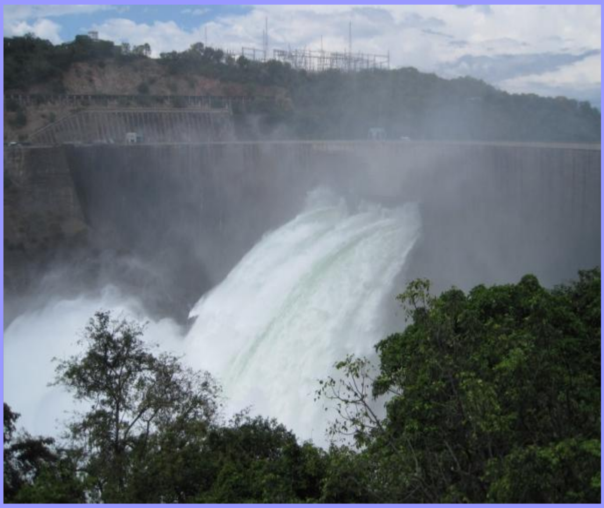
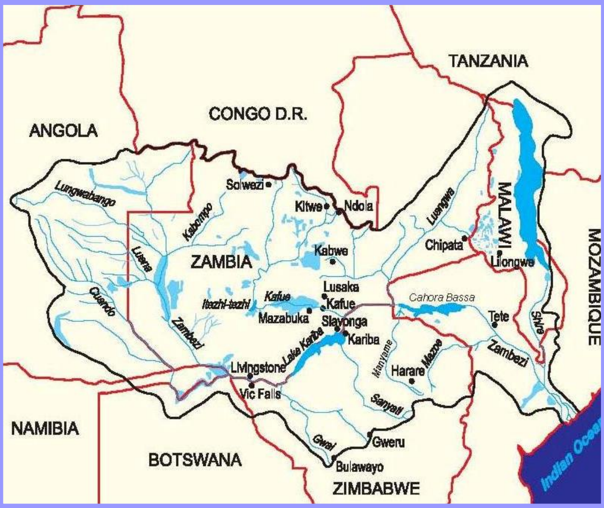
Transboundary Water Management in SADC

DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT





Annex 2

Concepts and Recommendations for Dam Management

31 March 2011

giz
On behalf of:
Federal Republic of Germany
The Federal Government
UKaid
from the Department for International Development
Australian Government
Aid Program

SWRSD Zambezi Basin Joint Venture

SSI
A DHV COMPANY
WRNA
W R Nyabeze and Associates
RANKIN
SEED
Sociedade de Engenharia e Desenvolvimento, Lda.
GRUPO DHV
Deltares
Enabling Delta Life

This report is part of the Dam Synchronisation and Flood Releases in the Zambezi River Basin project (2010-2011), which is part of the programme on Transboundary Water Management in SADC. To obtain further information on this project and/or progamme, please contact:

Mr. Phera Ramoeli
Senior Programme Officer (Water)
Directorate of Infrastructure and Services
SADC Secretariat
Private Bag 0095
Gaborone
Botswana
Tel: +267 395-1863
Email: water@sadc.int

Mr. Michael Mutale
Executive Secretary
Interim ZAMCOM Secretariat
Private Bag 180
Gaborone
Botswana
Tel: +267 365-6670 or +267 365-6661/2/3/4
Email: secretariat@zamcom.org

Table of Contents

List of Tables

List of Figures

List of Acronyms

AG	Advisory Group
ARA Zambeze	Regional Water Administration for Zambezi
CBO	Community Based Organization
CPC	Climate Prediction Center
DANIDA	Danish International Development Assistance
DNA	Direcção Nacional de Águas (Department of Water Affairs in Mozambique)
ECMWF	European Centre for Medium-Range Weather Forecasts
EDM	Electricity de Mozambique
EFR	Environmental Flow Requirements
ESCOM	Electricity Supply Corporation of Malawi
EU	European Union
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (German International Cooperation)
HCB	Hidroeléctrica Cahora Bassa
HYCOS	Hydrological Cycle Observation Station
ICOLD	International Commission of Large Dams
ICP	International Cooperating Partner
IFR	Instream Flow Requirements
IFRC	International Federation of Red Cross and Red Crescent Societies
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organization
IUCN	International Union for Conservation of Nature
Lake Malawi	Lake Malawi also known as Lake Nyasa, Lake Nyassa, Lake Niassa, or Lago Niassa or Nhiassa
METEOSAT	Meteorological Satellites
MoU	Memorandum of Understanding
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NGO	Non Governmental Organization
NOAA	National Oceanic and Atmospheric Administration
PC	Policy Committee
PMC	Project Management Committee
PMS	Performance Management System
PSC	Project Steering Committee
RBO	River Basin Organization
RSAP	Regional Strategic Action Plan
SADC	Southern African Development Community
SAPP	Southern Africa Power Pool
SARCOF	Southern Africa Regional Climate Outlook Forum
SIDA	Swedish International Development Agency
SWRSD JV	SSI, WRNA, Rankin, SEED, Deltares Joint Venture (the Joint Venture of Consulting Firms for this project)
ToR	Terms of Reference
TRMM	Topical Rainfall Measuring Mission
TTWW	Think Tank Work Week
TWM	Transboundary Water Management
UNZA	University of Zambia
USAID	United States Agency for International Development
USGS	US Geological Survey
UTIP	Unidade Técnica de Implementacáo de Projectos Hidroeléctricos
WB	World Bank
WMO	World Meteorological Organization

WWF	World Wide Fund for Nature
ZACPLAN	Zambezi Action Plan
ZAMCOM	Zambezi Watercourse Commission
ZAMWIS	Zambezi Water Information System
ZESA	Zimbabwe Electricity Supply Authority
ZESCO	Zambia Electricity Supply Company
ZINWA	Zimbabwe National Water Authority
ZRA	Zambezi River Authority

Executive Summary

The Zambezi River Basin is a complex system with two large man-made lakes, a large natural lake, large wetlands, and many small dams. The system stretches across 8 riparian countries and is integral to the economies of these countries supporting various activities including hydropower, irrigation, fisheries, navigation and tourism. Infrastructure on the system such as dams and barrages make the system present opportunities for regulation. However this infrastructure has largely been operated in a stand-alone mode with narrow objectives and a consideration of a single hydrological year. This operating mode is undesirable because it increases system vulnerability to threats from variability in climate and hydrology including floods, droughts and environmental degradation while missing the opportunity to maximise and share benefits.

Floods and droughts are part of the history of the Zambezi and have occurred in the situations with and without dams. Large floods and severe droughts are a fact of life in the Zambezi system. There is need to acknowledge that dams impound floods and alter downstream flow regimes. Dams cannot stop floods but can help manage them. In addition, while they cannot restore the original conditions, the operation of existing and new dams can minimize upstream and downstream impacts.

The major dams on the Zambezi except for Kariba will fill up every year on average. These other dams cannot capture and store large floods and on average they will spill every year. Unregulated tributaries on the Zambezi River System contribute significantly to flooding and they influence timing and magnitude of flood releases. “New” dams on the Zambezi main stem and tributaries are unlikely to be larger than Kariba but can reduce pressure on existing large dams and indirectly contribute to flood management. The operation of Kariba dam is thus very important for management of floods in the Zambezi river system.

This document proposes new “modes of operating” dams in the basin that simultaneously address different objectives including dam safety, hydro power production, drought and flood management and the needs of the environment. These are presented as “Recommendations and Concepts for Dam Management” which seek to achieve the following:

- Improve the modes of operation of the dams on the Zambezi in order to contribute to the balancing between the interests of environmental flows, flood reduction, hydropower generation and agriculture and;
- Improve cooperation between Dam Operators by providing them new insights, methods and improved confidence.

The recommendations are drawn from analysis on the following seven topics:

1. Long cycles and climate change
2. Wetland retention and its enhancement
3. Regulation of existing large reservoirs
4. Regulation of Lake Malawi/Shire river
5. New multipurpose dams on the Zambezi and its tributaries
6. Synchronization of dams for flood release and
7. Sediment management

The Lake Malawi/Shire subsystem is presented separately as dictated by the terms of references for this study.

The new modes of dam operation consider operating rules for the dams which incorporate multiple objectives and span over a number of rainfall seasons while giving due consideration for hydrological cyclicity.

An analysis of historical annual rainfall data reveals cyclic behavior in rainfall patterns. However, apparent cyclic behavior in annual rainfall limitations cannot be easily verified because of the short length of the data. Four plausible climate change scenarios for 2030-2050 were generated based on conclusions drawn from the literature review. These were presented as four combinations of plausible rainfall changes and temperature changes and ranged from a "very wet", "wet", "dry" and "very dry" periods. As such dams on the system need to be operated with due regard for these extended wet and dry periods.

An analysis of flood retention by wetlands for different seasons showed that the retention varied significantly probably because this capacity largely depends on antecedent water levels in the wetland. Established methods for enhancing wetlands retention capacity were interrogated and found to be unsuitable for application on the identified wetlands. However, climate change scenarios identified in this project may have adverse impacts on wetland functioning. These need to be investigated further.

A review of the operating rules for the large existing dams on the Zambezi River System showed that these rules primarily consider dam safety and provision of water and adequate head for hydropower production. Different flow categories can be linked to different ecosystems requirements but timing, frequency and duration are important. The Zambezi Basin serves many competing functions, therefore its water resources should be utilized with due regard of the health of the ecosystem. The study identified eight objectives as follows which need to be considered in operating rules:

- **Dam Safety**: Manage releases to avoid the reservoir reaching unsafe levels. Provide adequate capacity to safely storing and pass the design flood.
- **Hydropower**: Provide adequate head and firm yield for electricity generation. Failure of Hydropower has severe socio-economic consequences beyond the Zambezi basin riparians.
- **Flood management**: Avoid loss of life and reduce socio-economic impacts.
- **Environmental management**: Maintain flow characteristics. Provide quantity and quality of water required to maintain ecosystems and enable them to provide sustainable services and good quality water
- **Dry season floodplain agriculture**: Accommodate harvest period in release management
- **Plantation irrigation**: Provide adequate yield for crop production
- **Navigation**: Provide adequate flow for large ferry boats
- **Other water users**: These can also have their own sets of priorities according social considerations such as elimination of poverty and economic benefits.

Incorporation of these objectives can also contribute to improvement the ecology, of socio-economic conditions of the riparian population and beyond. However each of these other water uses has different links to the water resource system which need to be kept in balance through a multi-objective procedure. This would provide an answer on how dam management can incorporate the other uses. Synchronisation is required for allows objectives for a river reach to be set to support the objectives for another river reach. Monitoring and review are prerequisites for ensuring that the whole system is kept in balance. The establishment of environmental flow requirements for the Zambezi River basin requires more detailed studies.

In order to address these challenges new modes of dam operation were developed. These consider a five year operating window and distinguish between wet and dry cycles. The justification, development, testing, and evaluation of the proposed new operating modes was informed by analysis of long cycles and climate change; assessment of wetlands retention capacity; identification and the incorporation of multiple operating objectives. The simulations conducted on this study show that:

(a) During "wet" and very wet" periods dam operations can observe the dam safety rule, and meet other objectives and reduction in power output can be met through the provision of additional turbines on existing dams.

(b) During droughts or when storage and inflow are low, releases should be curtailed to avoid violation of minimum operating level for hydropower, protect that the lake environment and allow storage in the reservoir to recover. During these periods connection to the SAPP is essential for augmenting power supply.

The actual setting up of multiple objective operating rules should be informed by a set of guidelines and detailed studies. Inflow variability and climate change scenarios can be incorporated in dam operations by use of statistical approaches which consider historical patterns.

The main Dam Operators of the Zambezi River Basin are as follows:

Dam Operator	Dams
Zambezi River Authority (ZRA)	Kariba
Hidroeléctrica Cahora Bassa (HCB)	Cahora Bassa
Zambia Electricity Supply Company (ZESCO)	Kafue and Itezhi-Tezhi
Zimbabwe National Water authority (ZINWA)	Dams on Zambezi tributaries in Zimbabwe
Electricity Corporation of Malawi (ESCOM)	Barrages and diversion weirs/dams in Malawi
Various individual operators	Small and medium size dams

To ensure the greatest possible benefit from the efficient utilisation of the Zambezi River other stakeholders such as environmental and disaster management agencies who deal with the effects flows in the system such as floods and droughts want to be involved in a wider System Operating Forum.

Improvements in dam operations and synchronization requires corporation between the various stakeholders in the Zambezi River Basin. Changes in modes of operations are accompanied by costs, risks and benefits. Cooperation that is perpetually sustainable can only thrive where costs, risks and benefits are shared, reviewed and updated when conditions change.

The contribution of proposed multipurpose dams and extensions to existing ones to basin wide objectives is evaluated. This study identified twenty five possible new developments on the Zambezi and its tributaries comprising of new dams, new power plants, and extensions to existing power plants. The power plant extensions and new power plants will make it possible to generate more power during wet years and to supply peaking power during other normal years. The extensions and new schemes may also provide additional flexibility to implement Basin-wide objectives if accompanied by improved management of risks for Power Producers and Dam Operators. This includes the removal of constraints Southern Africa Power Pool (SAPP). The proposed new power plants on the Zambezi River main-stem will operate as run-of-river schemes which means they will either use or lose the incoming flows. This means that they can be operated to reduce pressure on Kariba and Cahora Bassa to store enough water for power security allowing them to meet other Basin-wide objectives.

Concepts for synchronization dam operations discussed consider **delaying**, **reducing**, **delaying and reducing** in flood peaks for flood protection and **managing releases to mimic natural flow regimes** for maintenance of ecosystem health.

The major dams on the Zambezi have 100% sediment trap efficiency during low floods. However the low Storage/MAR ratios of all current dams in Zambezi River Basin, except for Kariba, suggest that they cannot store major floods. The smaller dams will pass major floods together with their sediment load and for medium floods, the storage condition just before a major flood (which is affected by the operating rule) may also affect the transport and distribution of sediments from the contributing rivers. Bottom outlets for sediment flushing are not desirable for large dams. However, the new dams on the unregulated tributaries of the Zambezi should consider bottom outlets for release of minimum flows (contributing to environmental flows), sediment release and water quality management.

The Lake Malawi –Shire River system is regulated by the Kamuzu Barrage located at the outlet of Lake Malawi. The existing operating rule is for downstream hydropower production requirements. The Kamuzu Barrage is in urgent need of repairs/rehabilitation or upgrading as its current state poses serious risks should the Lake levels rise suddenly. The current operation of the Kamuzu Barrage does not consider avoidance of high Lake levels. There is need to review and update the existing operating rule to accommodate environmental requirements, flood management and socio-economic objectives of the Lake Malawi/Shire River system.

The main recommendations from this part of the study can be summarized as follows:

1. Promote the establishment of a Zambezi Basin System Operators' Forum
2. Support capacity building to facilitate better understanding of dam synchronisation and new modes of dam operation
3. Establish and implement a basin-wide flood and drought risk management plan
4. Facilitate the adoption of new modes of dam operation
5. Develop operating rules for new dams
6. Estimate and implement Zambezi Environmental Flows
7. Improve the quality of observed flow data for application on dam management
8. Simulate flow time series for the Zambezi River System
9. Develop climate change scenarios for the Zambezi River Basin
10. Improve the understanding of the hydrology and functioning of wetlands in the Zambezi River Basin
11. Implement a pilot project involving the Kariba, Itezhi-Tezhi, Kafue and Cahora Bassa dams on synchronisation, conjunctive operation of dams for introduction of e-flows and flood release management.

These are described in more detail in chapter 10 of Annex 2 report.

1 Introduction

This document is referred to as Annex 2 and it is one of six documents that make up the report "Dam Synchronisation and Flood Releases in the Zambezi Basin". The six documents are as follows:

(a) Executive Summary
(b) Main Report: Concepts and recommendations for improved basin wide management
(c) Annex 1: Summary reports of compiled literature and existing studies, geodata, measuring / gauging stations and available data
(d) Annex 2: Concepts and recommendations for dam management
(e) Annex 3: Concepts and recommendations for precipitation and flow forecasting
(f) Annex 4: Recommendations for investments

The relationships and linkages between these six documents are illustrated in Figure 1.1.

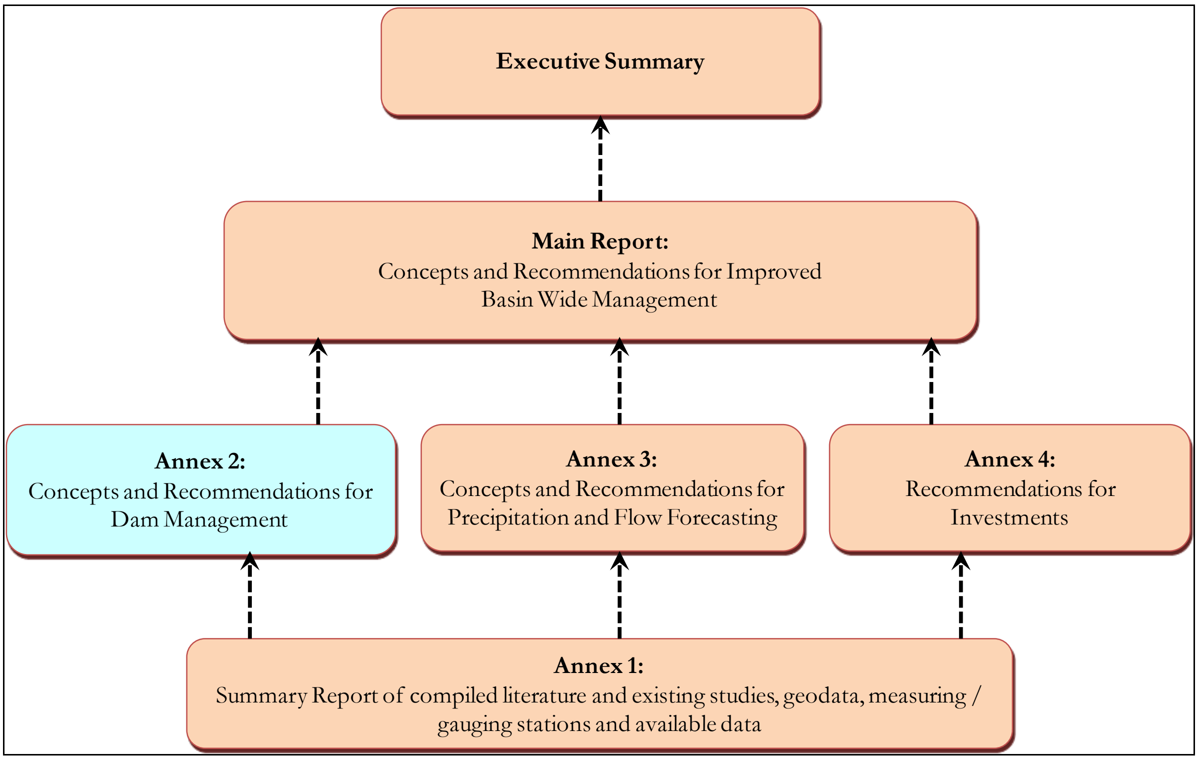


Figure 1.1: Alignment of project reports

1.1 Purpose and structure of this document

The Zambezi River Basin is a complex system with two large man-made lakes, a large natural lake and many small dams. The Zambezi and its tributaries are important to the economies of the southern Africa states through the provision of hydropower, irrigation water, fisheries, water transport and many other uses. Different requirements are imposed by the varied uses/users on the water resources presenting challenges for dam management. There has not been a coordinated basin wide approach to management of dam operations to demonstrate the advantages of synchronized dam operation. Current operating rules do not include benefit sharing and a demonstration of the advantages of synchronized dam operation can open up discussions on this issue. Dam operating rules which consider these various interests can result in optimal management of the water resource in the Basin.

This document proposes new “modes of operating” dams in the basin that simultaneously address different objectives including dam safety, hydro power production, flood management and the needs of the environment. These are presented as “Recommendations and Concepts for Dam Management” which seek to achieve the following:

- Improve the modes of operation of the dams on the Zambezi in order to contribute to the balancing between the interests of environmental flows, flood reduction, hydropower generation and agriculture and;
- Improve cooperation between Dam Operators by providing them new insights, methods and improved confidence.

