from Lake Naivasha in Kenya which was then compared with the results of the pan method gave a value of 5.46 mm/day. For the Kariba Dam, it is estimated that 20 % of all inflows are lost through evaporation (World Bank, 1993).

#### f) Discharge and Change in Storage

The major method of water loss from a lake is through the discharge at the outlet point. Change in storage calculations are based on a net change in stage data and the surface area of reservoir (Neff and Killian, 2003). Measurement of reservoir water levels is not a straightforward procedure. Phenomena such as wind set up and seiche can cause considerable variation in the water level within each lake.

#### 2.4 GIS AND REMOTE SENSING BASED RAINFALL-RUNOFF MODELLING

Runoff occurs when there is an excess of rainfall above interception and infiltration. It is expressed as a volume per unit area. Runoff is dependent on the intensity of rainfall and catchment characteristics which include time of concentration, geology, vegetative cover and topographical features (Shaw, 2004). Runoff estimation in ungauged catchments is probably one of the most basic and oldest tasks of hydrologists. This long-standing issue has received increased attention recently due to the PUB (Prediction in Ungauged Basins) initiative (Seibert and Beven, 2009). The PUB initiative of the International Association of Hydrological Scientists is a 10 year project seeking to improve the prediction of catchment responses in ungauged basins by improving the scientific basis of hydrology (Seibert and Beven, 2009).

A hydrological model may be regarded as a simplified representation of the hydrological cycle. Rainfall-runoff model is a mathematical expression that tries to relate the amount of rainfall received with the amount of runoff generated from a catchment. Also a model simply relates something unknown (the output) to something known (the input). In rainfall - runoff modelling, the known input is rainfall and the unknown output is runoff characteristics (peak discharge, volume, time to peak, etc.) and the watershed is the system being modelled (Fahad, 2005).

According to Linsley (1981), rainfall-runoff models can be classed as deterministic, conceptual, stochastic, theoretical, blackbox, continuous, routing or simplified. The main reason behind the using of modelling in general is the limitations of the techniques used in measuring and observing the various components of hydrological systems (Fahad, 2005). Furthermore, using hydrologic models will increase our understanding and explanation of the natural phenomena and its dynamic interactions with the surrounding systems (i.e. climatic terrestrial, pedologic, lithologic and hydrologic systems). Models such as the Soil and Water Assessment Tool (SWAT), Geospatial Stream Flow Model and the HEC Hydrological Modelling System (HEC-HMS) are examples of hydrological models imbedded into GIS and remote sensing techniques that try to show the interaction between natural phenomenon and the physical surroundings.

#### 2.4.1 Drainage Basin Area Ratio Method

The drainage-area ratio method is another method commonly used to estimate streamflow for catchments where no streamflow data was collected (Emmerson, et al., 2005). The method is easy to use, requires little data, does not require any development, and, many times, is the only method available because regional statistics or precipitation-runoff models have not been developed. This method is most valid in situations where watersheds are of similar size, land use, soil types, and experience similar precipitation patterns. Discharge is estimated by drainage area weighting using the following equation

Equation 2

$$Q_{Ungauged} = Q_{Gauged} x \frac{A_{Ungauged}}{A_{Gauged}}$$

Qungauged	=	the discharge from the Ungauged Catchment $(m^3/s)$
Qgauged	=	the discharge from the Gauged Catchment $(m^3/s)$
Aungauged	=	Catchment Area of ungauged river (km <sup>2</sup> )
Agauged	=	Catchment Area of gauged river (km <sup>2</sup> )

The basis of this catchment area method is that the catchments being compared be hydrologically similar. This can be done through a catchment comparison analysis of the parameters that most affect flow such as rainfall, land cover, soil type, topography, elevation and drainage density (Raghavendran and Jayarami, 1975).

#### 2.5 CATCHMENT PARAMETER COMPARISON

The problem often faced during the hydrological analysis of an ungauged catchment is to obtain the basin response function without adequate data (Raghavendran and Jayarami,

1975). This may be because the catchment under investigation has neither the input nor the output data available, or may have output but no input data. However, there may be adequate data available for catchments in a hydrologically similar region so that their results could be extended to the catchment under study through some physically meaningful parameters (Raghavendran and Jayarami, 1975).

In order to extend results from one catchment to another, a hydrological similarity between the gauged and the ungauged catchments need to first be established (Sreenivasulu, and Bhaskar, 2010). This was done through a comparison of the physical catchment characteristics based on data obtained from the hydro-processing of a digital elevation model of the study area in GIS.

The linking of the geomorphological properties with the hydrological characteristics of the catchment provides a simple way to understand the hydrological behaviour of the different catchments particularly of the ungauged catchment (Sreenivasulu, and Bhaskar, 2010). The geomorphological properties, which are important from a hydrological studies point of view, include the linear, aerial and relief aspect of the catchment. For quantification of various geomorphological parameters of the study area, the derived drainage map, DEM, slope map and aspects map were used.

Drainage characteristics that affect the hydrograph are basin area, basin shape, basin slope, soil type and land use, drainage density, and drainage network topology. Most changes in land use tend to increase the amount of runoff for a given storm.

#### 2.6 CAHORA BASSA DAM

The Cahora Bassa dam is 171 m high with a storage capacity of 63 x  $10^9$  m<sup>3</sup> and a surface area of 2,739 km<sup>2</sup> at full supply level (SADC, 2011). The dam commenced filling on December 5, 1974 before the wall was completed and the reservoir was rapidly filled in a single flood season (1974–1975). Cahora Bassa dam regulates runoff from part of the Middle Zambezi catchment between the Kariba and Cahora Bassa Gorges, including regulated flows from the Kafue Gorge and the Kariba dams and unregulated flows from the Luangwa, Manyame, Angwa, Musengezi, Sapi, Chewore and others.

#### 2.6.1 Operational Objectives

According to the Hidro-electrica de Cahora Bassa website (http://www.hcb.co.mz), the operational objectives of the Cahora Bassa are multipronged but based on power generation. The objective of the existing flood rule curve for Cahora Bassa is to ensure sufficient storage space for flood water and release of water for optimal hydropower production.

#### 2.6.2. Description of the Operating Rule

According to the SADC Report of March 2011, the releases from the Cahora Bassa dam are governed by hydropower generation requirements and a flood rule curve whereby the reservoir water levels are drawn down prior to each rainy season to provide additional capacity for safely storing and passing the design flood. Spillway discharges are based on all eight gates fully opened, with the crest gate operating for reservoir elevations above 327 m. Minimum water releases for social or environmental purposes are not considered in the rule curve. The existing operating rule for Cahora Bassa is shown in Figures 2.1 and 2.2.

For the Cahora Bassa, the inflows are primarily through river discharges, groundwater inflow and direct precipitation on the lake. The main rivers of interest regarding inflows are the Zambezi, Kafue, Chongwe, Luangwa, Manyame, Musengezi, Angwa and Mwanza Mutanda rivers. For outflows, the main outflows sources are managed releases, groundwater seepage and evaporation (Neff and Killian, 2003). Different methods have been used to estimate these different components of the inflows and outflows as indicated by Dominguez (1997), Wale *et al.* (2009) and Piper *et al.* (1986).



Figure 2-1: Cahora Bassa existing Operational Rule Curve (Adapted from SADC, 2011)



Figure 2-2: Cahora Bassa Operational Rule Curve with different rules at different water levels

#### **CHAPTER 3: MATERIALS AND METHODS**

#### 3.1 STUDY AREA

The study area lies almost entirely within the valley area of the Middle Zambezi basin from 28.267E to 32.753E and 14.825S to 17.079S at an elevation range of about 145 metres just downstream of the Cahora to 1700 metres in the plateau areas of the Angwa catchment. The area is shared by three countries Zambia, Mozambique and Zimbabwe (See Figure 3.1).