The recommendations are drawn from analysis on the following seven topics:

1. Long cycles and climate change
2. Wetland retention and its enhancement
3. Regulation of existing large reservoirs
4. Regulation of Lake Malawi/Shire river
5. New multipurpose dams on the Zambezi and its tributaries
6. Synchronization of dams for flood release and
7. Sediment management

The Lake Malawi/Shire subsystem is presented separately as dictated by the terms of references for this study.

This Chapter (Chapter 1) presents the purpose and layout of the document. Chapter 2 introduces the main water resource components of the Zambezi River System which were considered in this investigation. The analysis and results on the above topics are presented in Chapters 3 to 9 of this report. Figure 1.2 illustrates the inter-relationship between these different topics. Concepts are developed and tested in each of the Chapters where conclusions dawn up. These are brought together in Chapter 10.

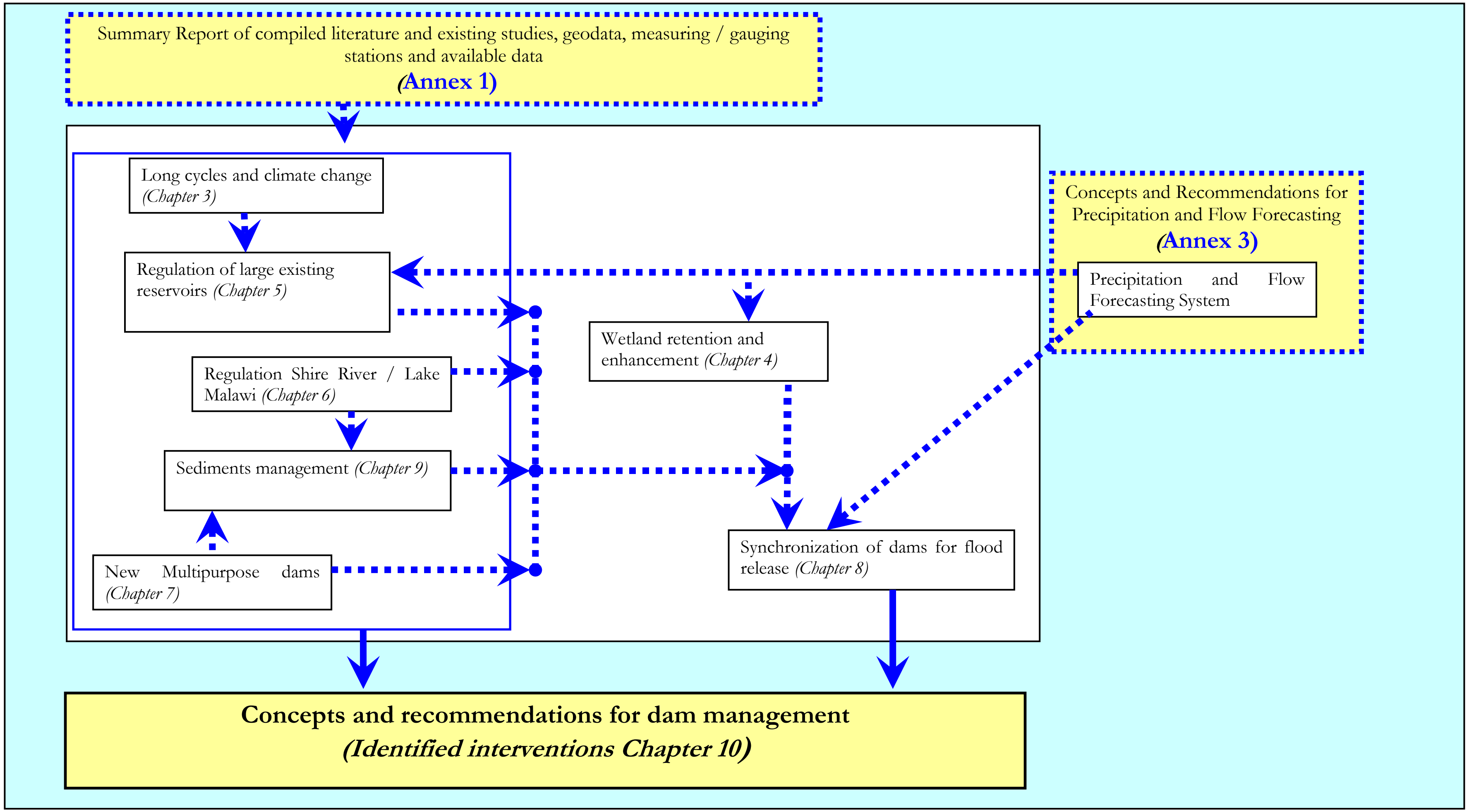


Figure 1.2: Structure of this report and the inter-relationship between the topics covered as well as the other components of this study

2 The Main Water Resource Components of Zambezi River Basin Relevant to This Study

The Zambezi river basin extends over some 1,390,000 km^2 and drains the 9 southern African countries namely Angola, the Democratic Republic of Congo, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe. The Zambezi River starts in the Upper Zambezi sub-basin and its main tributaries are the Kabompo, Kafue, Luangwa and Shire rivers.

Over the past 60 years, a number of large dams have been constructed in the basin, including the Kariba and Cahora Bassa dams. Lake Malawi with a total surface area of about 29,600 km^2 and having a storage volume of about 8,400 km^3 is a natural lake which is part of the East African rift valley system that includes Lake Tanganyika and many other lakes. The main features of the water resource components of the Zambezi River Basin relevant to this study are shown in Figure 2.1.

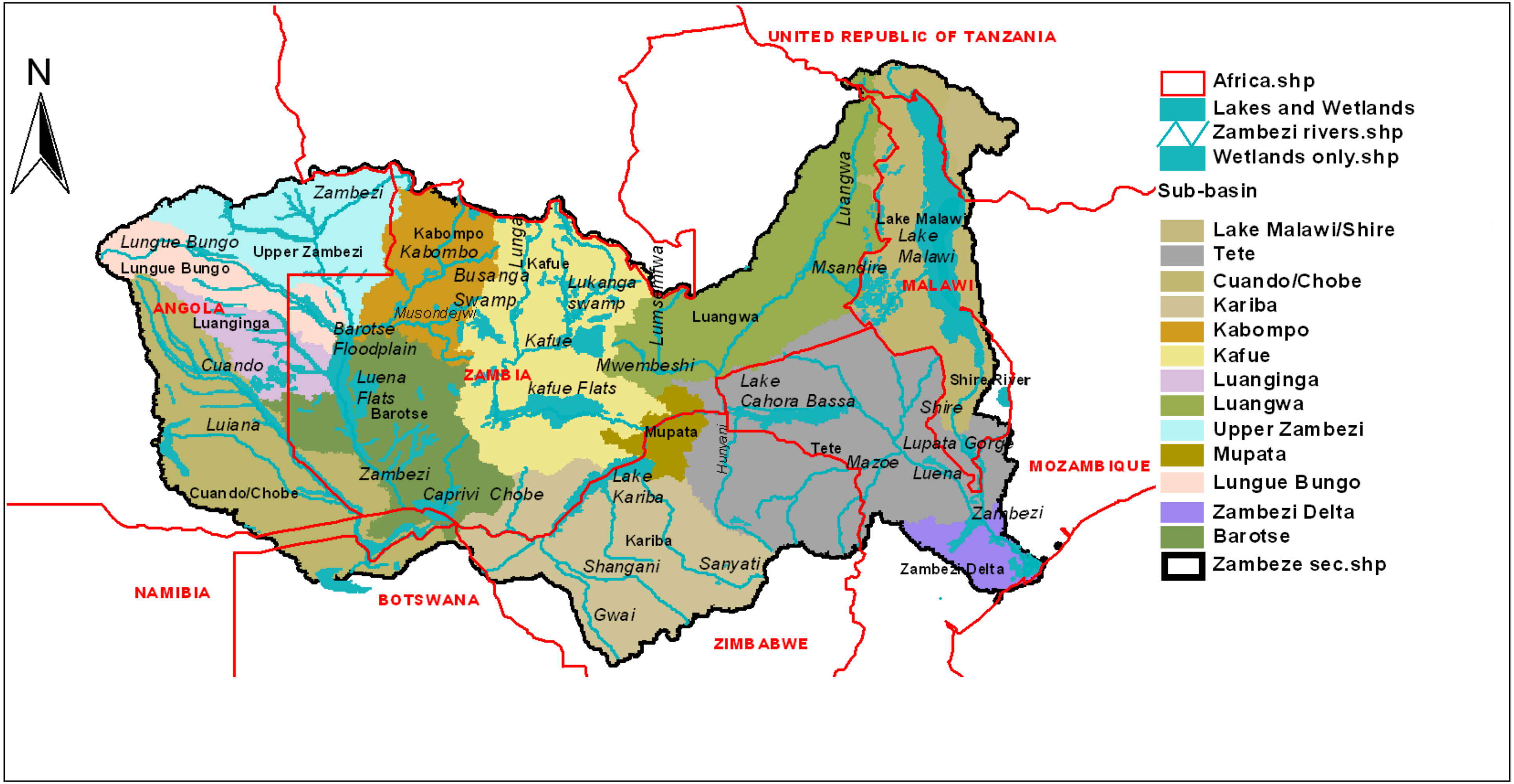


Figure 2.1: Main water resource components of relevance to this study

These components together comprise the main components of what is referred to in this study as the Zambezi River System. They are captured into a schematic/flow diagram as presented in Figure 2.3 to assist in interpreting this document.

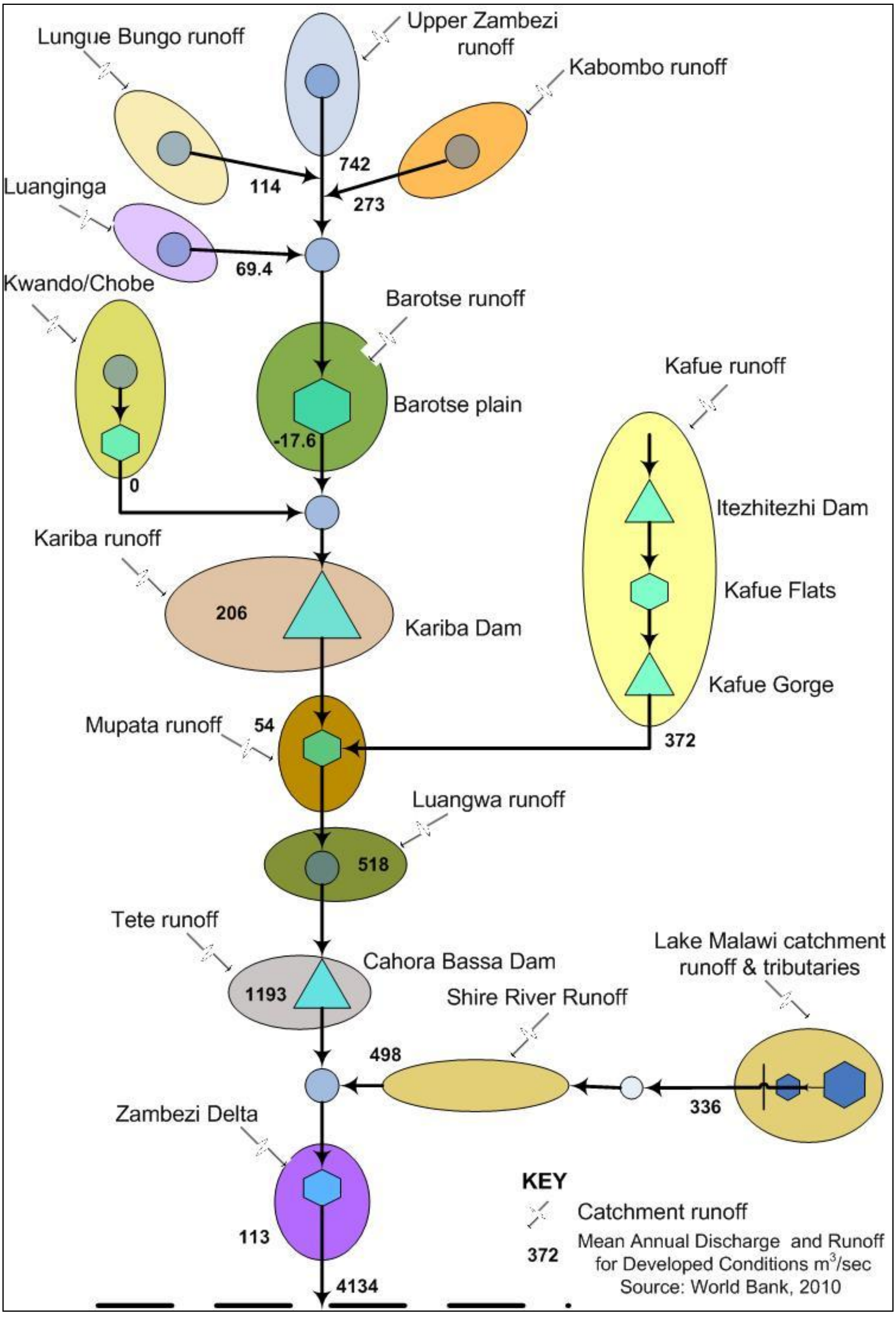


Figure 2.2: System schematic - main water resource components of relevance to this study

The Upper Zambezi (742m^3/sec), Kabompo (273m^3/sec), Kariba (206m^3/sec), Kafue (372m^3/sec), Luangwa (518m^3/sec), Tete (1193m^3/sec) and Lake Shire River/Malawi (498m^3/sec) together make up about 92% of the average discharge of the Zambezi River a shown in Figure 2.2. The main storage facilities on the Zambezi River system are Kariba dam, Cahora Bassa dam, Itezhi Tezhi dam, Kafue Gorge and Lake Malawi.

3 Effects of Long Cycle and Climate Change on Dam Operations

3.1 Introduction

This main objective of this chapter is to provide insights into the effects of climate change on dam operations in the Zambezi river system. Specifically, the following issues will be addressed:

- magnitude of dry and wet cycles over the different sub-catchments of the basin in relation to the storage in the main dams of the basin;
- magnitude of climate change and its impact on storage in the main reservoirs in the basin and
- the major causes are of critical situations (flood releases or drought conditions) through analysis of historical time series of water levels, inflows, precipitation and evaporation.

3.2 Review of Literature on climate sensitivities in the Zambezi Basin

For the purpose f this study the Zambezi River Basin was divided into three zones namely the Upper Zambezi (from source to Victoria Falls) Middle Zambezi, from Victoria falls to Cahora Bassa Dam; and Lower Zambezi, downstream of Cahora Bassa Dam to the river mouth at the Indian Ocean the Lake Malawi/Shire river sub-system falls into the Lower Zambezi.

The Zambezi River Basin catchment as a whole is characterized by wide variability in climate and rainfall, with an average Mean Annual Precipitation (MAP) of 950 mm/annum (World Bank Investment Report, 2009), although there is a marked variability in the rainfall distribution over the catchment as a whole. The north-western headwaters of the catchment, as well as the Tanzanian portion of the catchment, are very high rainfall (and runoff) areas, with the southern central catchment being a low rainfall area. According to Beilfuss (2001), rainfall varies over the Zambezi River Basin from 551 mm/annum (Luenha station, Mozambique), to 1702 mm/annum (Milange, Mozambique).

Rainfall over most of the Zambezi River Basin is strongly influence by the Inter-Tropical Convergence Zone (ITCZ), a zone of convergence between south easterly winds from the Indian Ocean and north westerly winds from the DRC and Angola. This zone moves in a north south direction from the equator to central Zimbabwe over the season and brings rain to wherever it is situated.

Upper Zambezi

In the Upper Zambezi River Basin, Beilfuss (2001) identified high rainfall periods as 1915-1925, and 1950-1980, while low rainfall periods in the early 1900's, 1930-1940's and 1980-1998. Subsequent to 1980 there has been a sharp reduction in rainfall, resulting in lower flows since 1983, with 15 of the 17 years to follow being below the long term average. He identified periods of low flow as 1907-1946 and 1982-1999, with a high flow period from 1947 to 1981 (including the 16 wettest years on record. The general characteristics show that the 1930's and 1980-2000 experienced below average flows, while the period 1950-1980 enjoyed above average flows (Mazvimavi and Wolski, 2006). They concluded that a long-term cyclic pattern exists in the flows in the Upper Zambezi due to the patterns of rainfall in the catchment.

Mazvimavi and Wolski (2006) also carried out a study on the Upper Zambezi River Basin and the Okavango catchment, to identify trends and decipher long term flow variability. They found that the Zambezi River experienced the largest floods on record in 1956-1958, whereas annual maximum flows on the Okavango River were below average during these years, concluding that the weather patterns responsible for extreme events are not simultaneous in the two basins. The annual minimum flows were above average during the 1951–1983 period. They also found that the Okavango and Zambezi rivers have similar long-term annual average and annual maximum flows, and that both rivers show a statistically significant decreasing trend in annual minimum flows. They concluded on the basis of the similar characteristics identified that the cyclic component of the two basins has a regional scale. Figure 3.1 shows standardized annual flows for the Okavango and Zambezi Rivers showing that the annual maximum flows of the river have similar variations over the years.

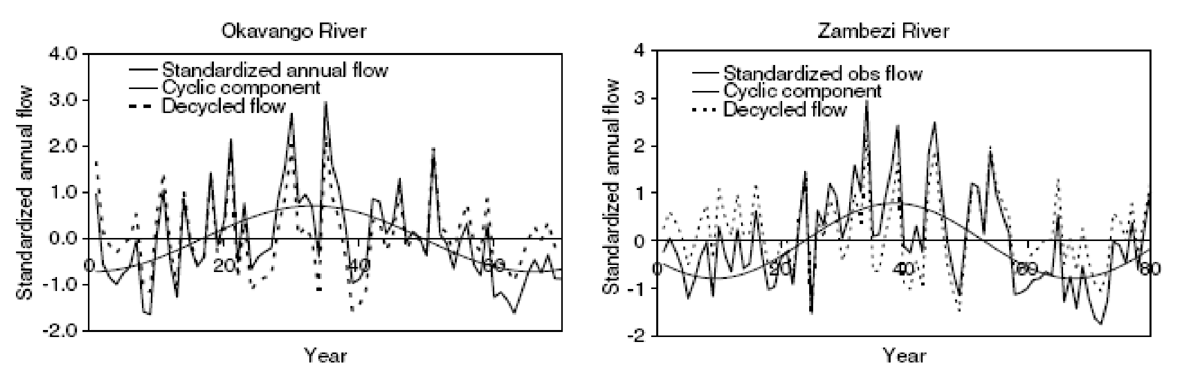


Figure 3.1: A comparison of the standard annual flow, cyclic component and de-cycled flows on the Okavango, 1933-2004, and Upper Zambezi Rivers, 1924-2004 (after Mazvimavi and Wolski, 2006)

The impact of climate change and development scenarios on flow patterns in the Okavango River confirmed that there are huge differences in climate change projections for this region across different scenarios and climate models (Andersson *et al*, 2006).

Mazvimavi and Wolski (2006) identified specific change points in annual flows of the Zambezi River in the 1979-1989 period. The time period analysed was 1924-2004 for the Zambezi River, and 1933-2004 for the Okavango River. They found that cyclicity is present in annual flows, as well as annual minimum and maximum flows for both rivers. When the cyclic components were removed from each of the time series, the results show trend free flows, showing clearly cyclic behaviour present within the data (see Figure 2.11). IPCC (2007) is in agreement, stating that no long term trends are noted for southern Africa. The Kendall Rank Correlation Test was used for the detection of trends, with the Wilk Shapiro Test and the Pettitt Test analyzing the general statistics of the datasets. Several statistical tests such as spectral analysis, Fisher's Kappa Test and Bartlett's Kolmogorov-Smirnov Test were also carried out for the detection of cyclic behaviour. The cyclic component of this analysis suggests that subsequent to 2000, flows are generally increasing, and therefore it is projected that we are moving into a period of above average flows. It is suggested that since the upper Zambezi is further away from the Atlantic Ocean than the Okavango, it is less affected by the south-west monsoons which occur. Although it is uncertain whether this is the cause for the differing duration of cycles for the two basins, the differing origin of rainfall over the Zambezi and Okavango basins could be the cause of this. What is interesting to note is that the two rivers do not share the same cycle duration even when the analysis is done for the same record period (1933-2004). Average annual discharges and annual maximum flows, however, have similar variations for the Zambezi and Okavango, and are closely correlated.

The duration of cycles of annual average, minimum and maximum flows identified by Mazvimavi and Wolski (2006) are shown in Table 3.1. These maximum flows correspond to the wet cycles and the minimum flows correspond to the dry cycles. It will be appreciated that cycles of 48 years are very difficult to properly identify within a 60 year record period and that these should be treated with caution.

Table 3.1: Rank and Duration of the 3 most important cycles in annual flow time series of the Zambezi River (after Mazvimavi and Wolski, 2006)

Rank	Zambezi River		
	Average Flows Duration (years)	**Minimum Flows Duration (years)**	**Maximum Flows Duration (years)**
1	48.0	40.0	40.0
2	24.0	5.7	10.0
3	6.0	2.6	8.0

Tumbare (2000) identified six main trends in the recorded Zambezi river flows at Victoria Falls (using a Differential Mass Curve. These are:

- Dry sequence : 1908 – 1938 (30 years);
- Average sequence : 1938 -1948 (10 years);
- Wet sequence : 1948 – 1980 (32 years);
- Dry sequence : 1980 – 1996 (15 years);
- Projected mixed wet/dry sequence : 2004-2020 (16 years) and
- Projected wet sequence: 2020-2050 (30 years).

This cyclicity is largely consistent with the findings of Beilfuss (2001). Tumbare later reanalyzed the data in 2008, and identified four main trends in the Victoria Falls flow record as:

- Dry sequence : 1908 – 1950 (42 years);
- Wet sequence : 1950 -1983 (32 years);
- Dry sequence : 1983 – 1999 (15 years) and
- Mixed sequence : 1999 – 2007 (15 years)

The updated results show slight variance with the results obtained with the longer record period, but they are not significant. Tumbare noted that forecasting is becoming more difficult due to the uncertainties around climate change, which affect weather patterns thereby making climate predictions more difficult. The HEC (Hydrologic Engineering Centre) 3 Model was used to synthesize flows up to 2038/39, which indicated lower than mean flows predicted at Victoria Falls.

Middle Zambezi

In the Middle Zambezi, Beilfuss (2001) identified that the runoff response to rainfall is rapid and a strong cyclic pattern exists in the annual flow time series, particularly in the Kafue River Basin. He concluded that the Middle and Upper Zambezi River Basins show similar runoff patterns and this cyclic behavior is due to the rainfall patterns, and not due to changes in land use (with the exception of deforestation in the Copper belt region).

It is interesting to note that the highest and lowest annual discharges (as from 2001) occurred during the same years in the Upper and Middle Zambezi (most likely due to the influence of the

ITCZ). Beilfuss identified the mean monthly maximum outflows at Kariba Dam as 1665m^3/s (with only sometimes reaching 1750 m^3/s), with the late 1990's at approximately 1200m^3/s. However, prior to construction of the dam, the flows were usually above 1750m^3/s (during February – May). The highest inflow to Kariba Dam was in 1957/58, which was the last year prior to the river being regulated. A severe drought occurred during 1981-2001, when the only flows released from Kariba Dam were through the turbines.

Beilfuss (2001) analysed both the Upper and Middle Zambezi and identified 'a strong cyclic pattern' particularly in the Kafue Flats, using a differential mass curve. This data displays a cycle of approximately 100 years for one full cycle. A general increase in runoff occurred in the Kafue catchment from the late 1930s until the early 1980s, followed by a sharp decrease over the period 1980-2000, SWECO (1971, cited in Beilfuss, 2001) identified that there has been an exponential increase in runoff as a percentage of rainfall over the Middle Zambezi River Basin. The runoff pattern in the Luangwa River Basin is not reflected in the rainfall time series, where the rainfall has fluctuated over much shorter cycles Beilfuss (2001) deduced that there is a clear trend in the catchment, but that it is different to that of the Upper Zambezi and Kafue catchment cycles. This may be due to the fact there are no major floodplains or wetlands in the mid Zambezi portion of the river unlike the Upper Zambezi and Kafue basins (Balek 1971b), rendering the hydrological characteristics of the Luangwa catchment different.

Lower Zambezi

The Lower Zambezi stretches from Cahora Bassa to the Zambezi Delta. It includes the Lake Malawi/Shire river subsystem. This zone shows a large annual variability in flows, with the most severe drought on record occurring in the Delta in 1972.

Norconsult (2001) concluded that the identified pattern in the historical record, which showed four distinct periods of low levels in **Lake Malawi** (due to low or no inflows to the lake) is indicative of a natural hydrologic variability of the lake, and therefore it may be assumed that this pattern will continue in the future. During these four events the net inflow to **Lake Malawi** was at or below zero, usually with duration of approximately 4-6 years, but with one such event having duration of over 20 years. It was concluded that this is indicative of a natural hydrologic variability of the lake. However, it was noted that runoff patterns may also be influenced by slash and burn agriculture in the Shire catchment, high erosion and thus rapid runoff response to rainfall.

The Zambezi Delta in Mozambique showed floods in 1840, 1939, 1952 and 1958, with a severe drought occurring in 1972 (Beilfuss, 2001).

3.2.1 Summary of cyclicity in the Basin

Table 3.2 below shows a summary of the high and low rainfall and runoff periods over the last century.

Table 3.2: Historical Precipitation and Runoff

Area	Precipitation		Runoff		Source
	High Period	Low Period	High Period	Low Period	
Southern Africa					
		1979-2000			Mazvimavi and Wolski (2006)
Upper Zambezi					
	1915-1925	Early 1900s	1947-1981*	1907-1946	Beilfuss (2001)
	1950-1980	1930s-1940s		1982-1999	Beilfuss (2001)
		1980-1998			Beilfuss (2001)
Middle Zambezi					
		1981-2001	1957-1958**		Beilfuss (2001)
			1962-1963		Beilfuss (2001)
			1968-1969		Beilfuss (2001)
			1977-1978		Beilfuss (2001)
Lower Zambezi					
		1972	1840		Beilfuss (2001)
			1939		Beilfuss (2001)
			1952		Beilfuss (2001)
			1958		Beilfuss (2001)
Lake Malawi ***					
				1900-1925	Norconsult (2003)
				1940-1945	Norconsult (2003)
				1951-1955	Norconsult (2003)
				1957-1962	Norconsult (2003)
				1991-1997	Norconsult (2003)
			1979-1984***	1915-1935***	Mazvimavi and Wolski (2006)
Zambezi					
		1991-1992	2000-2001		IPCC (2001)

* Includes 16 wettest years on record (as at 2001)
** Flooding caused redesign of Kariba Dam Spillway
*** Lake Malawi Levels

Table 3.3 provides a summary of the duration of annual flow cycles identified from existing literature.

Table 3.3: Summary of cyclic behaviour

Area	Cycle Duration (years)	Source
Upper Zambezi		
Victoria Falls	2.6, 5.7 and 40 for dry sequences 8, 10 and 40 for wet sequences	Mazvimavi and Wolski (2006)
	15 and 42 for dry sequences; 32 for wet sequences and 15 for mixed sequences	Tumbare (2008)
Middle Zambezi		
Above Cahora Bassa	100 *	Beilfuss (2001)

Area	Cycle Duration (years)	Source
Lower Zambezi		
Lake Malawi	4-6	Norconsult (2003)
Note: * The observation record is not longer than 100 years. Therefore the suggested cyclicity period of 100 years is not very robust.		

Tables 3.2 and 3.3 suggest that of cyclicity in the lower Zambezi exists and it will probably be in the order of magnitude of 100 years or more. It should also be noted that rainfall records for this region are poor.

3.2.2 Review of literature on Climate Change in the Basin

In this section, existing literature on the subject of climate change was examined to determining the likely impact of climate change on the management of the water resources of the Zambezi basin especially to derive insights into the effects of both long term cycles and climate change on the operation of dams in the Zambezi River Basin.

Climate change is a long-term change in the statistical distribution of weather patterns over periods of time that range from decades to millions of years. It may be a change to a defined statistical parameter for example a change in average weather conditions or the distribution of weather events. (http://en.wikipedia.org/wiki/Climate_change). The discussion being conducted here is based on review of existing documents and reports from various previous studies only, an not on any new modeling work.

Climate change is inherently an uncertain phenomenon. Generally the models used to assess climate change are dependent on forcing scenarios that reflect changes, such as greenhouse gases, on a very large scale. Therefore, any statement made on climate change is generally done on large scales. The following discussion in this section thus focuses on scales ranging from the whole African continent to the whole Zambezi to several large sub-regions.

Effects of climate change on river flows are more uncertain than temperature changes. General Circulation Models (GCMs) are only partly able to physically reproduce the mechanisms responsible for precipitation because of their coarse resolution relative to the spatial scale at which the process occurs. There are various down-scaling methods which have been developed to resolve this problem (Wilby *et al*, 2004). Instead, parameterizations are used to compensate the absence of the real process. This therefore makes it difficult to provide precise estimations of changes in runoff, given the precipitation scenarios, especially where small changes in rainfall equate to large changes in runoff (IPCC, 2007), as displayed in the Zambezi River Basin (Winsemius, 2009). Rainfall- runoff models have not been successfully applied to these data sets.

Previous studies are in agreement with the IPCC (2007) results that rainfall and runoff are on average decreasing, as shown in Table 3.4.

Table 3.4: Conclusions from various studies on Climate Change in the Zambezi Basin

Study	Conclusions
Usman and Reason (2004, as cited in IPCC, 2007)	There will be a significant increase in heavy rainfall events over southern Africa (including Angola, Namibia, Mozambique, Malawi and Zambia).
Tadross *et. al.* (2005a and New *et. al.*, 2006)	There is evidence of changes in seasonality and weather extremes for several southern African countries, including Mozambique, Malawi and Zambia.
Cambula (1999), as cited in IPCC (2001)	A decrease in surface and subsurface runoff of five streams in Mozambique, including the Zambezi, under various climate change scenarios. For the Zambezi basin, simulated runoff under climate change is projected to decrease by about 40% or more
Rousteenoja *et. al.* (2003, as cited in IPCC, 2007)	Using GCMs, predict an average warming for southern Africa of 7°C for the 2070-2099 period (which equates to approximately 0.7°C to 1.0°C per decade). He notes that Regional Circulation Models generally give smaller temperature increases than GCMs.
Hudson and Jones (2002, as cited in IPCC, 2007)	Predict a warming of 3.7°C for the Dec-Feb summer period (approximately 0.46°C per decade) and a warming of 4°C for the Jun-Aug winter period (approximately 0.5°C per decade) for southern Africa by 2080.
KNMI (2007)	For northern Botswana, western Zimbabwe and southern Zambia there is a decreasing trend with more extreme droughts; Zambia and Malawi will become generally drier; eastern Zimbabwe and Central Mozambique show no clear precipitation trend is projected over this area in the 21st century.
Strzepek and McCluskey (2006, as cited in IPCC, 2007)	As the projections for Africa get further into the future, the bandwidth of projections gets wider. For example, the projected range for changes in runoff for 2050 is -15% to +5%, while for 2100 it is -19% to +14%.
IPCC (2001)	Seasonal patterns of the Zambezi remained relatively unchanged, but the river is sensitive to temporal changes in the rainy season
Arnell (1999, as cited in Norconsult 2003)	For the next 100 years precipitation will decrease by 10-20% for the whole Zambezi. Evaporation will increase by 10-25% and runoff will decrease by 26-40%.
Vörosmarty and Moore (1991, as cited in IPCC, 2001	Potential impacts climatic change on the Zambezi can be substantial.
A research group in Zambia (Dr Yamba)	Modeling with rainfall runoff models, using different climate change scenarios. The Consultant has contacted Dr Yamba but results of the study are only available in the course of 2010.
Tumbare[3] (2008)	Predicts a decrease of up to 10% in precipitation at Kariba Dam.
Euroconsult Mott MacDonald (2008, as cited in Tumbare[3], 2008)	Although a drying trend is evident in rainfall, the decadal rainfall fluctuations at Kariba Dam will remain.

The Zambezi River has a low runoff coefficient and high aridity index, indicating a high sensitivity to climate change. The river is not only sensitive to changes in precipitation but also to climate warming itself. This is because the increase in temperature causes an increase in potential and lake evaporation. Consequently, runoff may decrease even if precipitation increases. It is expected that in the Zambezi River basin there will be a net deficit in river flows due to higher surface temperatures and therefore an increase in the rate of evaporation. This shows the significantly large role evaporation has in the complex hydrological cycle (IPCC Special Report, 2001).

IPCC (2001) stated that the Zambezi River has the worst scenario of decreased precipitation of approximately 15%, an increase in potential evaporative losses of about 15-25%, and as a result a diminished runoff of about 30-40%. Out of 11 African basins mentioned in the report, the Zambezi exhibited the 'worst' effects in response to climate change, due to the resonating effect of increase in temperature and decrease in rainfall on potential evaporation and runoff.

Precipitation changes over southern Africa are shown in the figures below for Spring and Autumn (Figure 3.3) and Summer (Figure 3.4). The large numbers on the figure represent the mean change, predicted by the climate models, the upper and lower numbers the deviation from this mean within 95% confidence. This climate outlook has been produced by KNMI (2007) by comparing the long-term historical climate and the natural variability of climate change predictions for the year 2100 (based on 4-6 models).

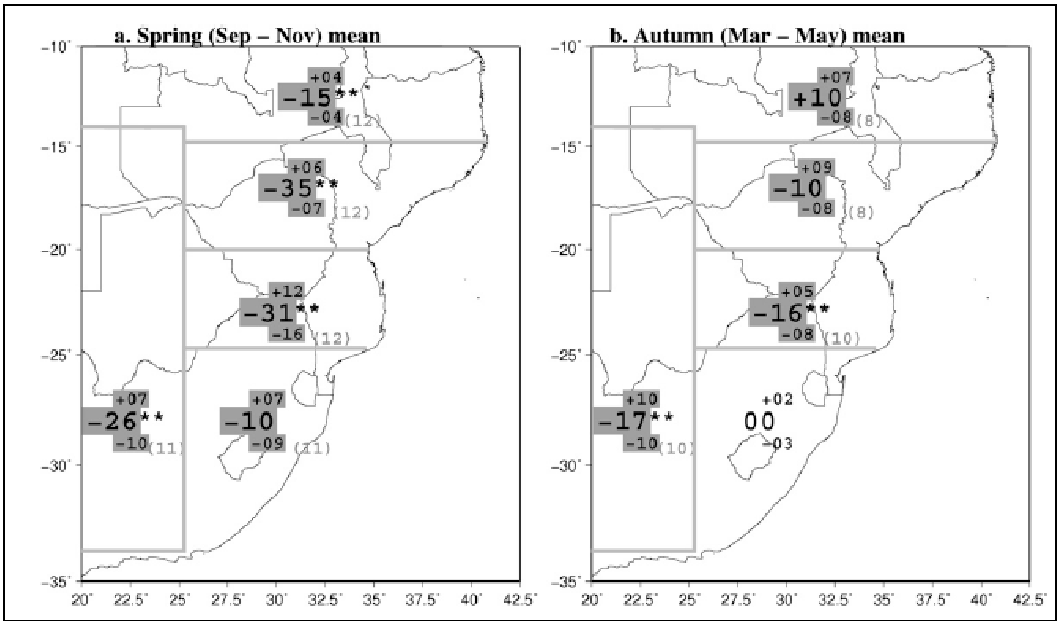


Figure 3.2: Precipitation changes during onset and cessation of rainy season (Sep-Nov) and (Mar-May) for 2100 (after KNMI, 2007)

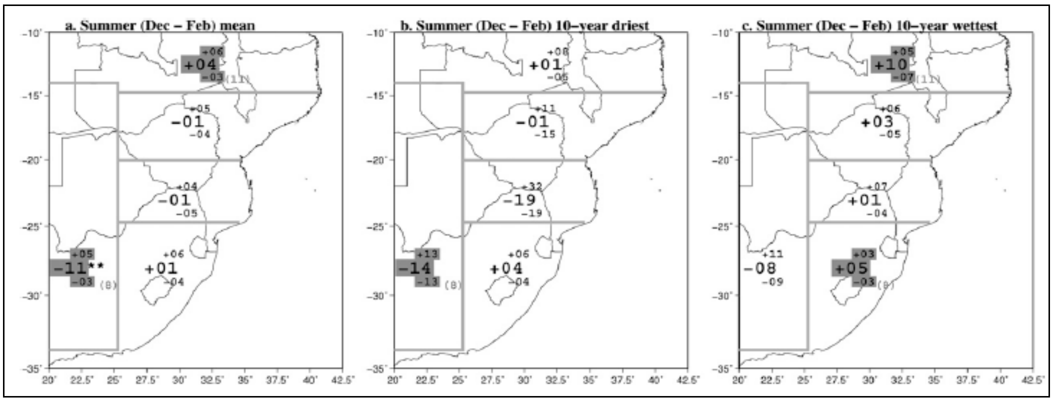


Figure 3.3: Precipitation changes during the mean, driest and wettest for summer (Dec-Feb) for 2100 (after KNMI, 2007)

The above figures show the mean change in rainfall over the Zambezi for each season is: -31% to -35% (Spring); -10% to -16% (Autumn); -31% to -34% (Winter-not shown in figure); and -1%

(Summer). This shows that the rainy summer season is in relative sense less affected than the other seasons, particularly Winter, when the least rainfall occurs. However, it is important to note that the figures suggest that rainfall regions for South Africa show a decrease in rainfall, but this goes against the general consensus from literature on for South Africa which suggests the opposite. Therefore results for the Zambezi basin should be used with caution.

Winsemius (2009) generated a runoff coefficient map of the Zambezi basin based on the Budyko curve (Budyko, 1974) which shows an approximation of the spatial variability in runoff coefficients (i.e. the fraction of rainfall that converts into river flow over long time scales) between 5% in the southern parts where rainfall totals are low, and about 25% in some of the northern parts with high rainfall – refer to Figure 3.4. Given the low runoff coefficients and non-linearity of rainfall-runoff processes, the runoff production is very sensitive to small shifts in the climate, such hat a small change in annual precipitation or annual potential evaporation has a large impact on annual river flows.

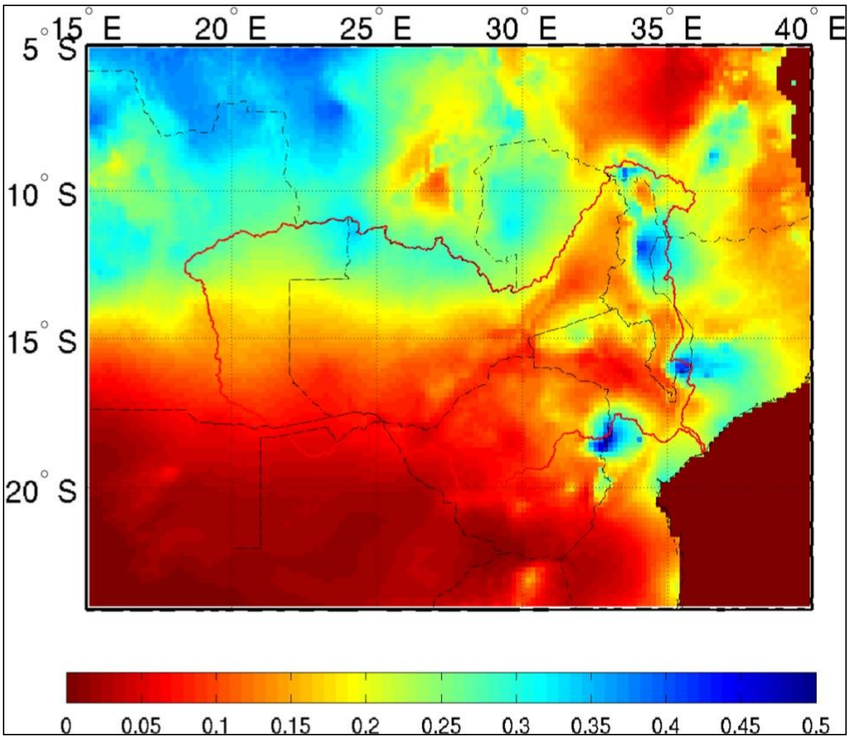


Figure 3.4 : Spatially variability of the runoff coefficient in the Zambezi, based on climatology data of the Climate Research Unit (New et al., 2002)

Upper Zambezi

- A case study by Tumbare (2008) on the impact of climate change **on Kariba Dam** shows an apparent irreversible increase in temperature linked to reduced flows at Victoria Falls resulting in lower inflows into Lake Kariba, with the 1995/1996 flows at Victoria Falls being the lowest on record since the start of records in 1907 (Tumbare[2], 2000). Beilfuss (2001) identified that in the late 1930's and early 1980's there has been a general increase in runoff for the Kafue Flats, with a sharp decrease over the past 20 years. Tumbare[2] (2000) also indicated that over the past 15 years, the Zambezi River has experienced below average flows.
- Tumbare (2008) showed that the mean temperatures decreased in the period 1965-1983, and have subsequently increased. Using the Differential Mass Curves for flow and temperature,

it was shown that a decrease in temperatures corresponds with an increase in flows, while an increase in temperatures corresponds with a decrease in flows, showing a direct link between temperatures and flows.