Figure 3-1: Study Area with major rivers and gauging stations

The rivers flowing through this area are the Zambezi from Kariba to Cahora Bassa, the lower sections of the Luangwa, Chongwe, Kafue, Angwa, Musengezi, Manyame, Kadzi, Mwanza Mtanda, Sapi, Chewore, Rukomechi, Marongora and a few other smaller ones. Except for a few gauging stations upstream of the Luangwa, Chongwe, Manyame and Musengezi rivers, the rest of the rivers in the area are ungauged resulting in the amount of runoff generated in the area being unknown. According to the SADC Report (2011), gauging stations are being installed on the Luangwa and Musengezi rivers as part of the SADCHYCOS project



Figure 3-2: Land cover of the Study Area (Source: FAO 2009 Global Land cover Map)

According to the Food and Agriculture Organisation (FAO) Global Land Cover map, the study area is predominantly savannah and perennial forests (Figure 3.2) with Game Parks in the area in all three countries (Mana Pools National Park, Chewore Game Management Area, Dande Safari in Zimbabwe and the Rufunsa Game Management Area in Zambia). The vegetation is predominantly of the Miombo structure that overlaps the three countries (Kusena, 2009).

#### 3.1.1 Types of floods affecting the study area

There are two types of floods that affect the area under study (Madamombe, 2004). The first and most frequent type of floods is the seasonal flood. This occurs in most years normally in January or February. This is at the peak of the rainfall season. The second is the reservoir operation induced flood. This has become more frequent than before due to the high water levels in the Cahora Bassa since 1999 due to the occurrence to two major cyclone events. In February 2000 cyclone Eline hit the basin bringing with it intense storms while in March 2003 the basin was again hit by cyclone Japhet which also caused flooding in the area.

When the Kariba and Kafue dams rise to a high water level of about 482 m, the flood gates are opened in accordance with the operational rule curve (Figure 3-3) to release water from the dams to avoid dam failure. Most releases are done between December and February. This causes the water flow in the Zambezi to increase substantially. Manyame and Musengezi rivers will thus not be able to discharge in the Zambezi resulting in water accumulating at the confluences of Zambezi and Manyame, Luangwa and Musengezi rivers leading to flooding in the study area. Cahora Bassa Dam levels continue to rise as releases from the dam are exceeded by inflows due to releases from Kariba and Zambezi tributaries. The swelling of the Cahora Bassa dam leads to flooding in the area under study. This has lead to loss of livestock and human life, crops and infrastructure has been destroyed leaving the rural folk in general poorer. The actual costs of the flood damages are not available as most of the assessments done so far are of a qualitative nature (Beilfuss, 2001).



Figure 3-3: Kariba Dam old and new safety rule curves (Source: SADC, 2011)

#### 3.1.2 Effects of the Floods in the Study Area

Along the Luangwa, the floods have had adverse effects on the population in diverse ways. According to Kaminsa (2008), the effect of the floods in the 2007/2008 season was not as bad as the 2006/2007 season, where the losses were higher and the district was cut off from the rest of the country due to the road link being severely flooded and washed away.

In the 2007/2008 rainy season, field visits by the Ministry of Agriculture of Zambia revealed that 8 % (474 hectares of land in low lying areas in the district) of farmers were affected by floods and their fields were washed away, while 92 % of the farmers who cultivated upland were not adversely affected by the floods (Kaminsa, 2008). Part of Luangwa Road, which is the main road link to other towns like Lusaka and Petauke, was submerged by floods and parts of the road were washed away. A number of other roads were also washed away making it difficult to reach some of the far flung areas in the district.

Kaminsa (2008) indicates that a survey undertaken within Luangwa reveals that a total of 28 houses collapsed due to floods. Other losses incurred include the death of goats, cattle, sheep and chickens. These were mainly due to disease resulting from floods and predators. Some animals were also swept away by the current in their grazing areas along Luangwa River. The floods had an adverse effect on water supply and sanitation in Luangwa as rivers and streams were contaminated as a result of poor sanitation as a result of lack of sewerage services and lack of water treatment. According to the Luangwa District Council Disaster Situation Report, (2007), a laboratory test undertaken indicated that most sources of water contained faecal matter. Although no disease outbreaks were reported, the people of Luangwa were exposed to waterborne diseases.

In Muzarabani, according to the ZRCS (2007), the 2007 floods caused extensive damage to houses, infrastructure and household property and swept away hectares of crops and livestock affecting approximately 1,000 families. Kanyemba's most recent flood was in March 2010 and affected 80 families (Herald Newspapers, 2010) with crops being washed away resulting in the need for food aid.

## 3.1 3 Climate

The Zambezi basin's climate is to a large extent influenced by the Congo air masses, north easterlies and the inter-tropical convergence zone (ITCZ). The tropical cyclones from the Indian Ocean also affect the Zambezi basin by bringing large storms of rain which of late has caused destruction of property and loss of lives through flooding. The climate of the basin is also affected by the presence of large water bodies such as Lakes Kariba, Malawi/Nyasa, Cahora Bassa and others (Madamombe, 2004).

The project study area covers a large swath of land mass that provides runoff into the Cahora Bassa dam but downstream of any gauging station. The outer boundary of the area is defined by gauging points at Luangwa Bridge, Manyame Nyakapupu station, Musengezi C68 station, Chongwe bridge station, Kafue gorge power station outlet and Kariba dam outlet. This area encompasses parts of Northern Zimbabwe, Southern Zambia and Western Mozambique while the impacts of flooding are generally felt in Mbire (Kanyemba) and Muzarabani (Chidodo) districts of Zimbabwe and Luangwa district of Zambia.

## 3.2 METHODS USED FOR THE DIFFERENT SPECIFIC OBJECTIVES

In order to address the main objective of the research, three specific objectives were identified and the following methods were used to arrive at answers that addressed the main research concerns.

## 3.2.1 The Water Balance Equation

According to literature, the water balance of a lake is based on the equation 3 given below

Equation 3

$$\frac{\partial s}{\partial t} = P - E + Q_{gauged} + Q_{ungauged} - Q_{out}$$

$$\frac{\partial s}{\partial t} = Change in storage (Mm^3/year)$$

$$\frac{\partial t}{\partial t} = Change in time (year)$$

$$P = Lake's areal rainfall [Mm^3/year],$$

$$E = Open water evaporation [Mm^3/year],$$

$$Q_{gauged} = Total gauged river inflow [Mm^3/year],$$

$$Q_{ungauged} = Ungauged river inflow [Mm^3/year] and$$

$$Q_{out} = Managed releases outflow [Mm^3/year].$$

## 3.2.2 Objective 1: Analyse flows into and out of the Cahora Bassa

#### Inflows

#### Gauged Flows

The first objective seeks to establish a water balance of the Cahora Bassa reservoir for a thirty year period from 1980 to 2010 noting the peak water levels and the occurrence of floods during this period.

To achieve this objective, the major water sources were identified first and flow data was then collected for each to determine the temporal and spatial flow regime changes over time. The inflows into the reservoir from various sources such as the major tributaries, releases from upstream dams (Kafue and Kariba), flows from gauged rivers such as the Luangwa, Chongwe, Manyame, Musengezi, rainfall on the lake surface were then calculated.

The gauged component of the inflows was determined from hydrological records of discharges from the Kariba dam, Kafue Gorge dam and flows from rivers such as the Upper sections of the Chongwe, the Luangwa, the Upper Manyame and Upper Musengezi. The demarcations between the gauged and ungauged portions of these rivers were determined by the location of gauging stations. For the Chongwe River, the gauging station in at the Chongwe bridge on the Great East Road while the Luangwa Bridge also on the same road marks the dividing line for the Luangwa River.

On the Manyame, the lowest gauging station (C64) at the start of this project was at Nyakapupu in Guruve while station C68 on the Musengezi River divides the gauged upper section and ungauged lower section. The flow data was collected from the Department of Water Affairs in Zambia, the Zimbabwe National Water Authority (ZINWA) the Zambezi River Authority (ZRA) and the Zambia Electricity Supply Corporation (ZESCO) which operates the Kafue Gorge dam hydro-electric scheme.

Hydrographs and flow duration curves were then used to understand the behaviour of the Zambezi and the major tributaries upstream of the Cahora Bassa and to show when peak flows are expected into the Cahora Bassa reservoir. Hydrographs from unregulated rivers such as the Luangwa gave a good picture of the catchment response. Upstream and downstream hydrographs helped determine the attenuation effects of the Cahora Bassa dam on flows.