Lower Zambezi

- Norconsult (2001) carried out a sensitivity analysis of climate change on **Lake Malawi**. using a simple water balance to show that under climate change, even small changes could have a significant impact on runoff. The equation used factors such as catchment area, lake surface area, rainfall and evaporation. It was shown that for a 1% decrease in rainfall, combined with a 1% increase in evaporation, the resultant runoff into Lake Malawi, plus rainfall on Lake Malawi, minus evaporation, decreased from 70mm/annum to 43mm/annum. This is mainly influenced by the large component of evaporation from the large surface area of the lake, of about 29,600 km^2.
- Chavula and Chirwa (1996) analysed the effect of climate change on water resources in **Malawi**, in which they predicted an increase of 2°C in temperature with a decrease in precipitation of 10%. Computed flow in the Bua River decreased by 38%, showing a high sensitivity to runoff even for moderate changes in climate (Norconsult, 2003).

Table 3.5 shows a summary of projected changes for evaporation and temperature. Those for precipitation and runoff are shown in Table 3.6.

Table 3.5: Summary of Projected Changes in Evaporation and Temperature

Reference	**Approximate Projection Timeframe**	**Projected Increase in Potential Evaporation**	**Projected Change in Temperature Per Decade**	
			Minimum (°C)	**Maximum (°C)**
Africa				
IPCC Working Group II (2001)	2050		0.2	0.5
Southern Africa				
Ragab and Prudhomme (2000)* (as cited in Norconsult, 2003)	2050		0.3	0.5
Ragab and Prudhomme (2000)* (as cited in Norconsult, 2003)			0.5	0.6
Rousteenoja *et. al.* (2003) * (as cited in IPCC, 2007)	2070-2099		0.7	1.0
Hudson and Jones (2002)* (as cited in IPCC, 2007)	2080		0.46 (Dec-Feb)	
Hudson and Jones (2002)* (as cited in IPCC, 2007)	2080		0.5 (Jun-Aug)	
Malawi				
IPCC (2001) (as cited in Norconsult, 2003)	2050	10-25%		
Zambezi				
Arnell (1999) (as cited in IPCC, 2001)	2050	10-25%		
World Bank Report, 2008	2050		General rise in temperatures	

* Approximate calculation

Table 3.6: Summary of Projected Precipitation and Runoff Changes (to approx. 2050)

Reference	**Area**	**Projected Changes**	
		Rainfall (decrease)	**Runoff (decrease)**
Christensen *et. al.* (2007) (as cited in IPCC, 2007)	Southern Africa	general decrease	
Ragab and Prudhomme (2000) (as cited in Norconsult, 2003)	Southern Africa	10-15%	
Hudson and Jones (2002 (as cited in IPCC, 2007)	Southern Africa	30%	
IPCC, 2007	South of 10°S	General decrease	
IPCC, 2007	South of 10°S	decrease number of raindays	
IPCC, 2007	South of 10°S	decrease average intensity of rainfall	
Strzepek and McCluskey (2006) (as cited in IPCC, 2007)	Southern Africa	Significant reduction	
KNMI (2007)	Zambia and Malawi Northern Botswana, western Zimbabwe and southern Zambia	Generally drier	
Cambula (1999) (as cited in IPCC, 2001)	Zambezi, Mozambique		40%
IPCC Report (2001)	Zambezi	15%	30-40%
Vörösmarty and Moore (1991) (as cited in IPCC, 2001)	Zambezi		40%
IPCC Report (2001) (as cited in Norconsult, 2003)	Zambezi	10-15%	26-40%
IPCC Report (2003)	Zambezi	10-15%	26-40%
Hulme *et. al.* (1996) (as cited in Norconsult, 2003)	Zambezi	15%	30-40%
Chavula and Chirwa (1996) (as cited in Norconsult, 2003)	Malawi	10%	38%

Historical evidence

The above model studies have to be seen in the light of conclusions of Mazvimavi and Wolski (2006) who claim that when the cyclic components were removed from each of the times series, the results show trend free flows, see previous paragraph.

Influence of Climate Change on Hydropower Generation

The major hydro power stations in the Zambezi River Basin are as follows:

Table 3.7: Major hydropower stations in Zambezi River Basin

Power Station	Power Company	Generation Capacity (MW
Victoria Falls North	Zambia Electricity Supply Company (ZESCO)	108
Kariba North		600
Kafue		990
Lusiwasi		12
Kariba South Bank	Zimbabwe Power Company (ZPC)	660
Cahora Bassa	Hydro Cahora Bassa (HCB)	2075
Nkula A	Electricity Supply Corporation of Malawi (ESCOM)	24
Nkula B		100
Tedzani I and II		40
Tedzani III		52.7
Kapichira		64.8

Kariba, Kafue and Cahora Bassa power stations can feed power into the Southern African Power Pool (SAPP). The SAPP holds a position which aims to be involved in climate change projects (mainly energy projects in the SADC region), through the SAPP Environmental Sub-Committee and the SAPP Planning Sub-Committee. These Committees strive to investigate the impacts of climate change and possible response measures, ensuring that the processes of climate change are taken into account in long term planning strategies. However, these studies tend to be high level and focused on the aims of the Kyoto Protocol relating to greenhouse gas emissions, and not the projected impacts of climate change on rainfall, runoff, temperature and evaporation, which consequently may affect the operation of dams.

GCMs are the most frequently used models to make climate change projections, as they are considered the most credible by the IPCC. However, tropical cyclones cannot be simulated in GCMs and therefore results may be very skewed, as these cause most flooding events along the eastern parts of southern Africa, meaning the expected changes in the frequency of wet extremes from the model results cannot be estimated. KNMI (2007) state that for the eastern parts of southern Africa, there is no evidence for changes in wet extremes, and this is more than likely a consequence of the GCM not simulating the south-west Indian Ocean tropical cyclones.

Using the GCMs and standard GCM-based scenarios, the IPCC (2001) found that hydropower production at Kariba Dam decreased slightly under 2 scenarios (GISS (NASA) and GFDL) due to the net deficit in river flows, caused by higher surface temperatures and associated increase in evapo-transpiration. However, the cooler scenarios (UKMO and GISS) led to small increases in power generation. Seasonality of flow had a greater effect on hydropower production. It was found that under climate change, there would be less water entering Kariba (IPCC[2] Special Report, 2001). The net effect is that lower hydropower production translates into a loss in revenue for electricity utilities and the ZRA (Tumbare[3], 2008).

The IPCC Report of 2001 does not make specific mention on effects on hydropower due to climate change in the Zambezi River Basin. However, Salewicz (1995, cited in 2001 IPCC Report) investigated the vulnerability of the Zambezi River Basin to climate change and noted that under each climate change scenario there will be an increase in rainfall in the Kariba Dam catchment, resulting in increased flows into the lake. He noted that there may be seasonal changes which, in agreement with the IPCC, may have negative effects on the hydropower generation capacity of the dam.

3.2.3 Conclusions on cyclicity and climate change

The following conclusions can be reached from the review of literature on this study:

Cyclicity

- The studies all indicate strong cyclicity over the whole Zambezi River Basin; however, sources differ on the duration of the cycle periods. Periods are as long as the data records (100 years) or only as short as 6 years. This could be explained by the fact that different sub-basins to the Zambezi River Basin receive their rainfall from different sources (e.g. either from westerly or from easterly winds, convective rainfall over land, or advected moisture from the ocean).

- It has been shown that cyclic behavior exists in the Zambezi and Okavango basins. These two basins showed similar characteristics in annual average, minimum and maximum flows therefore displaying regionality in the two catchments. However, the most important cycle lengths (for average annual flows, annual minimum and annual maximum) are different for the two basins.

- Some studies indicate that the cycle length is about 100 years, which is equal to the longest continuous period of existing climate and flow records. Derived residual mass curve comes to zero again. However, this is an ill-posed conclusion. It is inherent in the method. The cyclic behaviour may appear differently should a longer (or shorter) record period be used. In this light, the cycle may actually be longer than the originally identified cycle as a proper overview cannot be established.

- Studies mainly indicate the length of the cycle but not the amplitude and form.

- The long-term cyclicity that some authors conclude of 100 years or 48 years may be statistically convincing, but the Consultant does not recommend use of these cycles for predictions for operation of dams as the period of observed data applied in the analysis is too short. The length of data should be considerably longer than the predicted cycle to reduce errors associated with variability and uncertainty.

- The significant positive auto-correlation of observed annual flows may be partially attributed to the long-term memory of the basins (also mentioned by Mazvimavi and Wolski, 2006), although seasonal responses are sometimes quite immediate to rainfall rather than a strong groundwater influence. The amount of annual runoff is not only caused by the rainfall, but may also be influenced by the preconditions of the catchment (e.g. groundwater depth) and therefore years with high (or low) flows follow each other. This is especially the case in the upper Zambezi, where deep Kalahari sand layers have created a large storage capacity (see e.g. Winsemius, 2009). Therefore the cyclic behaviour detected within the catchment may be caused or enhanced by these characteristics of the basin. This autocorrelation could be useful for prediction annual flows in operation of dams.

Climate Change

- Climate change is inherently an uncertain phenomenon. Effects of climate change on river flows are even more uncertain than temperature and precipitation changes themselves. This is due to the non-linear or less direct relationship between rainfall and runoff and the fact that runoff coefficients in Africa, in particular in the Zambezi are small. GCMs show greater uncertainty regarding reproducing the mechanisms responsible for precipitation than other meteorological parameters such as temperature, wind, etc. and this therefore makes it difficult to provide precise estimations of changes in runoff, especially where small changes in rainfall equate to large changes in runoff, as displayed in the Zambezi River Basin. There are no case studies available yet on rainfall runoff models being applied on the Zambezi River Basin, using climate change scenarios.

- Historical data do not show significant trends subsequent to the removal of the cycles within the data, demonstrating that there is no evident trend displayed in the data, but rather the existence of natural cycles as discussed above.

- Climate change effects cannot be judged from one model alone. A recent study carried out by the University of Cape Town's Climate Systems Analysis Group recommended that nine GCMs be considered, and that it is important to consider the uncertainty reflected by the results from the different models. Most studies in the region report on one scenario only, with a band width of uncertainty. The risk is that the 'average' scenario is communicated as the forecast.

Rainfall

- Rainfall changes are predicted over the whole of the Zambezi River Basin, with a decrease of approximately 10-15% by 2050. However, apart from rainfall being difficult to model in GCMs anyway, for the Zambezi it is important that tropical cyclones cannot be simulated in GCMs. Therefore the frequency of wet extremes from the model results is uncertain.

Evaporation

- Evaporation has been estimated to increase 10-25% by 2050.

Temperature

- A warming is projected for the Zambezi River Basin, with the general consensus of results showing a range of 0.3-0.6°C per decade. A value as high as 0.8°C is projected however this is for the summer months only.

Runoff

- It is projected that runoff will significantly decrease in the Zambezi River Basin, with the projected range being between 26% and 40%.

3.3 Identification and Analysis of Multi-Year Pre-Drought/Flood Event Conditions

In order to identify wet and dry cycles for the major reservoirs, inflow data was requested and was obtained from Beilfuss (Beilfuss, R. Personal communication) for the Kafue Flats, Lake Kariba, Luangwa River and Cahora Bassa Dam. This was necessary because the ZAMWIS database did not contain continuous flow series, which was noticed during the qualitative analysis of the data. The data obtained consists of the following:

- Lake Kariba - Monthly flows for the Victoria Falls,1907 to 1957;
- Lake Kariba Dam - outflow,1958 to 1998;
- Kafue - Monthly flows at Kasaka, 1907 to 1969.
- Kafue Gorge Dam - Monthly outflows, 1970 to 1998;
- Kafue Hook - Monthly flows ,1973 to 2003;
- Luangwa - Incremental monthly flows into Cahora Bassa Dam, 1907 to 1954;
- Luangwa - measured monthly flows, 1955 to 1995 and incremental monthly flows to Cahora Bassa Dam, 1996 to 1998. It is to be noted that there are many problems with that rating curve, as the cross-section used for measurement is unstable and the Luangwa has high sediment flows and is highly variable, so the data should be viewed with caution and
- Cahora Bassa Dam - Median monthly flows calculated from daily flows for Lake Kariba outflow added to incremental inflows between Lake Kariba and Cahora Bassa Dam, the same data used by Beilfuss (2001) and in the ZAMWIS database.

Hydrographs and residual mass curves were developed to identify long dry cycles and are presented in this section.

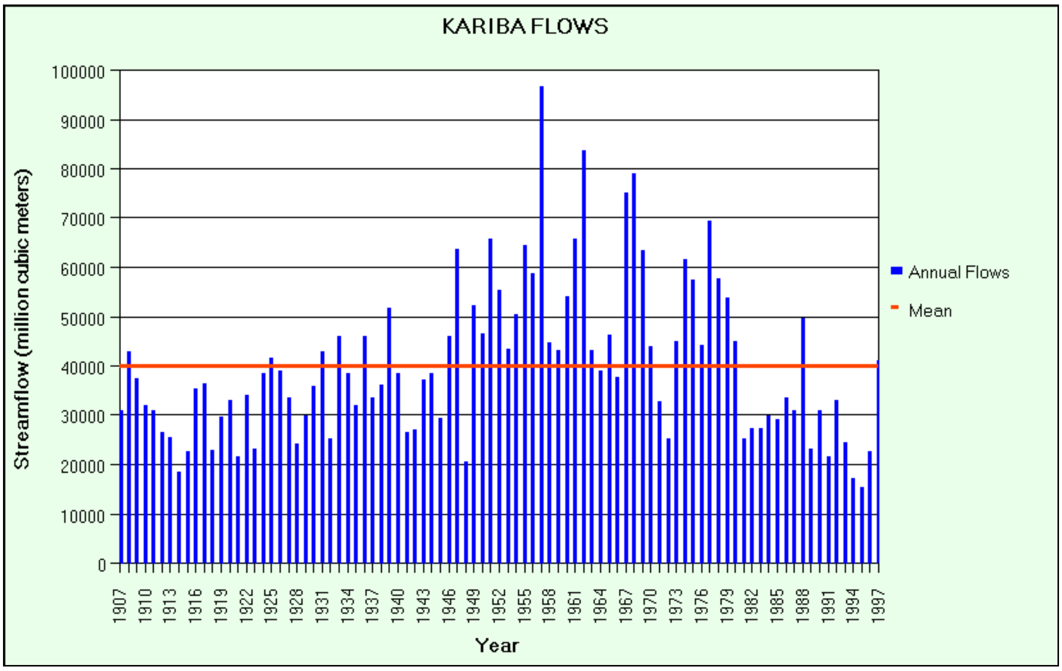


Figure 3.5: Hydrograph of inflow to Lake Kariba

While the hydrograph for Kariba (see Figure 3.5) residual mass curve (see Figure 3.6) show two very long dry cycles (i.e. 1907 to 1948 and from 1980) they are not sensitive enough to show the critical dry periods which have the most severe impact on the dam.

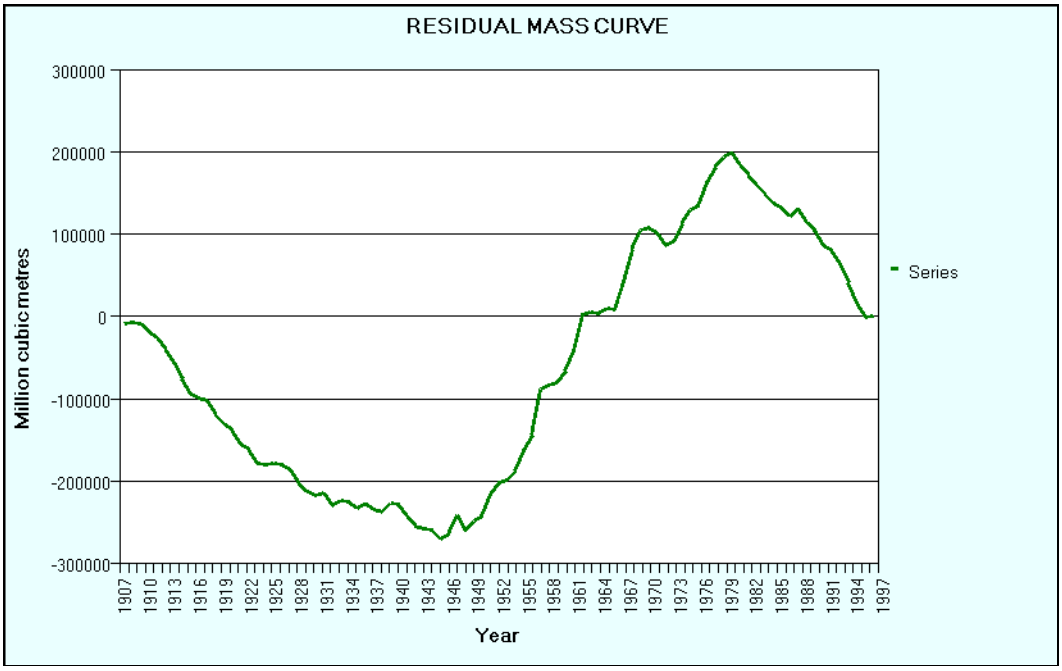


Figure 3.6: Residual mass curve of inflow to Lake Kariba

In the case of Lake Kariba, the periods for which historical storage dropped continuously spans the years 1989 to 1997 and from 1911 to 1924. It is of interest to note that both these periods are of similar duration, i.e. about 12 years.

Figure 3.7 shows the levels in Lake Kariba, 1960 to 2005, showing that, inter alia, that the critical drought ended in about 1996. The period from about 1990 to 1996 is the worst on record and, as Beilfuss determined, this period approximates to a 1:100 year drought based on the historical inflows data back to 1907. At the time when the 2000 floods were experienced, the water level was already at the flood rule curve (4m below the maximum level in February), so no extra storage capacity was available to store part of the flood. The levels in Kariba also give an indication that the long cycle pattern as suggested in Figure 3.6 did not recur after 1996.

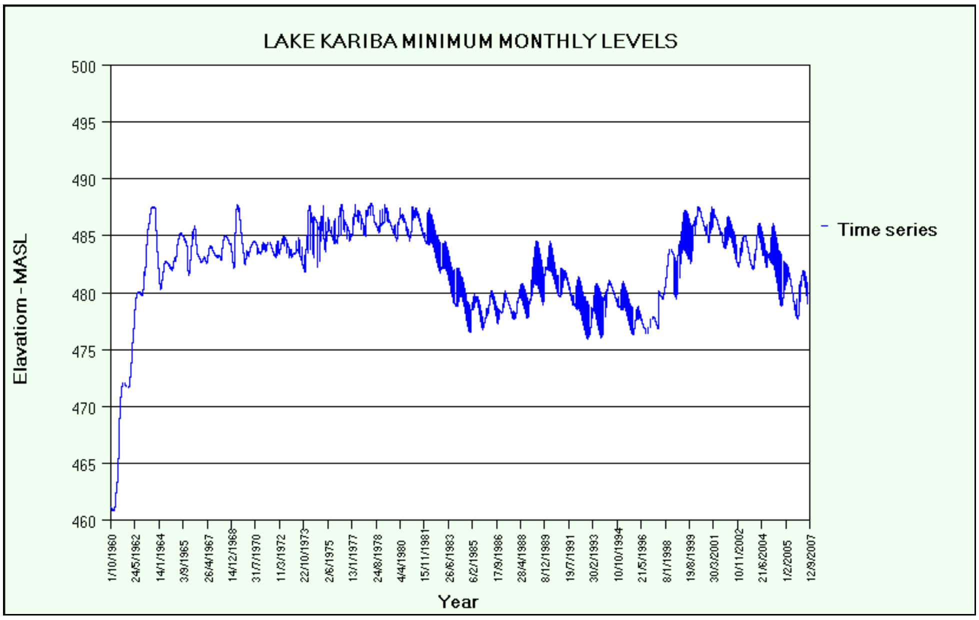


Figure 3.7: Levels of Lake Kariba

The cyclicity reported in the literature review could be due to dependency of annual flows on flows in previous years (autocorrelation in annual flows) rather than to cyclicity in the climate itself. The annual rainfall (averaged over Lake Kariba) over the period 1960-1996 has an autocorrelation coefficient of 9%, which is not significant. The historical inflows from Victoria Falls have an autocorrelation coefficient as high as 63% for the same period. The tributaries directly flowing into Lake Kariba have an autocorrelation coefficient of 49%. If the memory of the catchment causes autocorrelation, the Victoria Falls autocorrelation is expected to be higher than the correlation from the tributaries that flow directly into Lake Kariba. This is because of the size of the upstream catchment and because of the extensive wetlands. If extensive wetlands are very dry prior to the rains, they will absorb and not pass on large volumes of water, resulting in low flows being recorded in a good rainfall season. However, an analysis on the full time series from 1924-1997 of the annual flows at Victoria Falls only gives an autocorrelation of 0.18, which may make autocorrelation not sufficiently strong for seasonal forecasting.

It can be seen from Figure 3.5 that almost all 11 years that had a flow higher than 60,000 million m^3 were following a year of more than average flow. This can be taken as an indication that floods do not come completely unexpectedly, and that the likelihood of flooding can be partially predicted from prior year rainfall regime.

The inflow in to Kafue dam in Figures 3.8 and 3.9 shows the influence of Itezhi-Tezhi Dam which was completed in 1978. The figures show there is no real flood experienced after completion of Itezhi-tezhi Dam.

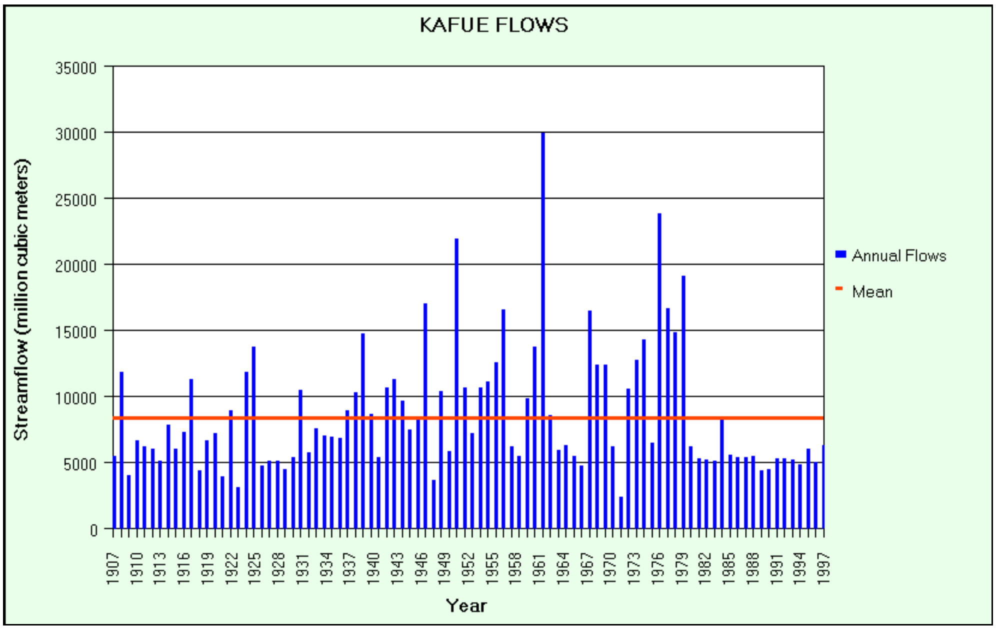


Figure 3.8: Hydrograph of inflow to Kafue Gorge Dam

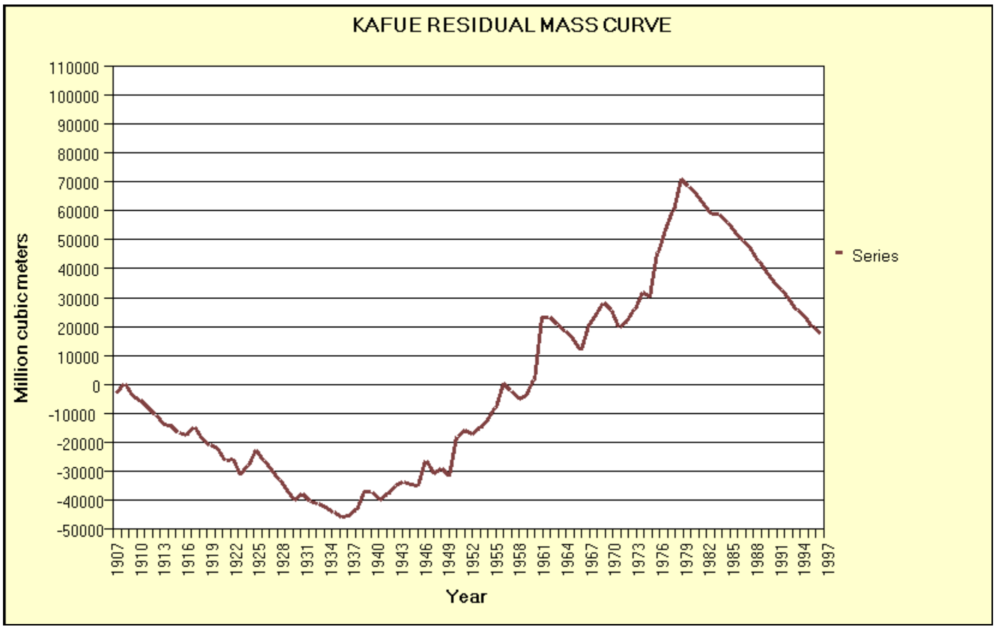


Figure 3.9: Residual mass curve of inflow to Kafue Gorge Dam

In order to obtain further insight on the effect Itezhi-tezhi Dam, a hydrograph and residual mass curve were developed for the Kafue Hook streamflow gauge upstream of Itezhi-tezhi Dam. These are given in Figures 3.10 and 3.11. The residual mass curve in Figure 3.11 for Kafue Hook gives a similar graph to Figure 3.9 and therefore confirms that Itezhi-tezhi Dam is not having any pronounced influence on the long term average monthly inflow into Kafue dam.

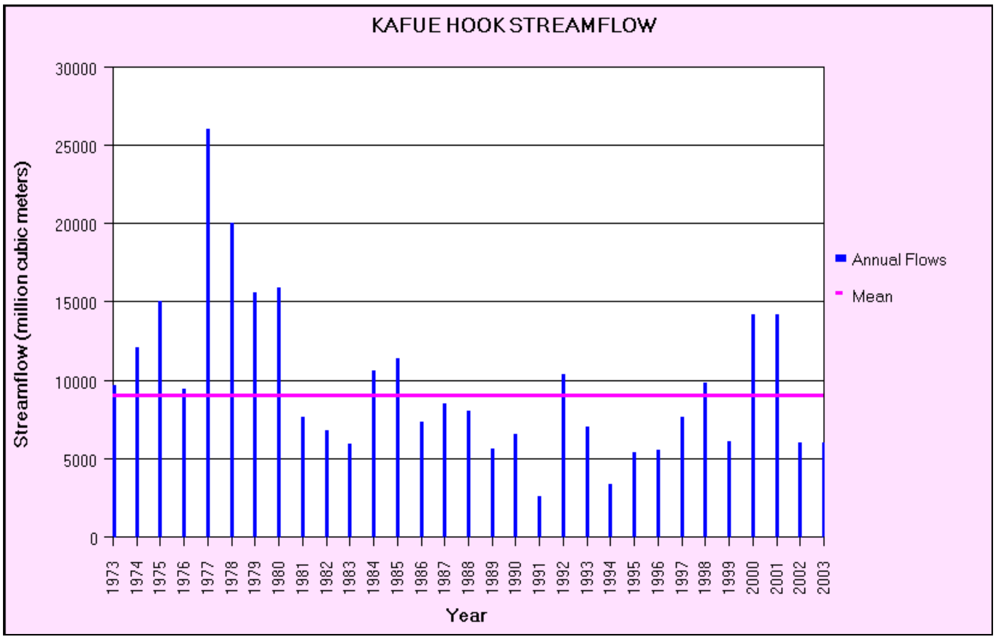


Figure 3.10: Hydrograph of flow at Kafue Hook

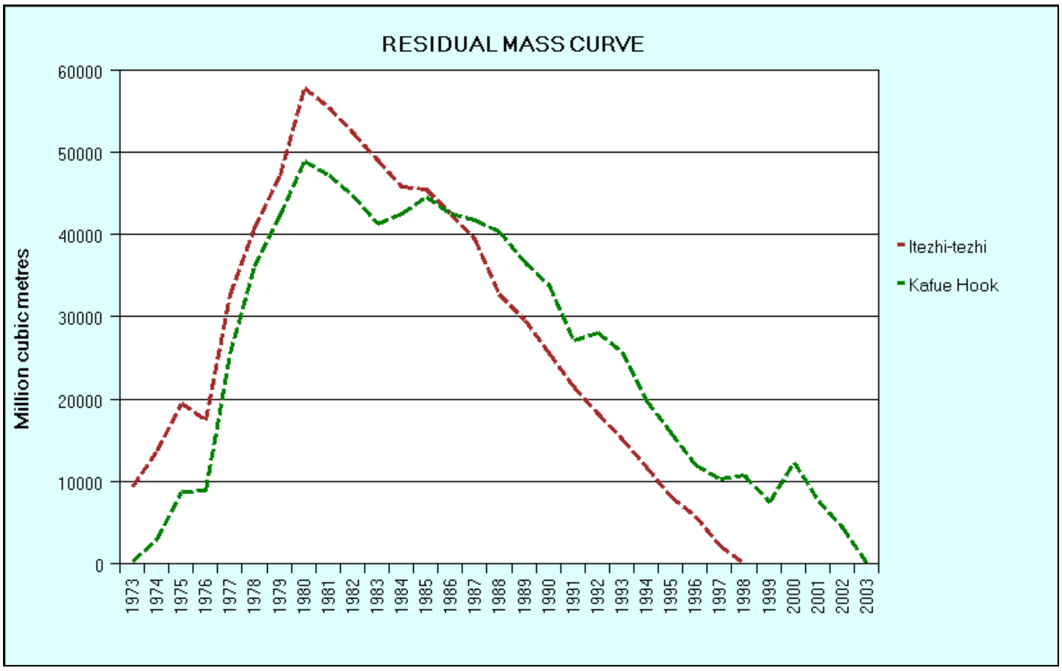


Figure 3.11: Residual mass curve of flow at Kafue Hook and inflow to Kafue Gorge Dam

Figures 3.12 and 3.14 show two completely different flow sequences, from 1907 to 1955 and from 1956 to 1997. This was explained by Beilfuss (2010) that the Luangwa River has only been gauged since 1955, so the more recent time period represents measured flow. The derivation of the flow series back to 1907 was done through a SADC hydrological analysis project in 1990 (Shawinigan-Lavalin and Hidrotécnica Portuguesa, 1990a&b; Batoka Joint Venture Consultants 1993; Li-EDF-KP Joint Venture Consultants, 2000). Furthermore, the rating curve has not been frequently updated and, as was pointed out at the beginning of section 3.3, the cross-section of the Luwangwa river is unstable due to the high sediment load of the river flows. Although this impacts the accuracy of the hydrograph, annual total flows are probably accurate enough for this analysis.

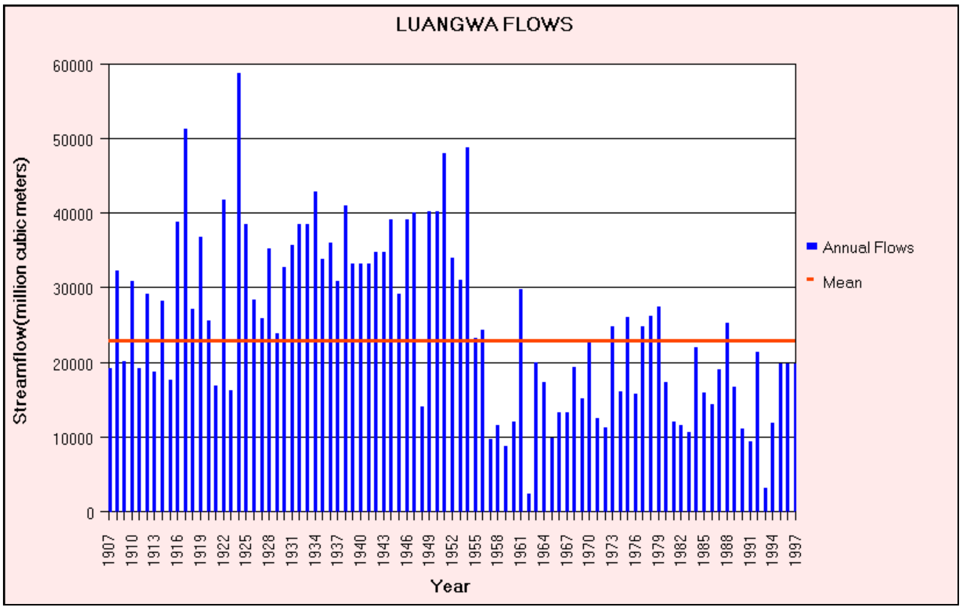


Figure 3.12: Hydrograph of the Luangwa River, including generated flows 1907-1997

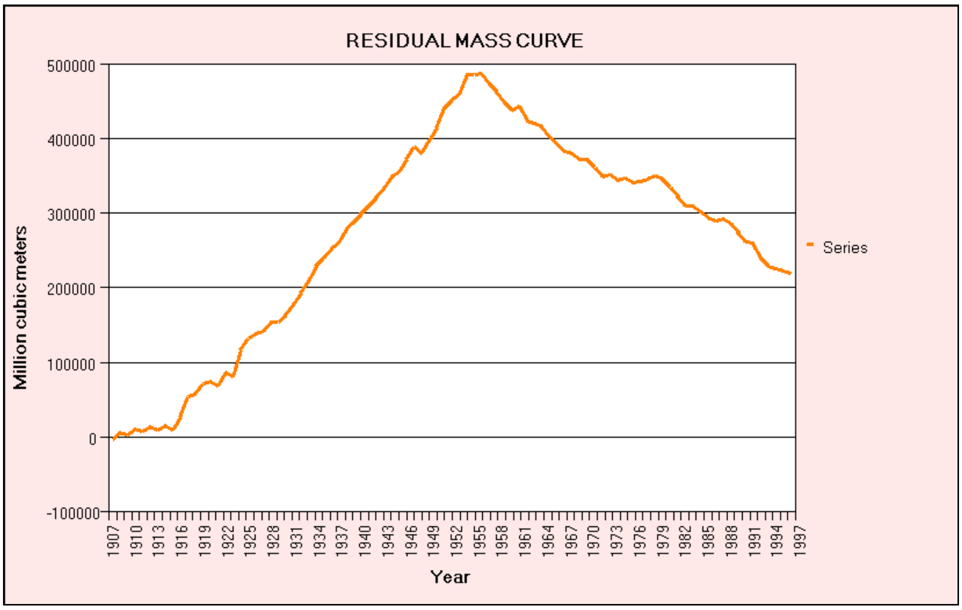


Figure 3.13: Residual mass curve of the Luangwa River, including generated flows 1907-1997

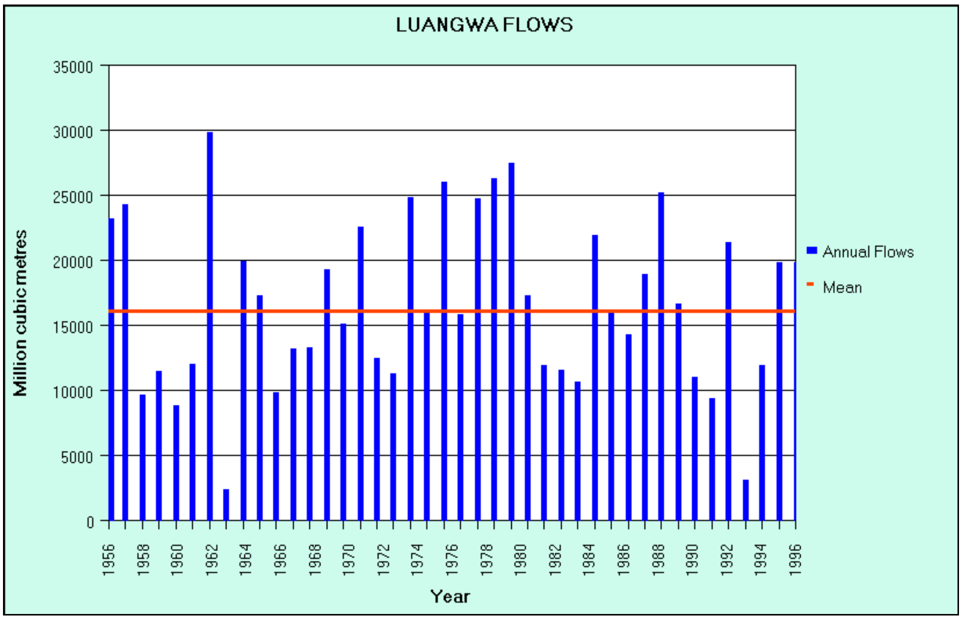


Figure 3.14: Hydrograph of the Luangwa River, measured flows 1956-1997

The hydrograph and residual mass curve for the period from 1956 to 1997 with measured flows only, are shown in Figures 3.14 and 3.15 respectively. This pattern shows that for the period after 1956, there was a considerable dry period until 1972, followed by a wetter period, 1972 to 1981, which, in turn, is followed by a more erratic period, which was generally dryer, 1982 - 1996.

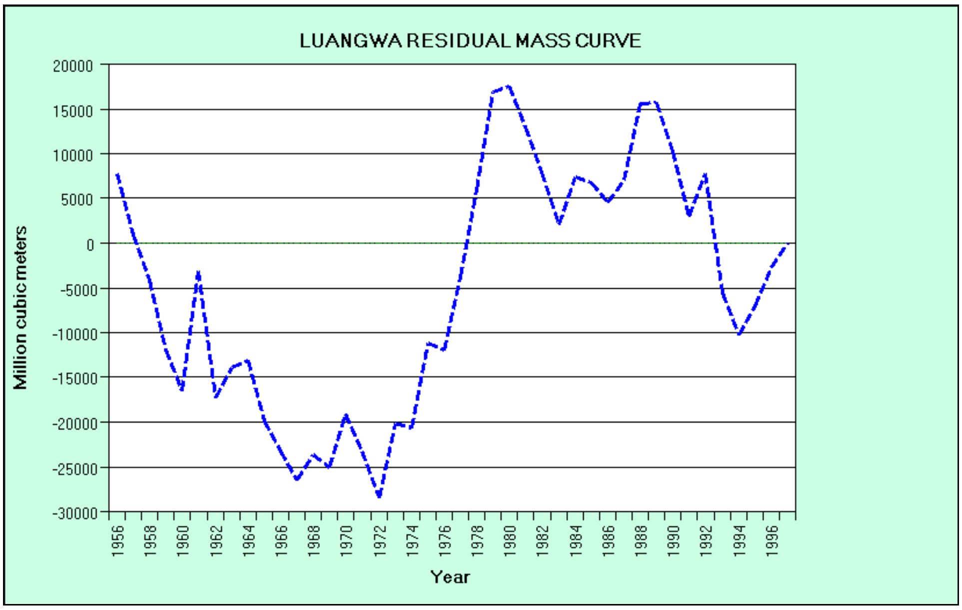


Figure 3.15: Residual mass curve of the Luangwa River, measured flows 1956-1997

For Cahora Bassa Dam less extensive data records were available, only since 1976.