#### Lake Areal Rainfall

Using rainfall data from three nearby stations at Luangwa, Kanyemba and Muzarabani (Figure 3.4), Thiessen polygons were produced in the Integrated Land and Water Information System (ILWIS) software showing the rainfall pattern over the lake (Figure 3.4).



Figure 3-4: Rainfall pattern on the Cahora Bassa lake using data from Luangwa, Kanyemba and Muzarabani meteorology stations

Figure 3.4 shows the spatial distribution of rainfall on the lake surface with 71 % of the lake receiving an average of 746 mm/year while 13 % receives an average of 754 mm/year while 762 mm/year falls on the other 13 %. With the Cahora Bassa lake surface area averaging 2400 km<sup>2</sup> during the rainy season from December to April, the areal rainfall contribution was calculated by multiplying the average monthly rainfall with the average lake surface area and then summing these values for the period from December to April.

#### Outflows

To quantify outflows from the Cahora Bassa, three components of the outflows were considered. These are releases as a result of electricity generation, spillage and evaporation. Records of releases from the dam based on reservoir operations combined with estimated evaporation were obtained from Hidro electrica de Cahora Bassa (HCB), the company running the reservoir. The total evaporation was calculated from the average daily evaporation multiplied by the reservoir area based on average reservoir storage. The outflows from the dam and the associated water levels were based on the combined discharge and evaporation data. The values are based on a spreadsheet model that HCB uses to calculate the lake water balance.

#### Discharge Volume

The outflow from the Cahora Bassa was determined based on discharge readings at the Cahora Bassa dam outlet. This data was provided by HCB. The outflow volume was calculated using the formula

Equation 4

 $V = Q_{out} * t$ Where:  $Q_{out} = Discharge from dam outlet in m^3/s$   $V = The outflow volume (m^3)$ 

t = 31,536,000 seconds in a year

#### 3.3.3 Objective 2: Determine the contribution from the ungauged catchments

This objectives seeks to quantify the flow from the ungauged component of the inflows into Cahora Bassa and, consequently, refine the water balance

According to Winsemius (2009), a large portion of the Lower Middle Zambezi is ungauged resulting in the absence of flow data for Mumbasha, Sapi, Rukomechi, Angwa, Mwanza Mutanda, Marongora, Chemutsi, Mukondore, Kadzi, Mkumbura and Runese rivers. In order to establish the ungauged component of the water balance and so determine its significance, the ungauged area was extracted using a 1km DEM of the middle Zambezi with the boundary of the ungauged area being determined by the locations of the most upstream gauging stations such as the Luangwa Bridge station on the Luangwa River, the Chongwe Bridge station on the Chongwe River, the Kafue Gorge Dam outlet on the Kafue River the Kariba Dam outlet on the Zambezi River, the Nyakapupu station on the Manyame River and the Musengezi C68 station on the Musengezi River.

#### Rainfall-Runoff Modelling

In order to estimate the runoff from ungauged catchments, a rainfall-runoff model called the HEC HMS was used to simulate flows. However, before using the hydrologic model, input parameters had to be collected from field work and from nearby gauged catchments with similar hydrologic response. The similarity between the gauged and ungauged catchments was established through a physical parameter comparison.

#### Catchment Parameter Comparison

In order to come up with a sound hydrological basis for transferring the validation parameters from the gauged Musengezi catchment to the ungauged catchments, a similarity in catchment hydrological response needed to be established (Sreenivasulu, and Bhaskar, 2010).

This was done through a comparison of the physical catchment characteristics based on data obtained from the hydro-processing of a digital elevation model of the study area in GIS. The hydro-processing results yielded the catchment area, the drainage network, the drainage density, upstream and downstream elevation, catchment perimeter and the longest flow length.

The land cover and the soil types of the different sub-catchments were also compared so as to understand the hydrological response of the different watersheds. The comparison of the catchments showed that the predominant soils in the study area have similar hydrologic properties as given by the Hydrologic Soil Group soil classification system developed by the United States Department of Agriculture (USDA) (National Engineering Handbook, 2007). Over 66 % of the soils are in groups C and D; groups with soils that are sandy but shallow or of a clayey nature and so tend to promote runoff rather than infiltration.

Rainfall is a key factor in determining discharge from a catchment. Rainfall from seven different stations in the study area was also compared to see if it varied significantly from one station to another.

#### HEC-HMS model

After conducting the physical parameter comparison, the HEC-HMS was then used to simulate flows based on inputs of rainfall, evaporation, soil type and hydrologic group, (soil moisture retention capacity), catchment area, lag time, peaking coefficient and runoff coefficient.

The HEC HMS model was selected because it has the Snyder Unit Hydrograph transformation subroutine specifically designed for ungauged catchments making it ideal for use in this study (HEC-HMS user manual, 2010).

#### Loss method used

For this study, the loss method used is the deficit and constant which is ideal for simulations of long periods. The deficit and constant is a quasi-continuous model of precipitation loss where by initial loss can recover after a prolonged period of no rainfall (HEC-HMS Technical Reference Manual, 2000). The maximum deficit represents the total soils storage depth while the initial deficit represents the empty storage depth at the beginning of the simulation. Soil moisture recovery rates can be specified in mm/day.

Soil data forms an important input into the model as this largely explains the loss method through infiltration. The soil data used in this model was obtained from Food and Agriculture Organisation (FAO) World Resource Base (WRB) map with a 300 metre resolution that was created by remote sensing techniques and verified using selected ground control points.

The map was then reclassified using the United States Department of Agriculture (USDA) soil classification system showing the soils hydrologic groups based on the infiltration rates of different soil types.

#### Soil Hydrologic Groups

Soils are classified into hydrologic soil groups (HSGs) to indicate the minimum rate of infiltration obtained for bare soil after prolonged wetting (National Engineering Handbook, 2007). The HSGs are A, B, C and D. Figure 3.7 shows the predominant soil types in the study area based on the Hydrologic Soil Group classification. The four groups are defined by Soil Conservation Service (SCS). Group A soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist of deep, well to excessively drained sands or gravels and have a high rate of water transmission (greater than 7.62 mm/hr).



Figure 3-5: Study area soil map showing the dominant soil types

Group B soils have moderate infiltration rates when thoroughly wetted and consist mainly of deep, well drained soils with moderately coarse textures. These soils have a moderate rate of water transmission (2.54-7.62 mm/hr). Group C soils have low infiltration rates when thoroughly wetted and consist of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (1.27-2.54 mm/hr). Group D soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0-1.27 mm/hr).

The soil classes in the study area as presented in Figure 3.5 show that the dominant soil types are Chromic Luvisols, Ferric Luvisols, Lithosols, Ferralic Arenasols and Orthic Ferrasols. The Ferralic Arenosols are in the HSG B while Orthic Ferrasols are in HSG A. The rest of the soils are all in the HSGs C and D. This means over two-thirds of the study area have soils with hydrologic properties that promote more runoff than infiltration.

#### Transformation method

Transformation methods control the time of concentration of water into a river channel. The Snyder Unit Hydrograph developed in 1938 was used as it is the most documented analysis for ungauged catchments using HEC HMS. Based on the observed peak discharge of 80.69  $m^3$ / for Musengezi and 6,020  $m^3$ /s for the Luangwa catchment and areas of 951  $km^2$  and 144.000  $km^2$  for Musengezi and Luangwa respectively, the Snyder Unit Hydrograph through Equation 5 was used to calculate the basin lag and the runoff coefficient based on the rational method.

Equation 5

 $Q_{p} = 0.28CIA$ 

 $Q_p$  = Peak discharge (m<sup>3</sup>/s)

С	=	Runoff coefficient
Ι	=	Rainfall intensity (mm/hour)
А	=	Catchment area (km <sup>2</sup> )

0.28 = Conversion factor from imperial to metric units

#### Meteorological Model in HEC-HMS

Data types required for the meteorological model of HEC-HMS are daily rainfall, mean monthly evaporation and the gauge weights of the different rainfall stations. The weather data was obtained from the Meteorology Departments of Zambia and Zimbabwe for stations in Kanyemba, Muzarabani, Luangwa, Guruve, Karoi, Marongora and Rukomechi. Thiessen polygons were then produced in Arcview to determine the spatial distribution of rainfall in the study area and also to determine the gauge weights of each rainfall station. The average monthly evaporation rates were calculated from the daily pan evaporation obtained from the Hidro electrica de Cahora Bassa (HCB).