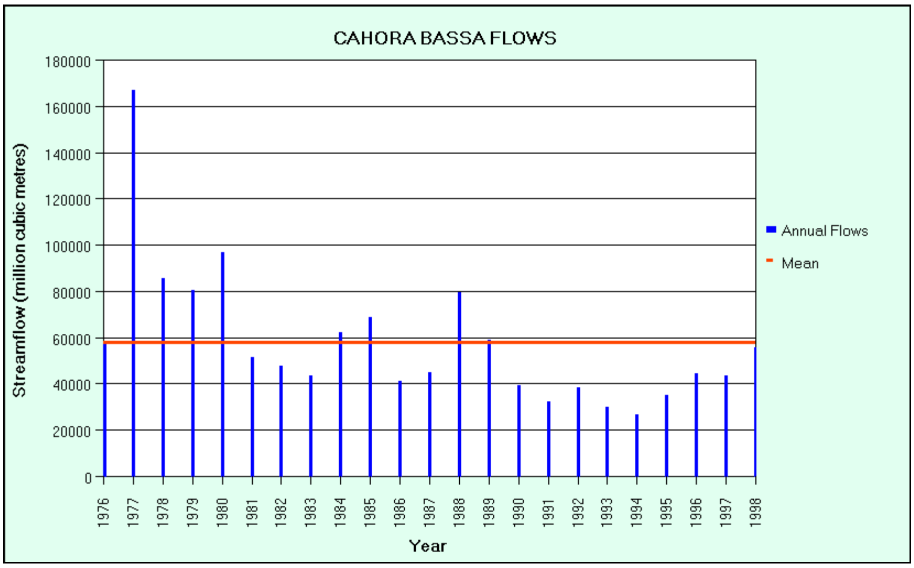


Figure 3.16: Hydrograph of the Cahora Bassa Dam

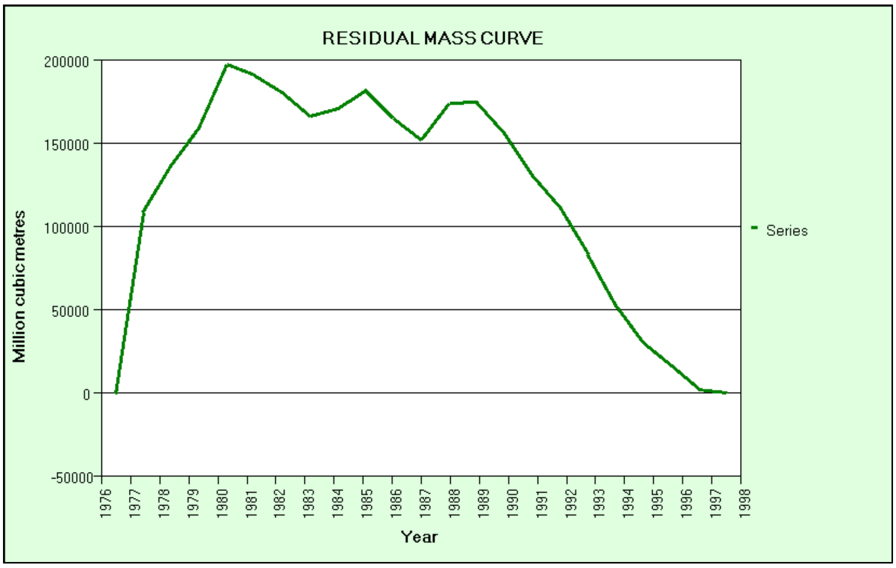


Figure 3.17: Residual mass curve of the Cahora Bassa Dam

The above graphs for Cahora Bassa Dam show that there is a period of continuous drop in storage from about 1990 until 1996 (the end of the streamflow data) which is the worst on record but the situation from 1998 is not captured in the data. The Luangwa River graphs show that the data is unreliable prior to the gauging start year in 1955.

A comparison of the flows and residual mass curves of the three main stems that flow into Cahora Bassa Dam (inflows to Lake Kariba and flows in the Kafue and Luangwa rivers) is shown in Figure 3.18 and in Figure 3.19 respectively. These figures show that there is a high correlation between inflows to Lake Kariba and flow in the Kafue River. Furthermore, the two figures show that there is a small deviation between Luangwa River floods and the cumulative flows. Lake Kariba inflows are relatively large in comparison to Luangwa and Kafue river annual flows, noting that the Kafue annual flows are highly influenced by Itezhi-tezhi Dam since 1978. Inflows into Lake Kariba are considerably higher than flows from the Luangwa and Kafue rivers combined. The Luangwa River floods are however more concentrated in February to March whereas Lake Kariba inflows are more concentrated in April to May (refer to Figure 3.21).

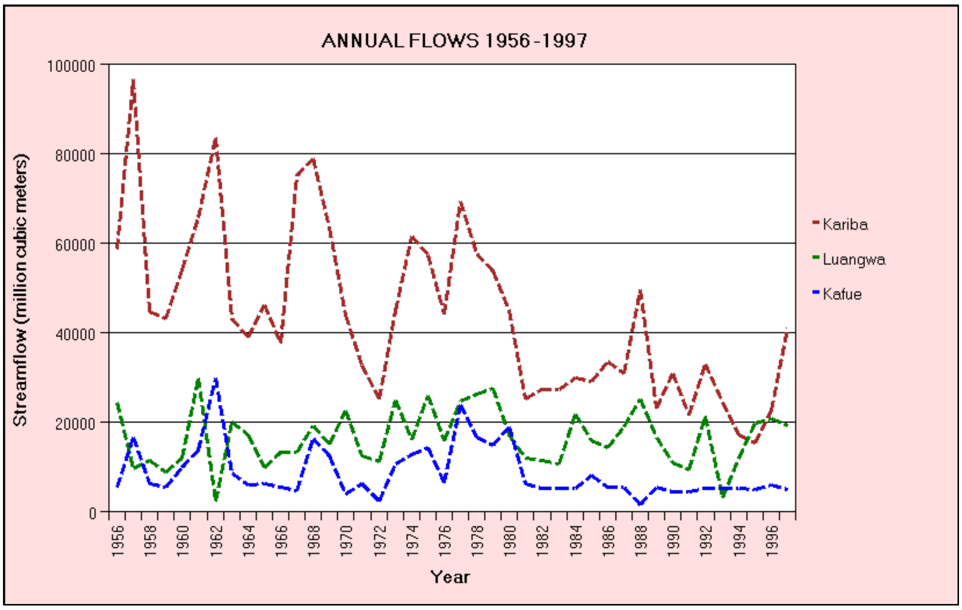


Figure 3.18: Annual inflow to Lake Kariba, annual flows of the Kafue and the Luangwa rivers 1956-1997

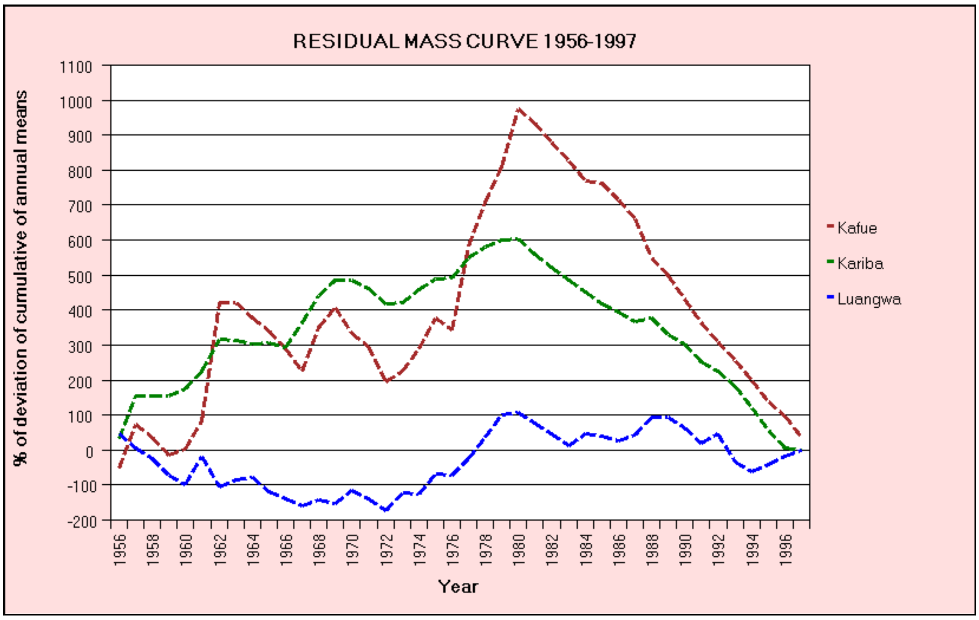


Figure 3.19: Residual mass curve of the inflow to Lake Kariba, the Kafue and the Luangwa rivers 1956-1997

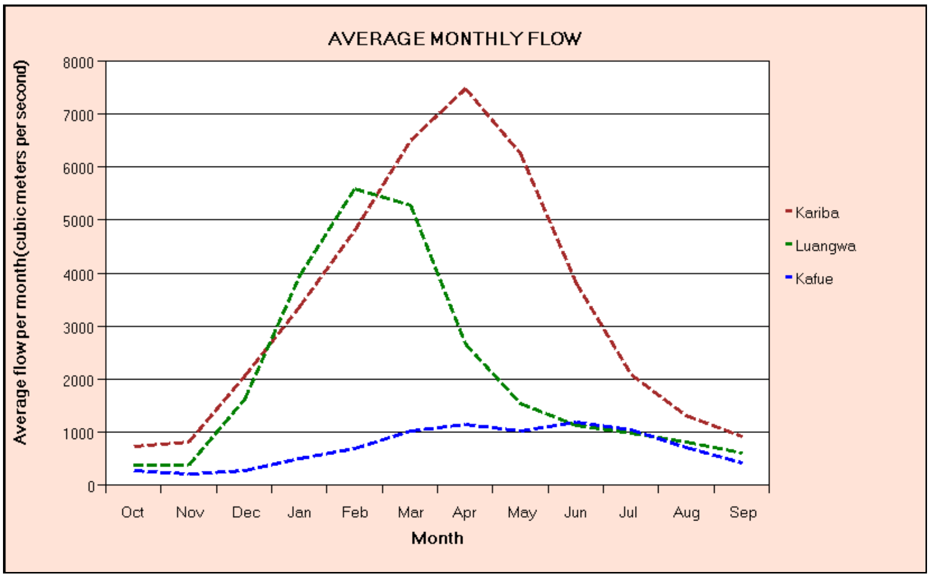


Figure 3.20: Average monthly flows for the inflow to Lake Kariba, the Kafue and Luangwa rivers 1956-1997

Conclusions on the basis of the data analysed:

- In the time series 1956-1997, the year 1981 is a turning point from wet to dry for most tributaries;
- Autocorrelation and residual mass curve analysis do not give significant evidence for multi-year pre-event conditions, i.e. no conclusive evidence was found that flood years are preceded by certain multi-year events in terms of flow. However, large floods seem to follow a year with higher than mean flows.
- Kafue flows and Lake Kariba inflows seem to be correlated, which makes it more difficult to avert floods.
- For the Luangwa River there is very little indication of multi-year cycles.

3.4 Scenarios to Predict the Impact of for Climate Change on Water Resources, Based on Historical Time Series

3.4.1 Approach

Climatologists express climate change scenarios in terms of changes in temperature and changes in precipitation regimes. While these are important for water resources and reservoir management, these parameters need some form of 'translation' to quantities that are directly relevant to a reservoir's water balance. What is directly relevant to reservoir management are potential evaporation from the open water bodies and changes in natural runoff in the catchments that feed the reservoirs.

With Lake Kariba and Cahora Bassa Dam being multiyear storage reservoirs, a full analysis of the possible pre-event scenarios, and long time series would be necessary. This can only be generated stochastically on the basis of extensive statistical analysis. Such scenarios, however, often suffer from the disadvantage that the correlation between different tributaries is difficult to simulate. The literature review and data analysis indicated that there might be multi-year cyclicity, but the limited length of the time series compromised an exact quantification thereof. Furthermore, section 3.3 shows that the annual flows from the different tributaries are correlated, (i.e. when a wet year is experienced upstream of Kariba, the Kafue basin also experiences a wet year).

It is therefore justified to use historical time series as the basis for climate scenarios and we superimpose a climate change effect on these historical series. This approach ensures preservation of both temporal and spatial correlation in a way that is at least plausible given the fact that it happened before. Furthermore, in later analyses, we can put specific focus on the periods wherein reservoir operation was critical and the conditions before, found in section 3.3. The uncertainty in the current knowledge about climate change is such that a historic time series of say 20 years, transferred to 2040, can appear already in 2030 or only happen in 2050.

Flood management and dam operations in the Zambezi require hydrological data on a time scale of the order of days or weeks. However, with the information available from climate prediction models, going back to a time scale less than a year creates a false impression of accuracy. The scenarios generated are for annual totals or means and they are more appropriate for sensitivity analysis as they are not a realistic representation of future climates in the 2030-2050 horizon. Climate change experts on Southern Africa based at the University of Cape Town's Climate Systems Analysis Group have indicated that insights in regional impacts are rigorously changing at this very moment. In addition the literature review on this study indicates only changes in average conditions, while it is known that climate change contributes to changes in the variability of climate and in the distribution of rainfall over the season. It also indicated that in General Circulation Models the effect of Climate Change on Cyclones (very relevant to floods in the Zambezi) is not yet covered correctly.

3.4.2 Changes in temperature, rainfall, evaporation, runoff and climate change scenarios

The generated scenarios need to be realistic combinations of changes in temperature, rainfall, evaporation and runoff. For the time horizon of 2030-2050 the following assumptions were made:

(i) temperature increases in the order of 0-2 degrees Celsius.

(ii) rainfall changes vary between decreases of -15% to increases of 15%. The decrease of -15% is supported by literature review (see Section 3.2.2). An average increase of 15% in rainfall is not supported by climate change literature. However, the cyclicity in rainfall patterns and potential increase in variability in a changing climate could results in an extreme wet season, more extreme than observed in the past records.

(iii) the changes in (i) and (ii) were assumed homogeneous over the whole catchment.

In order to estimate what the effect of temperature and precipitation changes are on the governing potential evaporation and runoff regime, the Hargreaves equation (Hargreaves and Samani, 1982) is used for the relation between temperature and potential evaporation, and the Budyko curve (Budyko, 1974) for the relation between potential evaporation and precipitation on the one hand, and runoff on the other. As a reference for the current rainfall and potential evaporation regime, we used the Climate Research Unit (CRU) database (New *et al.*, 2002). Using this method, several scenarios were generated, all representing a different combination of temperature and rainfall changes.

A relatively small change in precipitation results in a high change in the amount of runoff, because in semi-arid regions such as the Zambezi, only a small fraction of annual rainfall (about 15%) comes to runoff. Most of the rainfall evaporates and a decrease in rainfall will impact more on reducing runoff than of evaporation. The order of magnitude of these numbers is also confirmed in the literature review.

For the purpose of dam operation and generating worst case scenarios, the following scenarios were translated into time series:

- Scenario 1:- “Very dry”: 2 degrees Celsius increase, 15% decrease in rainfall
- Scenario 2:- “Dry”: 2 degrees Celsius increase, 0% change in rainfall
- Scenario 3:- “Wet”: 1 degree Celsius increase, 15% increase in rainfall
- Scenario 4:- Higher variability: A time series which introduces increased variability. It makes dry years drier and wet year’s wetter, by multiplying the deviation of the historical time series of the historical mean with a constant factor for years drier than the mean and another constant factor for relatively wet years. These constant factors are derived by making sure that each parameter for the driest year matches with the same year in the very dry scenario. In addition, each parameter for the wettest year matches with that for the wettest scenario.

For the “wet” scenario a smaller increase in temperature was used than for the “dry” scenarios. By not having an extremely high temperature increase, evaporation increases were limited resulting in higher runoff.

3.4.3 Results for Kariba reservoir

For inflow into Lake Kariba, rainfall, evaporation and derived changes in runoff were analysed for the part of the Zambezi river basin upstream of Victoria Falls. A separate analysis was done for inflows into Lake Kariba downstream of Victoria Falls. Also, the changes in evaporation from Lake Kariba and rainfall into Lake Kariba were computed. As inflows from non-gauged catchments downstream of Lake Kariba were available from 1961/62 to 1996/97 this time series was used (Beilfuss, 2001). The wet part of the cycle is up to 1980 and the dry part of the cycle is from 1981 onwards.

Combinations of changes in temperature, rainfall, evaporation runoff

Figure 3.21 gives the change in annual runoff (as a percentage of the total amount in the current climate), as a function of temperature and precipitation change. As an example, one can read from this graph that a temperature change of +3 degrees C. combined with a decrease in precipitation of -10% will cause an estimated reduction in the amount of annual runoff of approximately -35%.

Table 3.7 gives for a selected number of combinations of temperature and precipitation changes, the change in runoff coefficient and change in total annual runoff response. Scenario number 10 was used as the "very dry" scenario, scenario number 15 as the "dry" scenario and scenario 18 as the "wet" scenario.

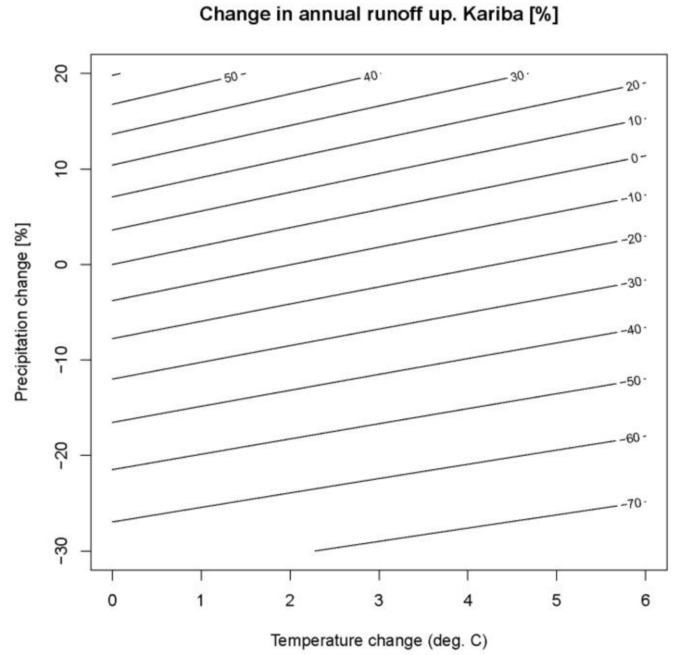


Figure 3.21: Estimated rate of change in annual runoff (contour lines show the percentages) for Victoria Falls inflow as a function of temperature and precipitation changes, computed with the Budyko curve.

Table 3.8: The effect of a selected number of combinations of temperature and precipitation regime change, on flows at Victoria Falls.