#### Calibration and Validation of the Model

Before any simulations could be done, the model was calibrated using daily flow data from Upper Musengezi catchment at station C68 and rainfall from Guruve and Mount Darwin for the years 1990 to 1994 and flows from the Upper Luangwa Catchment with rainfall from Chipata and Petauke. Validation was done with data from the same station but for the period 1998 to 1999. The parameter optimisation algorithm of the HEC-HMS was used in the calibration process to determine the most optimal parameter values and also establish the most sensitive parameters.

Using observed peak discharge values of 80.69  $\text{m}^3$ /s and a catchment area of 951 km<sup>2</sup>, for the gauged Musengezi C68 catchment, the runoff coefficient was calculated at 0.52 while for the Luangwa catchment, a peak discharge of 6,020  $\text{m}^3$ /s and an area of 97,000 km<sup>2</sup> resulted in a runoff coefficient of 0.42. Since there was an established similarity between the gauged Musengezi and Luangwa and the ungauged catchments, the average of these two runoff coefficients was used as the runoff coefficient for ungauged catchments as well. The catchment lag time, an input into the HEC HMS model, for the different ungauged catchments was then calculated using the equation 7.

#### Equation 6

(km)

 $t_p = CC_t (LL_c)^{0.3}$ 

tp	=	Basin lag time (hours)
С	=	Conversion constant of 0.75
$C_t$	=	Runoff coefficient from gauged catchment
L	=	Stream length of the longest channel from outlet to divide (km)
Lc	=	Length of the main stream from the outlet to the watershed centroid
Other equation terms such as the L and  $L_c$  were obtained by hydro-processing of the study area DEM.

#### Model Simulation

The simulation of runoff was done for the whole catchment based on the parameter values obtained from the Musengezi catchment with the changes made being the catchment area, soils types, rainfall, initial soil moisture deficit and the maximum deficit. A semi-distributed rainfall-runoff model, the Hydrological Engineering Centre Hydrological Modelling System (HEC-HMS) was then used to simulate runoff based on input parameters such as rainfall, evaporation and physical catchment characteristics like soil type and area.

Performing a semi-distributed rainfall-runoff modelling requires a large amount of input data. Part of this input data was obtained through processing and analysis of a Digital Elevation Model (DEM) in combination with information extracted from other remotely sensed images of the selected model area. Thus 35 watersheds of the lake system were developed under GIS-based catchment modelling taking advantage of the DEM hydroprocessing algorithm of the ILWIS software. The major catchments extracted were the lower Luangwa, lower Chongwe, lower Kafue, the Angwa, lower Manyame, and a combination of the lower Musengezi, Kadzi and Mkumbura rivers. The corresponding watershed characteristics such as the area of the sub-catchments, the drainage density, the topography, soil type, land cover and elevation were derived.

#### Catchment Area Ratio Method

The results of the HEC-HMS model simulation were then compared with the results of the Catchment Area Ratio method to see how close the two were. The catchment area was obtained by GIS hydro-processing of the study area DEM while the gauged catchment used was the Upper Musengezi with the outlet at station C68.

#### Assessing Model Efficiency

The evaluation of hydrologic model behaviour and performance is commonly made and reported through comparisons of simulated and observed variables (Krause *et al.*, 2005). Frequently, comparisons are made between simulated and measured streamflow at the catchment outlet. In distributed hydrological modelling approaches, additional comparisons of simulated and observed measurements for multi-response validation may be integrated into the evaluation procedure to assess overall modelling performance. In both approaches, single and multi-response, efficiency criteria are commonly used by hydrologists to provide an objective assessment of the "closeness" of the simulated behaviour to the observed measurements.

In this study, the Nash-Sutcliffe Index for model efficiency was used to determine the goodness of fit of the simulated to the observed values. Quantitative assessments of the degree to which the modelled behaviour of a system matches with the observations provide an evaluation of the model's predictive abilities. In this context, the Nash–Sutcliffe efficiency index is widely used in water resources sector to assess the performance of a hydrologic model (Sharad and Sudheer, 2007; Krause et al., 2005). The formula for the Nash-Sutcliffe index as given below compares the measured flows against the simulated flows. The relative volume error (RVe) is another method for assessing and used the same parameters as the Nash-Sutcliffe coefficient.

Equation 7

$$E = 1 - \frac{\sum_{t=1}^{T} (Q_0^t - Q_m^t)^2}{\sum_{t=1}^{T} (Q_0^t - \overline{Q_0})^2}$$

Equation 8

$$RVe = \left(\frac{Q_{sim} - Q_{obs}}{Q_{obs}}\right) * 100$$

Where  $Q_0$  is observed discharge and  $Q_m$  is modelled discharge.  $Q_0^t$  is observed discharge at time t and *E* is the Nash-Sutcliffe model coefficient.  $\overline{Q}$  is the mean of observed data

#### **Gauging Ungauged Catchments**

In moving from ungauged to gauged catchments, two runoff stations were installed at Manyame Mapomha 15 km away from the border with Mozambique and at the Angwa Bridge. Cross sections of the two rivers were taken and the seasonal peak flows were noted based on water marks left on the Angwa and one season stage readings for the Manyame.



Figure 3-6: Cross section of the Manyame River at Maphoma Village



Figure 3-7: Cross Section of the Manyame River at Mapomha Village where a gauging station was installed and the accompanying Rating Curve

Using the Flow Master software, the stage-discharge relationship was developed and a rating curve for the river section produced. One season flow data gives the peak flow at Mapomha at 5 metres giving peak discharge of 299  $m^3/s$ .

The same was done at Angwa Bridge which had a peak discharge of 920  $\text{m}^3$ /s. Together with the catchment area, rainfall intensity was calculated which was then used to determine the lag time and the peaking coefficient; both inputs into the HEC-HMS model. In ungauged catchments where the peak discharge was not known, the formula was used to calculate the peak runoff.

# 3.2.4 Objective 3: Investigate link between the operation of the Cahora Bassa reservoir and flooding frequency in the riparian areas

For this objective, a comparison of the discharge hydrographs was conducted to establish how Cahora Bassa responds to the releases from Kariba dam and the Kafue Gorge hydroelectric scheme upstream. The hydrographs of the Luangwa, Musengezi and Manyame rivers were also plotted to show the peak flows and the timing of these peak flows in relation to the water levels of the Cahora Bassa Dam. This helps to determine how the two interact to cause floods in the study area.

A comparison of flooding events due to backwater effect from the Cahora Bassa Dam and as a result of flood flows in the tributaries was conducted. Contour lines were also drawn to show the spatial extent of the Cahora Bassa surface area at different water level and how this relates to the area flooded.

# **CHAPTER 4: RESULTS AND DISCUSSIONS**

This chapter presents the findings from the study whose main objective was to conduct a refined surface water balance of the Cahora Bassa dam by including the ungauged catchments and establishing if there is a link between reservoir operations and flooding in Luangwa, Kanyemba and Muzarabani districts.

The results and analyses are presented according to the three objectives with a summary of the discussion of the results obtained.

### 4.1 EXTENT OF UNGAUGED AREA

The study area, which comprises districts in Mozambique, Zambia and Zimbabwe, covers the lower part the middle Zambezi and has several major rivers such as the Manyame, Angwa, Musengezi, Rukomechi, Sapi Kafue, Chongwe and Luangwa Rivers that all directly or indirectly feed into the Cahora Bassa dam.



Figure 4-1: A Digital Elevation Model of the study area overlaid with the river network showing the old and new gauging stations

Figure 4.1 shows that there are 7 gauging stations upstream of the study area on the Kafue, Chongwe, Luangwa, Manyame, Dande and Musengezi Rivers. These stations have been used to estimate the flows into the Cahora Bassa Dam. Angwa and Manyame Mapomha stations were installed as part of this project.

According to the results of DEM hydro-processing, the spatial extent of the ungauged area given in Figure 4.2d is about 71,000 km<sup>2</sup> and a perimeter of 2,171 km. The lower boundary of the study area is the Cahora Bassa Dam wall while the outer boundaries are given by 7 gauging stations. The area covers catchments of the Lower Luangwa, Lower Chongwe, the Mombasha, the Kafue River downstream of the Kafue Gorge dam, Chewore, Rukomechi, Sapi, Runese, Mwanza Mtanda, Angwa, Lower Manyame, Kadzi, Mkumbura and the Lower Musengezi.



Figure 4-2: Extent of the ungauged area

# 4.2 WATER LEVEL AND LAKE SURFACE AREA

The relationship between the water level in the Cahora Bassa Dam and the total inundated area is given by the area-capacity curve shown in Figure 4.3. The results of the curve provided by the *Hidro Electrica de Cahora Bassa* (HCB) were then compared with the results of contours drawn at different water levels in the lake to show the extent of the lake when filled to different capacities.

The maximum flood level of the Cahora Bassa is 329 metres above sea level giving an inundated area of  $3,000 \text{ km}^2$ . However, because of the flat land terrain in the flood plain along the Luangwa, Musengezi and Mwanza Mtanda rivers, the extent of the floods goes further due to these rivers breaking their banks during high flows.

To get a truer picture of the inundated area, contour lines showing the spatial extent of the flood water at different lake levels were then drawn and the area inside these lines was then calculated and the results compared with those from the area-capacity curve. Comparing the results of the contour methods with those of the Stage-Area relationship, the contour method shows that the expanse of lake increases from 1,901 km<sup>2</sup> at 318m level to 2,651 km<sup>2</sup> at a 324m and 3,246 km<sup>2</sup> at full capacity as opposed to the area-capacity curve results which give 2,050 km<sup>2</sup> at 318 m, 2,550 km<sup>2</sup> at 324 m and 3,000 km<sup>2</sup> at full supply level of 329 m.



Figure 4-3: Stage-Area relationship of the Cahora Bassa Dam (Source: Hidro electrica de Cahora Bassa)

The change in elevation of the lower Luangwa catchment from the Luangwa Bridge to the Luangwa-Zambezi confluence is only about 100 metres over a 100 km distance. This results in the Luangwa breaking its banks during high flow periods and also when the Cahora Bassa Dam is at high level. The level at the confluence is approximately 335 m while the elevation at the Luangwa Bridge 100 km away is 474 m.

When the Luangwa breaks its banks, the floods reach up to 2.5 km away from the main river channel as shown in Figures 4.4 and 4.5 up to a distance of 27 km upstream of the Luangwa translating into an inundated area of  $52 \text{ km}^2$ .



Figure 4-4: The Luangwa with the blue line showing the extent of floods when the Luangwa breaks its banks (Source: Google Earth)

For the Mwanza Mutanda, the inundated area is much less due to the smaller size of the river compared to the Luangwa and the Musengezi Rivers (See Figure 4.5). Despite the Musengezi being a smaller river than the Luangwa, the flooding is almost of the same magnitude due to the low slope of the area.



Figure 4-5: Flooded areas in Muzarabani, Kanyemba and Luangwa shown by the red shapefile (Source: Google Earth)

### 4.3 CAHORA WATER BALANCE

#### 4.3.1 Inflows

#### **Gauged Inflows**

The ideal total inflow series of the Cahora Bassa is based on the flows from the Kariba Dam, Kafue Gorge Dam Luangwa, Chongwe, Mombasha, Mwanza Mtanda, Manyame, Musengezi, Mkumbura, Sapi, Rukomechi and Chiwore rivers. However, the absence of gauging stations on some of the smaller rivers resulted in the initial inflow series being based on a summation of the gauged flows from the Upper Luangwa, Upper Musengezi, Upper Manyame and Upper Chongwe with the releases from the Kariba and Kafue dams. This accounted for over 92 % of the total inflows into the Cahora Bassa.



Figure 4-6: Flows from the gauged rivers and managed dam releases

Figure 4.6 and Appendix B1, B2, B3 and B4 show the total flows from the gauged portions of the Luangwa River, Chongwe River and Musengezi River and the managed releases from

the Kariba Dam and Kafue Gorge Hydropower Scheme from 1980 to 2010. While all the other rivers are regulated, the Luangwa is unregulated and as shown by its large variation in peak and low flows. The hydrograph of the Luangwa River gives a very good indication of the catchment response to rainfall activity. Musengezi and Chongwe rivers are smaller in terms of flow and marked on the secondary axis on the right hand side. However, Chongwe and Luangwa rivers despite being different in magnitude show a similar trend or pattern of flow with similar peaks and troughs.

Due to the difference in magnitude of discharge among the various rivers, Chongwe and Musengezi rivers are plotted on the secondary axis while Kariba dam releases and spillage are plotted on another axis together with the releases and spillage from the Kafue Gorge power station and the flows of the unregulated Luangwa River.

The Kariba releases account for 51 % of the total Cahora Bassa inflows while Luangwa River accounts for 35 % with Kafue providing 11 % (Figure 4.7 and Table 1). These three sources account for a total of 97 % of the gauged flows going into the Cahora Bassa Dam.



Figure 4-7: The average annual percentage contribution from the different gauged sources

Source	Percent Contribution
Manyame River	1.22
Musengezi River	0.24
Chongwe River	0.20
Luangwa River	35.39
Kafue River	11.75
Kariba releases	51.20

Table 1: The average annual percentage contribution from the different gauged sources

However, according to the SADC Report (2011), the flows of the Luangwa may not actually be accurately known because the rating curve of this river is not updated regularly despite it

having a high sediment load. This may result in errors in the water balance especially in times of high flows.

Over the 30 year period under study, a combination of the total average gauged flows gives an average inflow of  $64.17*10^9 \text{ m}^3$  which is just about the capacity of the Cahora Bassa dam. This means the Cahora Bassa fills every year and passes any excess flows downstream.

#### Direct rainfall on Lake Surface

The contribution from direct rainfall on the lake surface was calculated based on the average areal rainfall and the average lake surface area during the rainy season.

The average areal rainfall was based on the results of Thiessen polygons of the study area (Figure 4.8) looking at the rainfall data from seven meteorological stations at Luangwa, Kanyemba, Muzarabani, Mana Pools, Karoi, Mount Darwin and Guruve. The rainfall pattern on the lake surface was given by Thiessen polygons with data from three rainfall stations at Luangwa, Kanyemba and Muzarabani.



Figure 4-8: Thiessen polygons showing the rainfall pattern in the study area

The calculation of direct rainfall contributions to inflows was based on the average surface area of the lake (Figure 4.9) during the rainy season (December to April) and the total annual rainfall for the 30 years period under consideration. Over 70 % of the Cahora Bassa lake surface receives rainfall in the range 742 mm/year to 752 mm/year while the rest of the lake surface receives between 952 mm/year to 783 mm/years of rainfall. Based on a n average rainfall of 749 mm/ years, the calculation of areal rainfall gave a rainfall contribution directly on the lake surface of  $1.64*10^9$  m<sup>3</sup>, a value of about 2.5 % of the total Cahora Bassa inflows.



Figure 4-9: Thiessen polygons of the rainfall patterns over the lake surface

Figure 4.10 shows the relationship between extent of the lake surface area and the inflow contribution from direct rainfall on the lake surface. The graph shows a direct relationship between the two.



Figure 4-10: Relationship between rainfall on the lake surface and the area of the lake surface during the month of January

#### 4.3.2 Volume of Outflows

#### Discharge

The outflow volume from then Cahora Bassa was determined based on discharge reading provided by HCB at the Cahora Bassa dam outlet. The outflow volume was calculated using equation 4.

For the period from 1980 to 2010, the outflow volume from the Cahora Bassa ranged from a minimum of  $19 * 10^9 \text{ m}^3$ /year to a maximum of  $137 * 10^9 \text{ m}^3$ /year with an average of  $48 * 10^9 \text{ m}^3$ /year.