Number of scenario	Temperature change (degrees C)	Precipitation change (%)	Potential evaporation change (mm/year)	Runoff coefficient change (%)	Total runoff change (%)
1	0	-30%	0	-50%	-65%
2	0.5	-30%	25	-52%	-66%
3	1	-30%	45	-53%	-67%
4	1.5	-30%	70	-55%	-68%
5	2	-30%	90	-56%	-69%
6	0	-15%	0	-26%	-37%
7	0.5	-15%	25	-28%	-39%
8	1	-15%	45	-30%	-40%
9	1.5	-15%	70	-32%	-42%

Number of scenario	Temperature change (degrees C)	Precipitation change (%)	Potential evaporation change (mm/year)	Runoff coefficient change (%)	Total runoff change (%)
10	2	-15%	90	-34%	-44%
11	0	0%	0	0%	0%
12	0.5	0%	25	-3%	-3%
13	1	0%	45	-5%	-5%
14	1.5	0%	70	-8%	-8%
15	2	0%	90	-10%	-10%
16	0	15%	0	25%	44%
17	0.5	15%	25	23%	41%
18	1	15%	45	20%	38%
19	1.5	15%	70	17%	34%
20	2	15%	90	14%	31%

Time series for four scenarios

Table 3.8 gives for the selected four scenarios the main effects on the water balance of Lake Kariba. Figure 3.22 up to Figure 3.26 give an indication of the effect of climate change scenarios on the water balance components of Lake Kariba. Of relevance is the following:

- Changes to flows in the Wet scenario are +38% for the area contributing to flow at Victoria Falls (Figure 3.23) and almost +50% for the lower catchment areas flowing into Lake Kariba downstream of Vic Falls (Figure 3.24);
- Changes to flows in the Dry scenario are -56% to -51% respectively;
- Direct rainfall and evaporation changes are relatively small compared to their effect on river inflows;
- Changes to Victoria Falls flows have the largest impact on the changes in water balance;
- The "very dry" scenario, imposed on the series of wet years within the available historical time series, results in a situation which is as dry as the historical dry part of the time series and
- The combined effect of changes in inflow, rainfall and evaporation translates into impact on the water available for either storage, turbines or spillage as shown in Figure 3.26. The changes in evaporation and rainfall on the lake itself increase the impact on the water balance initiated by the change in inflows.

Table 3.9: Main characteristics of scenarios for Lake Kariba.

Scenarios	Very Dry	Dry	Wet	Higher variability	
Temperature change	2	2	1		
Rainfall change	-15%	0%	15%		
Effects on water balance	Percentages of historical values			Driest year	Wettest year
Rainfall into lake	85%	100%	115%	85%	115%
Evaporation from lake	106%	106%	103%	106%	103%
Vic Falls inflow	56%	90%	138%	56%	138%
Kariba Lower inflow	49%	87%	147%	49%	147%

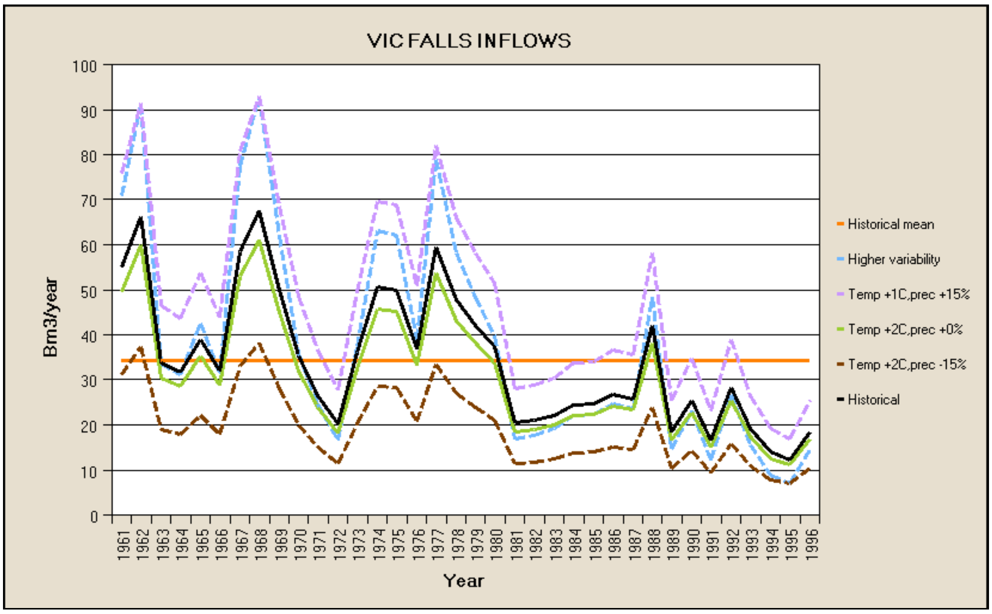


Figure 3.22: Scenarios for inflow Lake Kariba at Victoria Falls

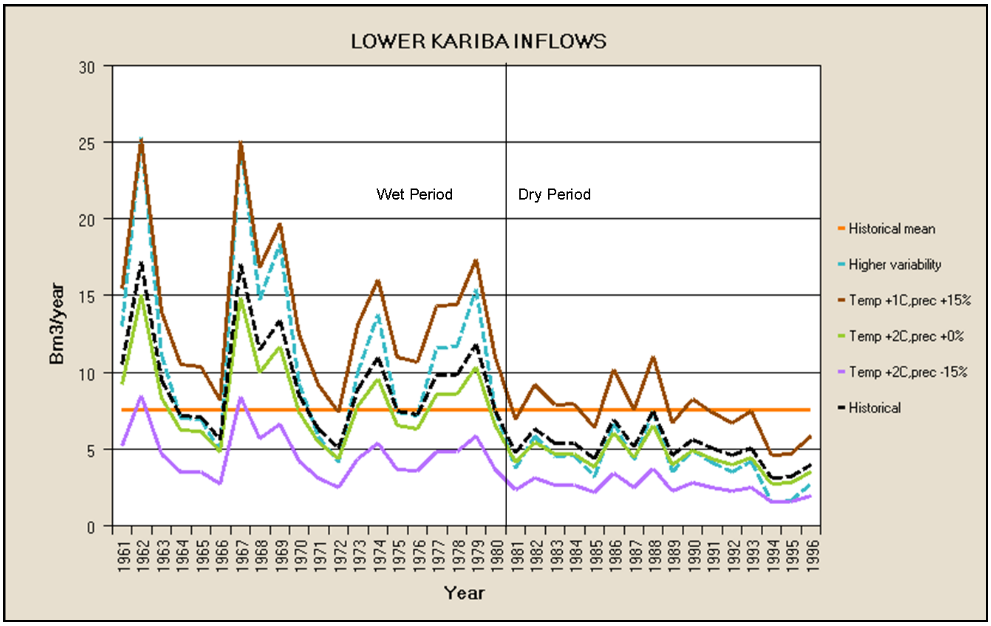


Figure 3.23: Scenarios for inflow Lake Kariba from other rivers than main Zambezi

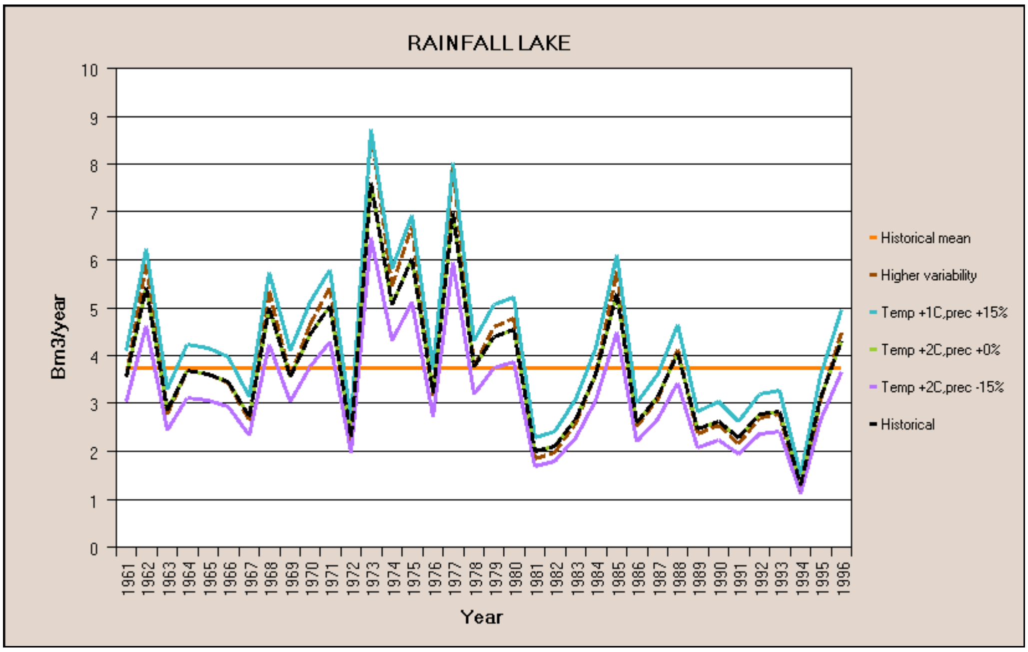


Figure 3.24: Scenarios for rainfall into Lake Kariba

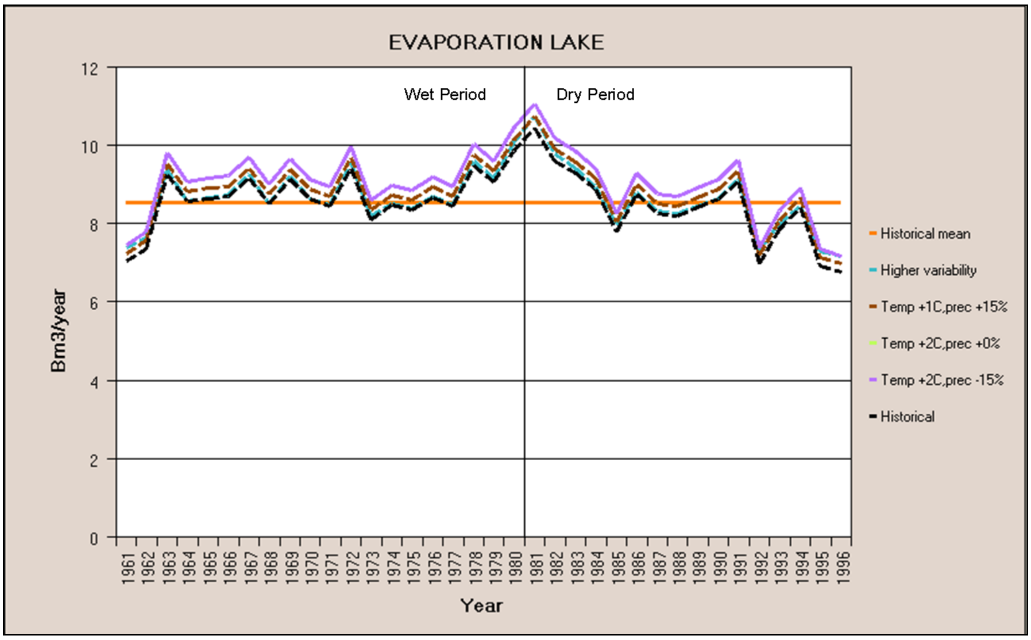


Figure 3.25: Scenarios for evaporation from Lake Kariba

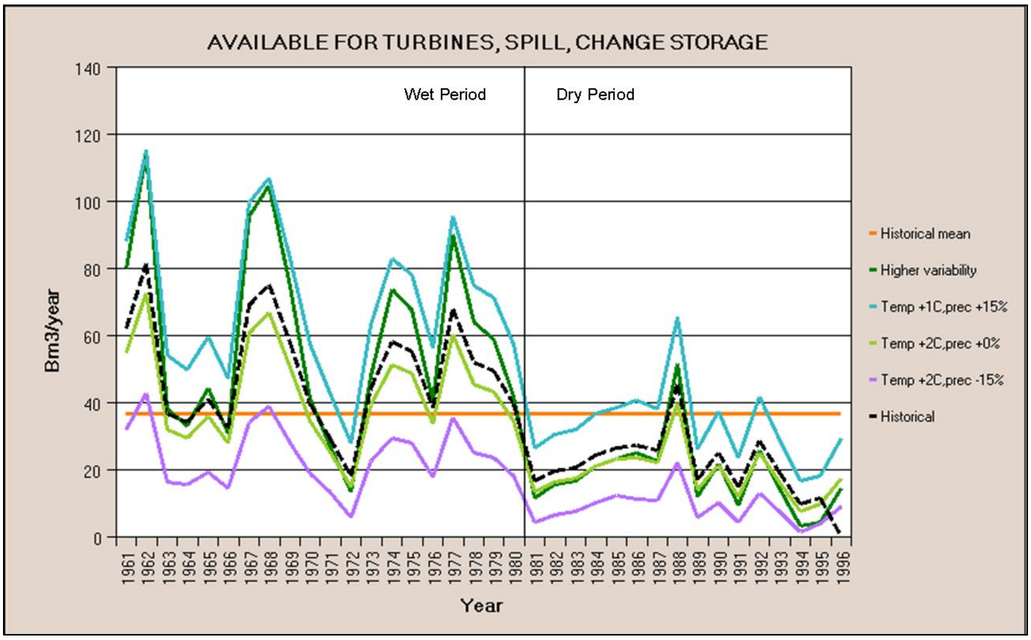


Figure 3.26: Scenarios for water available for storage change, hydropower production or spilling

In order to examine the Victoria Falls and lower Kariba inflows subject to the above scenarios, a monthly analysis was done for the following:

- 1990 to 1997 for the critical drought period
- 1971 to 1978 for the critical flood period.

Figures 3.28 and 3.29 show the critical drought period for Victoria Falls inflows and lower Kariba inflows respectively. Figure 3.30 and 3.31 show the critical flood period for Victoria Falls inflows and lower Kariba inflows respectively.

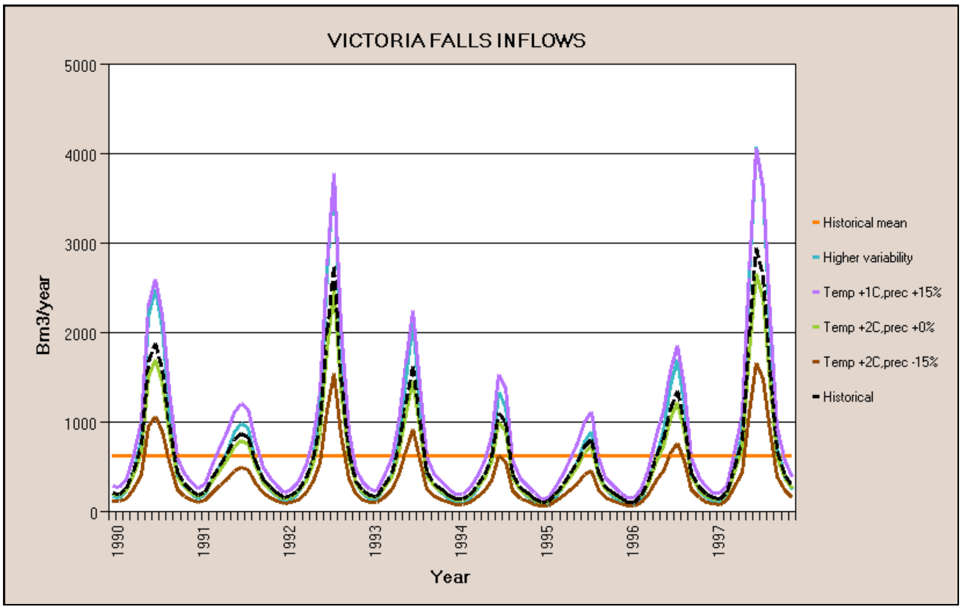


Figure 3.27: Monthly analysis of the critical drought period for Victoria Falls inflows

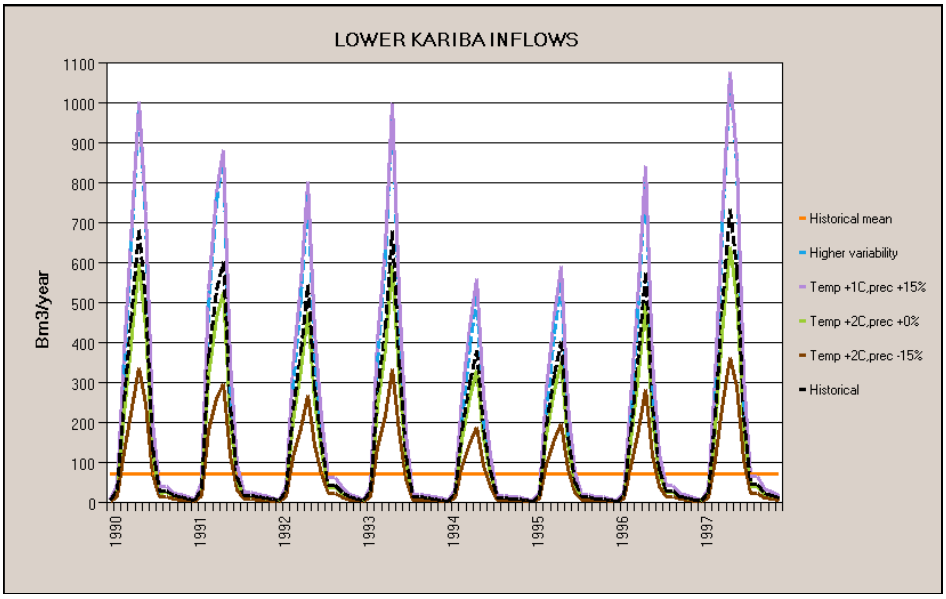


Figure 3.28: Monthly analysis of the critical drought period for lower Kariba inflows

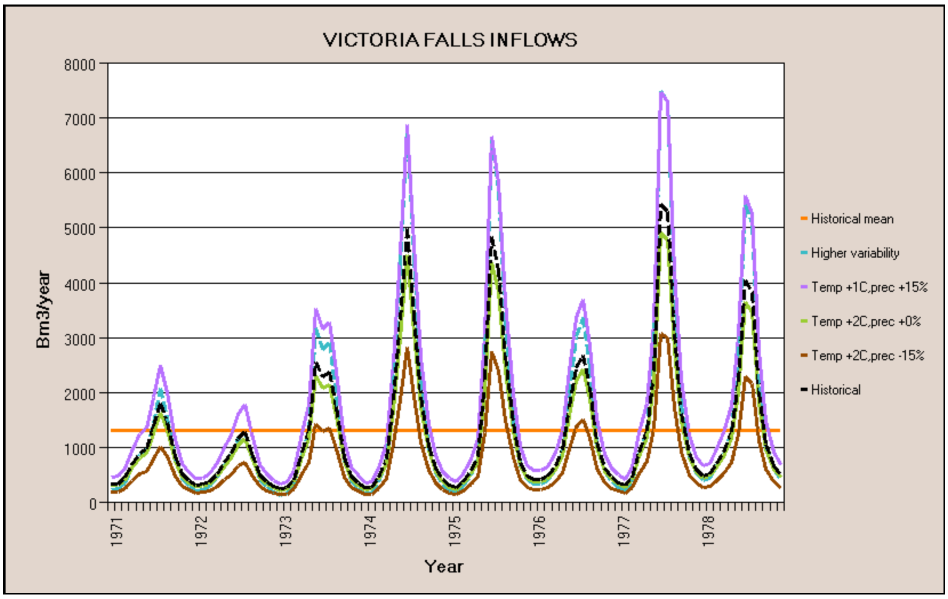


Figure 3.29: Monthly analysis of the critical flood period for Victoria Falls inflows

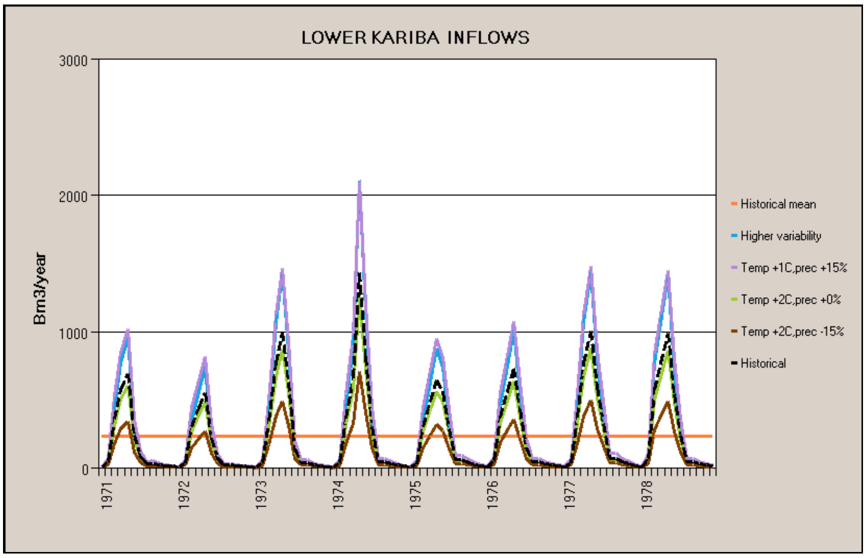


Figure 3.30: Monthly analysis of the critical flood period for lower Kariba inflows

3.4.4 Results for Cahora Bassa Dam

For Cahora Bassa Dam the available records on rainfall and evaporation from the lake itself are limited. Therefore the method was applied on inflows only coming from Zambezi, Luangwa and Kafue. It needs to be realized that these inflows are influenced by releases from Itezhi-tezhi Dam and Lake Kariba and that tributaries directly flowing into Lake Kariba are not taken into account.