#### Evaporation

In addition to the managed discharge, evaporation accounted for significant amounts of water loss from the reservoir. Evaporation data was provided by the HCB together with the average monthly lake surface area which when plotted in Figure 4.11 shows a direct relationship between the two inputs. Based on this data, the evaporation from the dam due to surface evaporation was estimated at  $3.8*10^9$ m<sup>3</sup> which is about 7.32 % of the total outflows.



Figure 4-11: The relationship between lake evaporation and lake surface area measured in the month of January

# 4.4 UNGAUGED FLOW CONTRIBUTION

The contribution from ungauged catchments was based on the results of the HEC-HMS model that was used to simulate flows from inputs of rainfall, soil type (texture, depth), land cover, initial soil moisture content. For the ungauged rivers, the peak flows were estimated using the rational equation using runoff coefficient, rainfall intensity and catchment area as inputs.

## 4.4.1 HEC HMS Model Calibration and Validation

#### Model Calibration

The model was calibrated with flow data from the Upper Musengezi Catchment at station C68 using flows for the period 1990 to 1994 and the Upper Luangwa Catchment at the Luangwa Bridge station for the period 1995 to 2000. The initial model simulation run gave an outflow of  $71.3 * 10^6$  m<sup>3</sup>/year compared to the observed value of  $68 * 10^6$  m<sup>3</sup>/a for the Upper Musengezi catchment giving a relative volume error (RVe) of 4.85 %. However, despite the low RVe, the Nash-Sutcliffe model efficiency was -4.675 indicating that the observed mean is a better predictor of flow than the modelled mean. This is particularly so because the observed and simulated graphs are out of synch as seen in Figure 4.12. Nash-Sutcliffe model efficiency coefficient values ranges from - $\infty$  to 1. Values below 0 show that the observed mean is a better predictor of flow than the modelled while values close to 1 show a very good fit between observed and modelled flow data.



Figure 4-12: Initial Model Performance

For the Luangwa Catchment, the initial model performance gave a discharge of  $22.87*10^9$  m<sup>3</sup>/a compared to the observed discharge of  $95.97*10^9$  m<sup>3</sup>/a giving a RV<sub>e</sub> of -95.59 and a Nash-Sutcliffe model efficiency value of 0.6. Figure 4.13 shows that the model initially under-estimated the discharge from the Luangwa catchment resulting in higher losses through infiltration, interception and evaporation.



Figure 4-13: Initial Model Performance for the Luangwa Catchment

#### Parameter Optimisation

In order to improve the model performance, the parameter optimisation function in the model was then used to come up optimal parameter values for calibration. The parameters used for calibration and optimisation are the constant loss rate, the initial deficit, the maximum deficit based on the soil type, the Muskingum K and Muskingum X values.

After parameter optimisation, the simulation run gave an annual outflow volume of 70.5 \*  $10^6 \text{ m}^3$  against an observed outflow of  $68 \times 10^6 \text{ m}^3$  giving a relative volume error of 1.54 %,

while the model efficiency as given by the Nash-Sutcliffe improved to 0.067 indicating that the model was able to simulate the catchment response as indicated by Figure 4.15. The poor performance of the model with the Upper Musengezi catchment was due to the high number of small private dams in the catchment that attenuated and translated discharge. The attenuation effect of these dams affects the observed lag time resulting in observed and simulated graphs being out of sync as shown in Figure 4.14. The effect of the many dams in the catchment can be seen from the two months time lag between the observed and simulated hydrograph peaks. Because of lack of rating curves for these numerous dams, they were not included in the model resulting in the attenuation effects of the dam being replicated by the model.



Figure 4-14: Model Performance after Calibration



Figure 4-15: Model Performance after Calibration and Parameter Optimisation for the Luangwa Catchment

For the Luangwa Catchment, after parameter optimisation, the model gave a  $RV_e$  of 8.42 and a Nash-Sutcliffe coefficient of 0.97 indicating that the model was able to simulate the catchment response as given in Figure 4.15.

### Model Validation

After calibration, the model was then validated with flow data for the Upper Musengezi for the period 1998 to 1999. The model gave a better performance (Figure 4.16) resulting in a relative volume error of 2.71 % and a Nash-Sutcliffe model efficiency coefficient of 0.07.



Figure 4-16: Model performance during Validation using Upper Musengezi Catchment

Model validation in the Luangwa Catchment was done using flow data for the period 2004 to 2007 and rainfall from Chipata and Petauke meteorological stations. The validation results given in Figure 4.17 give a  $RV_e$  of -8.11 and a Nash-Sutcliffe coefficient of 0.191 indicating a model performance that was acceptable.



Figure 4-17: Results of Model Validation for Luangwa Catchment

The model was then further validated with one season flow data from the Manyame at Mapomha Village station set up as part of this project objective of gauging ungauged catchments. The results of the validation with the Manyame Mapomha station flows give a hydrograph shown in Figure 4.18. The results of this validation show that the model can perform in a different catchment.



Figure 4-18: Performance of the model when used on the Manyame Catchment

Figure 4.18 gives the results of the validation with the Lower Manyame catchment data which gave a  $RV_e$  of 3.20 % while the Nash-Sutcliffe coefficient was 0.66 suggesting a good fit between simulated and observed flows at the gauging station.

## 4.4.2 Catchments Comparison

Before transferring the model parameters from the gauged Upper Musengezi and Upper Luangwa catchments to the ungauged catchments, a comparison of the physical catchment parameters that influence discharge was done based on the work by Sreenivasulu and Bhaskar (2010). Since runoff is a function of catchment hydrological response which is itself related to rainfall, soil type, slope (Figure 4.19), elevation (Figure 4.20), land use and land cover, and catchment area, these physical parameters where compared to see how closely related the sub-catchments.



Figure 4-19: Slope class map for the study area



Figure 4-20: Digital Elevation Model of the study area showing the elevation differences

Figure 4.21 shows that most of the land in the study area is flat typical of a valley area leading to higher time of concentration similar to the slope class of the Upper Luangwa (Figure 4.21(c). Figure 4.20 shows the elevation range of the study area (315 to 1310 metres) from the plateau to the valley but also shows that most of the land in the valley has an elevation of between 315 and 514 metres.

Other physical catchment parameters such as catchments area, drainage length, drainage density, longest drainage length and the elevation are given in the Table 2 based on the results of hydro-processing in ILWIS are some of the parameters considered for comparing the sub-catchments.

These parameters are most important in influencing the catchment runoff and other hydrological processes. One of the most important comparison parameters is the drainage density which shows how well drained as area is. All the sub-catchments in the study area have a drainage density of 32 m/km<sup>2</sup> to 88 m/km<sup>2</sup>. Both the Luangwa and Musengezi are predominantly flat terrain as shown in Figures 4.20 and 4.21c while the elevation ranges within 200 m to 2000 m (Figures 4.20 and 4.21a).



Figure 4-21: Slope, Elevation and soil maps of the Luangwa catchment compared with the study area



Figure 4-22: Comparison of monthly rainfall for the six stations in the study area

Another comparison between the gauged and ungauged catchments was based on meteorological properties from six stations (Figure 4.22 and Appendices A1, A2, A3, A4 and A5). Monthly rainfall from the six stations in the study area show a similar trend as indicated in Figure 4-22. The mean annual rainfall ranges from 657mm to 803mm.

## 4.4.3 Model Simulations

#### Parameter Transfer

Before simulating discharge from the ungauged catchments, parameters from the gauged catchments were transferred through the Snyder Transformation using the calculated values of catchment lag time and peaking coefficient. These parameters are important as they are influenced by meteorological (rainfall) and physical (slope, area, land cover, drainage length e.t.c.) catchment characteristics.

#### Model Simulation

Based on the parameters from the Upper Musengezi and the Upper Luangwa catchments, stream flows were simulated for the remaining ungauged rivers in the catchment to come up with the ungauged contributions to the flows into the Cahora Bassa dam.

Figure 4.23 together with Appendices D1 and D2 shows the outline of the basin model of the HEC-HMS used to simulate runoff so as to come up with discharge figures for the different sub-catchments as shown in Appendix D2 giving a total for the whole ungauged area. Runoff from these catchments using a seven years simulation run gave a mean outflow volume of  $8.76 * 10^9$  m<sup>3</sup> which is 11.78 % of the total inflows into the Cahora Bassa dam. The peak outflow from the 35 ungauged sub-catchments is 2,513 m<sup>3</sup>/s and occurs at the end of the month of January.

Sub- catchment	Perimeter (km)	Catchment Area (km <sup>2</sup> )	Total Drainage Length (km)	Drainage Density (m/km)	Longest Flow Length (km)	Longest Drainage Length (km)	Outlet Elevation (m)	Upstream Elevation (m)
1	102.1	259.1	13.0	50.2	46.4	13.0	316.0	490.0
2	118.0	394.9	20.7	52.5	52.7	20.7	316.0	472.0
3	171.8	870.6	57.9	66.5	83.8	57.9	316.0	940.0
4	152.2	607.3	41.4	68.1	77.5	41.4	372.0	1,088.0
5	238.8	1,028.2	90.7	88.3	116.9	90.7	358.0	1,206.0
6	114.3	428.7	20.5	47.9	39.9	20.5	316.0	466.0
7	95.4	288.7	16.5	57.1	36.6	16.5	358.0	976.0
8	100.9	540.7	28.9	53.5	49.1	28.9	336.0	877.0
9	65.5	202.3	6.6	32.6	28.2	6.6	316.0	449.0
10	145.7	523.3	32.9	62.8	61.5	32.9	361.0	871.0
11	107.9	356.3	21.3	59.8	51.6	21.3	343.0	1,132.0
12	255.5	1,365.3	89.1	65.3	92.0	73.5	323.0	1,255.0
13	129.7	503.1	34.4	68.4	62.7	30.4	361.0	781.0
14	152.7	753.4	34.5	45.8	53.7	26.4	358.0	854.0
15	242.1	1,620.4	129.1	79.7	122.4	95.6	358.0	1,160.0
16	114.2	560.6	28.2	50.2	41.1	19.7	358.0	1,102.0
17	173.1	1,439.0	94.4	65.6	94.8	62.6	316.0	735.0
18	279.1	2,026.4	148.5	73.3	111.0	85.8	316.0	1,117.0
19	343.5	2,467.1	168.3	68.2	155.7	123.2	358.0	1,326.0
20	265.5	2,383.3	97.9	41.1	91.1	70.9	316.0	699.0
21	247.2	2,050.9	150.4	73.3	113.0	80.3	317.0	1,080.0
22	274.2	1,813.9	135.4	74.7	127.3	104.3	358.0	1,186.0
23	221.2	1,890.4	108.5	57.4	87.7	71.1	336.0	1,692.0
24	210.3	1,892.8	123.7	65.3	76.7	45.7	316.0	1,312.0
25	398.7	3,600.9	188.7	52.4	161.5	134.1	358.0	1,168.0
26	392.9	3,633.8	219.4	60.4	156.0	126.1	316.0	1,170.0
27	168.0	969.2	65.0	67.0	87.4	59.3	336.0	1,253.0
28	319.2	2,798.3	201.2	71.9	143.7	121.1	316.0	824.0
30	569.5	6,607.3	389.1	58.9	174.2	145.8	330.0	1,076.0
31	635.7	9,491.3	532.7	56.1	251.1	229.5	346.0	1,244.0
33	326.4	2,338.8	150.2	64.2	136.1	109.3	316.0	1,145.0
34	467.0	7,347.4	439.2	59.8	85.0	143.8	358.0	711.0
35	1,661.3	7,159.2	690.5	96.5	445.9	416.5	316.0	1,383.0

Table 2: Summary of key physical catchment parameters used for catchment comparison

Figure 4.24 shows the pattern of outflow from the ungauged catchments for the seven years simulation period. The discharge from the various sub-catchments is directly proportional to the area of the sub-catchment and the dominant soil types with larger sub-catchments and sub-catchment with dominant soils being of the C and D class having a higher runoff.



Figure 4-23: An outline of the catchments in the study area used in the HEC-HMS model. Junction 4 is the final outlet for the whole area



Figure 4-24: Hydrograph of simulated flows from the ungauged catchment over a 7 years period

#### 4.5 THE WATER BALANCE

From the literature, it has been shown that the water balance may be obtained from the following equation:

Equation 9

$$\Delta S / \Delta t = Q_{in} - Q_{out} + (P - E)A$$

Where:  $\Delta S = Change in storage (Mm<sup>3</sup>)$ 

=	Change in time (year)
=	Inflow into the reservoir $(m^3/s)$
=	Outflow from the reservoir $(m^3/s)$
=	Precipitation on the lake surface (mm/year)
=	Evaporation from the lake surface (mm/year)
=	Surface area of the lake (km <sup>2</sup> )
	= = = =

Table 3: The refined surface water balance of the Cahora Bassa including the ungauged flow

Source	Percentage	Volume
Gauged Flows	85.99	62,536,000,000
Ungauged Flows	11.76	8,569,000,000
Lake Rainfall	2.24	1,636,948,000
Total Inflows		71,106,948,000
Evaporation	7.32	3,810,319,000
Discharge	92.68	48,245,221,000
Total Discharge		52,055,541,000
Residual Storage		20,686,406,000

The refined surface water balance of the Cahora Bassa shows an average annual inflow over the thirty year period of  $71.1 \times 10^9 \text{ m}^3$  which is slightly more than the capacity of the reservoir, an average annual outflow of  $52 \times 10^9 \text{ m}^3$  and a residual storage of  $20.68 \times 10^9 \text{ m}^3$ . A contribution of 85.97 % of the inflows comes from gauged catchments while 11.78 % comes from the local ungauged catchment. Using the Catchment Area Ratio method given in Equation 2, the ratios of the gauged area to the ungauged area and the ungauged discharge to the gauged discharge were compared.

The Upper Musengezi gauged area was estimated to include all the area upstream of the Musengezi C68 station. This area covers 951 km<sup>2</sup> while the Luangwa gauged area includes all the land upstream of the Luangwa Bridge station and in estimated at 144,700 km<sup>2</sup>. The ratio of the ungauged flow to the gauged flow is 0.137 (or 13.7 %) which is quite close to the 11.78 % ratio of ungauged flows to gauged flows indicating that the simulation is quite close to the true discharge.

# 4.6 RELATIONSHIP BETWEEN RESERVOIR OPERATIONS AND FLOODS IN STUDY AREA

To establish whether or not there is a relationship between the operation of the reservoirs and the frequency of flood occurrence in Muzarabani, Kanyemba and Luangwa, the following analyses were done

- Comparison of the tributary rivers peak flows and Cahora Bassa water level,
- Ascertain the dam water level during times when floods were reported,
- Ascertain rivers flow during times when floods were reported

A comparison of the reservoir operations over the last thirty years with the Operational Rule Curve was done to see if the Cahora Bassa was being operated based on its rule curve as shown in Figure 4.25. The figure shows that Cahora Bassa has essentially been operated below the rule curve except during the period between January and March in the years 2001/02, 2003/04, 2008/09 and 2009/10 when the water level rises above the rule curve. This period also coincides with the period when floods are experienced in the study area indicating a possible link between reservoir operations and flood occurrence.



Figure 4-25: A comparison of the Operational Rule Curve with the average dam water level in different months of the year

An analysis of Cahora Bassa inflow-outflow relationship (Figure 4.26 and Appendix B2) shows a similar pattern between the total inflows and the total discharge due to electricity generation, spillage and managed releases. When read in conjunction with Figure 4-25, Figure 4-26 and Appendix B2 show that floods are most likely during the time when the dam is filling between January and March.



Figure 4-26: Comparison of inflows and Cahora Bassa discharge

While flows from the Luangwa peak in January, Cahora Bassa Dam according to its rule curve anticipates this peak by releasing more water in December. The other sources of inflow from the Kariba Dam and the Kafue Gorge Dam do not fluctuate as much as the Luangwa as indicated in Figure 4-27. A plot of Cahora Bassa Dam water levels with time and flood occurrence incidences from literature (Figure 4.28) shows that while most floods since 2000 have occurred during times of high water levels, the water level at these times was still lower, below 324 metres, than the peak water levels in April of between 324 and 328 metres when no floods occurred.



Figure 4-27: Inflow-outflow relationship of the Cahora Bassa Dam and the three major inflow sources



Figure 4-28: Shows the water level changes in different years and in different months while the green circles indicate the occurrence of notable floods

Figure 4-29 read in conjunction with Figures 4-27 and 4-28 shows that most floods since 2000 have occurred between the months of February and May when the water level in the Cahora Bassa has gone above 324 m. One exception was the 2003 flood which occurred two months earlier in December when the water level was just above 321 metres. This event however was heavily influenced by the occurrence of Tropical Cyclone Japhet which ravaged Southern Africa for much of the 2003 rainy season according to the Southern African Development Community (SADC) Floods and Drought Hazards Network report (2003).



Figure 4-29: Dam water level and how often critical levels have been exceeded in the last ten years



Figure 4-30: Water level changes in the Cahora Bassa due to releases from Kariba and Kafue dams

Figure 4.30 shows the water level changes in the Cahora Bassa with the accompanying releases from the Kariba and Kafue dams upstream while Figure 4-31 shows the inflowoutflow relationship of the Cahora Bassa and the accompanying water level changes. Figure 4.30 shows that Kariba releases makes a major contribution to the flows into the Cahora Bassa Dam and that there is a direct relationship between releases from Kariba and changes in the water level in Cahora Bassa.



Figure 4-31: Inflow-outflow relationship of the Cahora Bassa and the associated water level changes



Figure 4-32: Showing high flows in 1999, 2000 and 2001 some of the years of floods

Analysis of gauged peak flows of the Luangwa and Musengezi Rivers show that the occurrence of floods around these rivers coincides with high flows during these years. This shows that, while each factor i.e. high lake levels and high river flows, can separately result in a flood, a combination of the two heightens the probability of occurrence of a flood.



Figure 4-33: Satellite image of the Cahora Bassa showing the rivers (blue) and high water level contour (red). The black circles show areas in Muzarabani, Kanyemba and Luangwa that are flood prone

Figure 4.33 shows that extent of flooding in the study area due to the high water level in the lake combined with high flows in the Luangwa, Mwanza Mtanda and Musengezi rivers indicating that Muzarabani is more flood prone than either Luangwa or Kanyemba.

# **CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS**

Based on the findings of this study, the following conclusions can be drawn:

- \* The surface water balance of the Cahora Bassa Dam for the period 1980 to 2010 gives an average annual inflow of 71 x  $10^9$  m<sup>3</sup>, a managed discharge of 48.2 \*  $10^9$  m<sup>3</sup>, evaporation of 3.8 \*  $10^9$  m<sup>3</sup> and a residual storage of 20 \*  $10^9$  m<sup>3</sup>. Direct rainfall on the lake surface contributes only 2.5 % (1.8 \*  $10^9$  m<sup>3</sup>).
- \* The ungauged catchment is 71,112 km<sup>2</sup> and lies in a low rainfall part of the Zambezi basin with average rainfall of 742 mm/year compared to the plateau areas which have rainfall rates of more than 1000 mm/year. However, evaporations in also relatively higher especially during the hot dry months of August, September, October and November.
- \* Based on a ten year rainfall runoff simulation using the HEC-HMS model, the runoff from ungauged catchments is  $8.7 \times 10^9$  m<sup>3</sup>/annum, which translates to about 12 % of the total inflows into the Cahora Bassa Dam.
- \* From 1982 to 1998, Cahora Bassa was at its lowest level not going above 322 metres but this has changed since 1999 when the water level rose to 326 metres, reaching a peak of 328 metres in 2008. This period of high lake water levels has coincided with the increased occurrence of floods in the study area suggesting a link between water level and flooding.
- \* Floods occur in the study when the lake water level exceeds 318 metres.

Floods have also been observed in years when the three major water sources for the Cahora Bassa, Kariba, Kafue and Luangwa, have produced high discharges as seen in 1999, 2000, 2003 and 2007. This leads to the conclusion that there is a direct relationship between operations of the reservoirs in the lower middle Zambezi and the occurrence of floods in the study area.

In view of these conclusions drawn, the following recommendations are suggested:

- ✓ An analysis of the socio-economic impacts of the floods should be done to establish the costs and benefits of the floods. This is necessary since the population is increasing in these areas as more people venture into the fertile plains left behind by the flood waters.
- ✓ Future studies should be conducted with a better set of flow and rainfall data for model calibration and validation. This will be particularly so after a longer time series of flow data has been collected from the Angwa and Manyame runoff gauging stations that were set up as part of this study.

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# **APPENDICES**

# **APPENDIX A: RAINFALL ANALYSIS**



Appendix A 1: Karoi Annual Rainfall

Appendix A 2: Guruve Annual Rainfall





Appendix A 3: Kanyemba Annual Rainfall

Appendix A 4: Luangwa Annual Rainfall





Appendix A 5: Muzarabani Annual Rainfall

# **Appendix B: Runoff Analysis**



Appendix B 1: Flows from the Chongwe and Musengezi rivers

Appendix B 2: Comparison of Cahora Bassa inflows and outflows




Appendix B 3: The fluctuations in water level at the confluence of the Zambezi and Luangwa rivers

Appendix B 4: Mean monthly water levels in Cahora Bassa



## **Appendix C: Cross Sections and Rating Curves**



Appendix C 1: Manyame River Rating Curve at Manyame Bridge in Mushumbi

Appendix C 2: Angwa River Rating Curve at Angwa Bridge





Appendix C 3: Cross Section of the Angwa River at Angwa Bridge





## APPENDIX D: HEC-HMS INPUTS AND OUTPUTS

Appendix D 1: Sub-catchments in the ungauged area used to model runoff



Sub-catchment	Drainage Area	Peak Discharge	Time of Peak	Volume x 10 <sup>3</sup>
	(km²)	(m³/s)		(m³)
kafue	7,347.4	34.6	16-Jan-96	300,646.5
chongwe	3,600.9	6.5	23-Dec-98	50,473.4
rukomechi	2,467.1	5.8	16-Jan-96	50,475.4
zam_1	1,028.2	214.7	24-Jan-98	181,683.5
zim_2	753.4	2.6	16-Jan-96	16,722.7
zim_6	607.3	4.1	16-Jan-96	26,961.4
zim_1	503.1	1.2	16-Jan-96	10,293.0
angwa	9,491.3	14.1	11-Feb-97	157,145.0
luangwa	6,607.3	32.6	29-Jan-98	261,345.9
manyame	2,338.8	5.5	11-Feb-97	51,250.1
chewore	1,813.9	5.1	29-Jan-98	36,788.5
zam_2	1,620.4	338.4	24-Jan-98	286,327.9
zam_3	560.6	117.1	24-Jan-98	99,065.7
mwanza	540.7	1.5	29-Jan-98	10,966.4
moz_1	356.3	74.4	24-Jan-98	62,957.3
zim_3	288.7	1	16-Jan-96	6,409.4
mkumbura	2,798.3	203.7	01-Jan-99	108,366.3
moz_2	2,050.9	428.4	24-Jan-98	362,412.8
msengezi	1,890.5	12.8	18-Jan-99	87,108.6
kadzi	1,365.3	3.2	11-Feb-97	29,917.3
zim_7	969.2	80.9	20-Feb-94	37,735.7
moz_4	870.6	298.1	31-Dec-98	271,861.8
moz_3	523.3	109.3	24-Jan-98	92,474.5
zim_4	428.7	35.6	31-Dec-98	6,144.2
moz_8	394.9	135.2	31-Dec-98	123,329.1
moz_9	259.1	88.7	31-Dec-98	80,916.2
zim_5	202.3	29	27-Dec-97	10,763.1
Zambezi	7,159.2	18.7	03-Feb-98	40,921.4
moz_5	3,633.8	644	25-Jan-98	642,114.2
moz_6	2,926.4	611.2	24-Jan-98	517,114.9
moz_12	2,383.3	693.2	28-Dec-97	744,240.3
moz_7	1,892.8	335.5	25-Jan-98	334,463.0
moz_10	1,439.0	426	28-Dec-97	515,277.8
Total Ungauged Flow	71,112.8	1639.1	29-Jan-98	8,711,073.9

Appendix D 2: Simulated flows from the ungauged sub-catchments