Combinations of changes in temperature, rainfall, evaporation runoff

Figure 3.31 gives the change in annual runoff (as a percentage of the total amount in the current climate), as a function of temperature and precipitation change for inflows into Cahora Bassa Dam. Table 3.9 gives for a selected number of combinations of temperature and precipitation changes, the change in runoff coefficient and change in total annual runoff response.

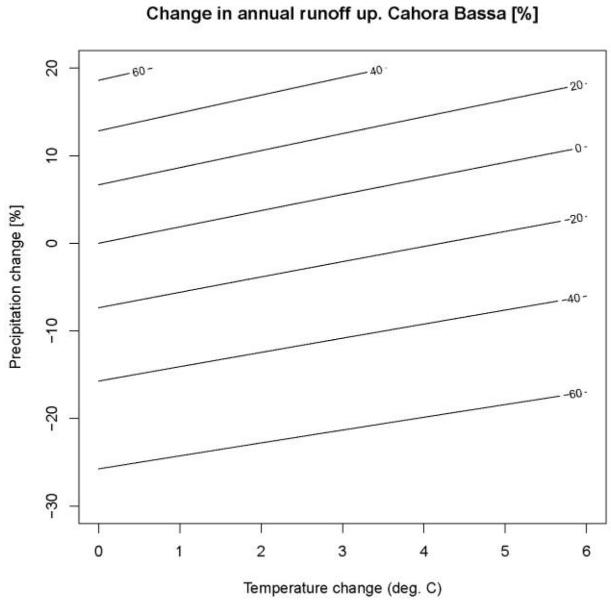


Figure 3.31: Estimated rate of change in annual runoff for Cahora Bassa Dam inflow as a function of temperature and precipitation changes, computed with the Budyko curve.

Table 3.10: The effect of a selected number of combinations of temperature and precipitation regime change, on flows into Cahora Bassa Dam.

Number of scenario	Temperature change (degrees C)	Precipitation change (%)	Potential evaporation change (mm/year)	Runoff coefficient change (%)	Total runoff change (%)
1	0	-30%	0	-53%	-67%
2	0.5	-30%	25	-55%	-68%
3	1	-30%	45	-56%	-69%
4	1.5	-30%	70	-58%	-70%
5	2	-30%	90	-59%	-71%
6	0	-15%	0	-27%	-38%
7	0.5	-15%	25	-30%	-40%
8	1	-15%	45	-32%	-42%
9	1.5	-15%	70	-34%	-44%
10	2	-15%	90	-36%	-45%
11	0	0%	0	0%	0%
12	0.5	0%	25	-3%	-3%
13	1	0%	45	-5%	-5%
14	1.5	0%	70	-8%	-8%
15	2	0%	90	-10%	-10%
16	0	15%	0	28%	47%
17	0.5	15%	25	25%	44%
18	1	15%	45	22%	40%
19	1.5	15%	70	19%	37%
20	2	15%	90	16%	34%

Time series for four scenarios

Table 3.11 gives for the selected four scenarios the main effects on the inflow into Cahora Bassa Dam. Figure 3.33 gives an indication of the effect of climate change scenarios on the inflow into Cahora Bassa Dam. As records on the historical evaporation from and rainfall into the lake were not available, these have not been computed.

Table 3.11: Main characteristics of scenarios for inflows into Cahora Bassa Dam

Scenarios	Very Dry	Dry	Wet	Higher variability	
Temperature change	2	2	1		
Rainfall change	-15%	0%	15%		
Effects on inflow	Percentages of historical values			Driest year	Wettest year
Inflow from upstream Kafue, Luangwa, Zambezi	55%	90%	140%	55%	140%

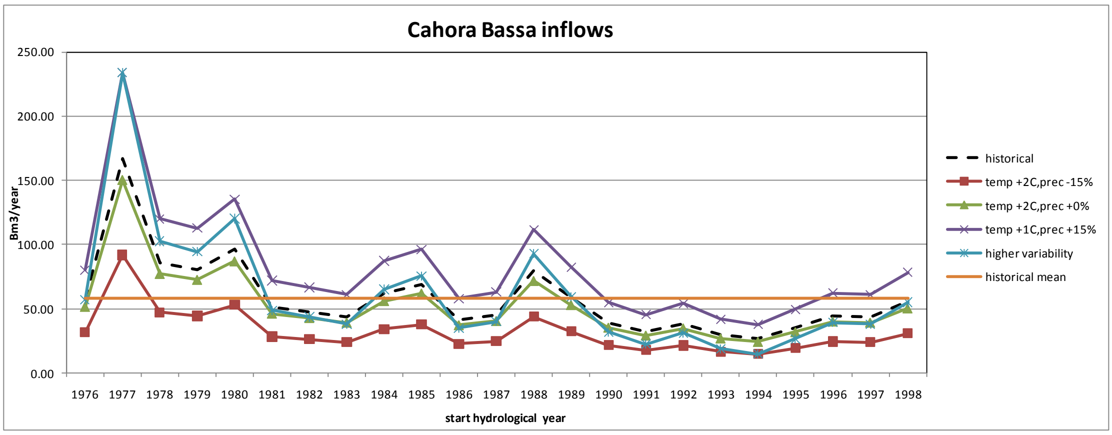


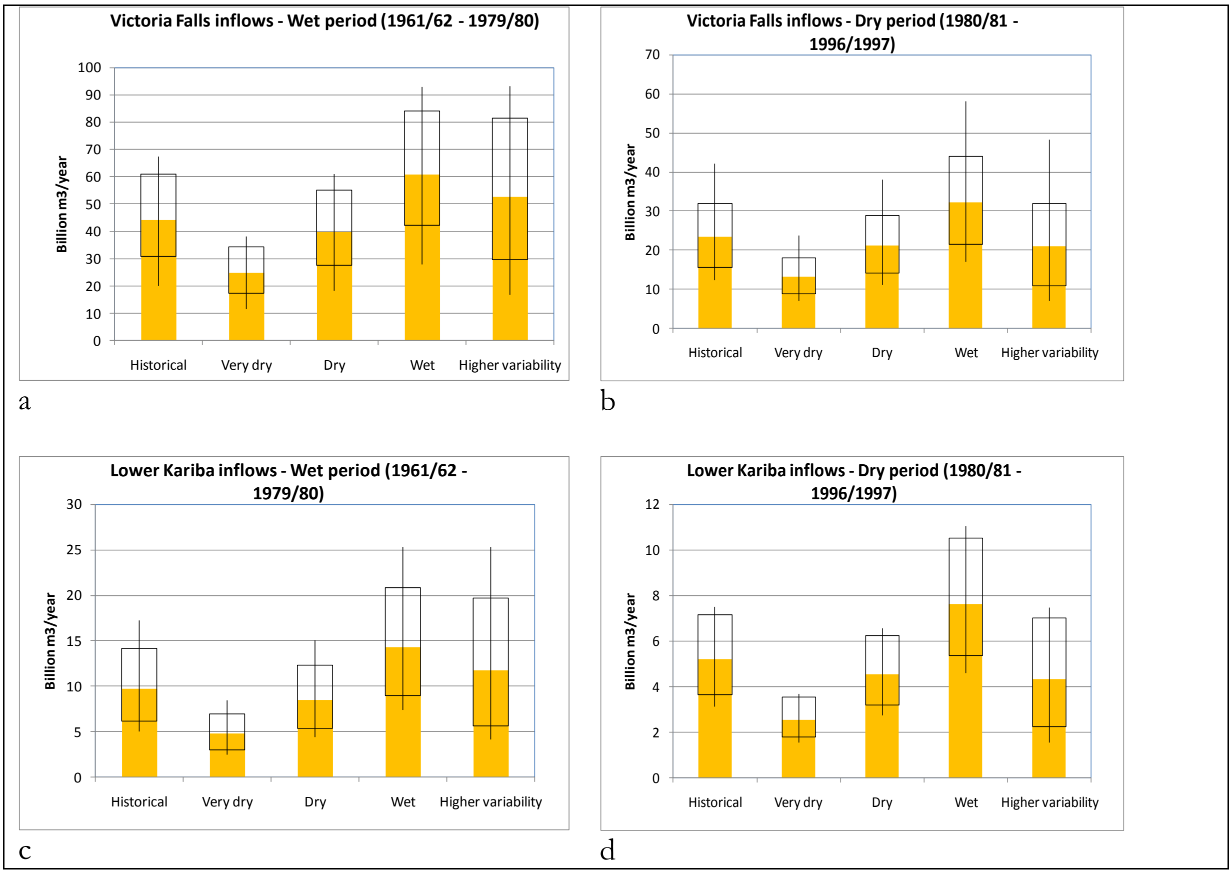
Figure 3.32: Scenarios for inflow into Cahora Bassa Dam

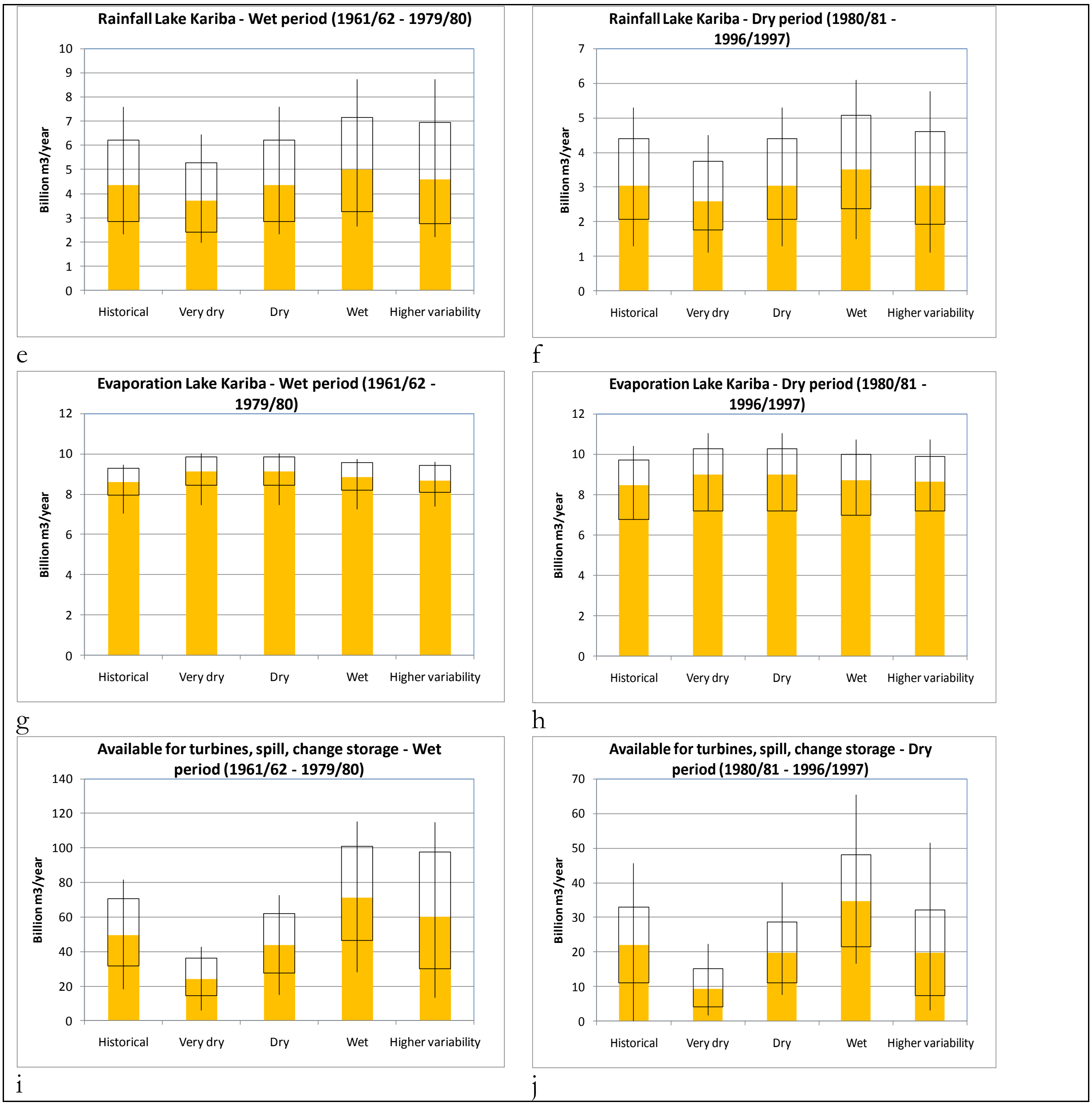
3.5 Expected effects of climate change on low water and floods

As was pointed out earlier, the evidence of cyclicity or autocorrelation is not sufficiently significant to use this for forecasting over different seasons. Also, the uncertainty in climate change is so large that the generated scenarios should rather be used for sensitivity analysis. Dam operations are sensitive the flood season becoming shorter and concentration of flows over a short period.

Figures 3.33 and 3.34 show the wet and dry periods as "box and whisker" plots where;

- The top end of the "whisker" is the maximum value for the period and the bottom end is the minimum
- The top end of the orange bar represents the mean value.




Rainfall Lake Kariba - Wet period (1961/62 - 1979/80)

Rainfall Lake Kariba - Dry period (1980/81 - 1996/1997)

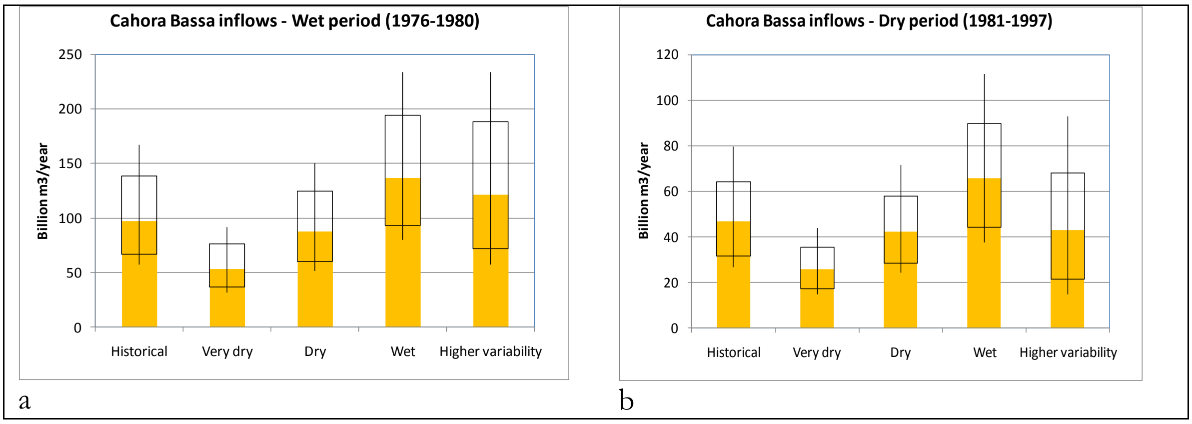
Evaporation Lake Kariba - Wet period (1961/62 - 1979/80)

Evaporation Lake Kariba - Dry period (1980/81 - 1996/1997)

Available for turbines, spill, change storage - Wet period (1961/62 - 1979/80)

Available for turbines, spill, change storage - Dry period (1980/81 - 1996/1997)

Figure 3.33 a-j: Comparison of scenarios for Lake Kariba for wet and dry periods, with indication of maximum, 10% highest, mean, 10% driest, minimum, for each parameter analysed.


Cahora Bassa inflows - Wet period (1976-1980)

Cahora Bassa inflows - Dry period (1981-1997)

Figure 3.34 a-b: Comparison of scenarios for Cahora Bassa Dam for wet and dry periods, with indication of maximum, 10% highest, mean, 10% driest, minimum, for each parameter analysed.

Notes: On Figures 3.33 i and j, the term "available for turbines, spill, change storage" essentially means inflows and rainfall less evaporation. Rainfall and evaporation are expressed in volumetric terms (billion m^3/year) so that the impact on the water balance of the dam can be judged.

From the above graphs it can be concluded that:

- Differences between maximum and minimum and between 10% wettest and 10% driest are higher for the wet than the dry scenarios. This is implicit in the method which uses proportions for all years; with relative variability staying the same;
- The "very dry" scenario (2 degrees Celsius change and -15% rainfall) which is the most probable according to the literature review has an immense impact on availability of water. The mean annual inflow available for storage increase, turbines or spilling is less than the was available historically 10% driest years for the simulated period 1956-1997 and
- The "wet" scenario (2 degrees Celsius change and +15% rainfall) applied on a wet period, implies that peaks in annual inflow have to be accommodated, of which the 10% wettest year gives a far higher inflow than is the historical maximum in the period 1956-1997. The mean is already higher than the 10% wettest year.

For use in further analysis it is suggested to use only worst case scenarios and the scenarios that reproduce the expected higher variability. This means as pre-conditions:

- For a worst case scenario for floods, the scenario for wet period, wet scenario can be used.
- For a worst case scenario for droughts, the scenario for dry period, very dry scenario can be used.
- For both wet and dry periods, the higher variability scenario can be used.

3.6 Conclusions

Literature review and data analysis shows that there are two major processes that may influence the management of the reservoirs in the future:

- **Natural cyclic behaviour:** many authors have observed cyclic behaviour in the annual rainfall and resultant persistent periods of wetness and droughts. It is not clear if this is indeed cyclic behaviour in annual rainfall or autocorrelation in annual rainfall in combination with long term memory of the catchment. The data analysis shows no convincing evidence, but gives an indication of flow autocorrelation that is higher than autocorrelation in rainfall.
- **Climate change:** most studies consistently stated that the Zambezi will become drier. For this project, this means that climate change needs to be considered as a potential threat to water availability and, to a lesser degree, to an increase in potential flood occurrences. Nonetheless, the high variability, apparent in the available historical time series, together with increasing awareness by climate scientists that variability may increase in a changing climate, may also result in incidental occurrences of more extreme wet seasons than the ones that have been observed in the past.

The period 1960-1997 was considered useful for generation of scenarios, containing both a wet period (1960-1980) and a dry period (1981-1997). A critical dry period was from 1990 to 1996 which approximated to a 1:100 year drought.

Autocorrelation or cyclicity was not sufficiently conclusive factors for the assertion that floods would occur after certain pre-event conditions. Therefore several pre-event conditions were possible. However, it was noted that for Lake Kariba all eleven years with annual flows above 60,000 million m^3/annum were preceded by a year with above average flows.

Climate change scenarios were generated for the Lake Kariba water balance parameters, as well as for Cahora Bassa Dam, for the purpose of sensitivity analyses on dam operation. Four plausible scenarios for 2030-2050 were generated based on conclusions drawn from the literature review: "Very dry" (+2 degrees Celsius, -15% rainfall), "dry" (+2 degrees Celsius, + 0% change in rainfall), "wet" (+1 degree Celsius, +15% change in rainfall) and Higher Variability. The Higher Variability was to address the expectation that climate change would give drier droughts and wetter wet years and was simulated using input from the other scenarios.

It is recommended that the "wet" scenarios be used as worst case for floods and the "very dry" scenarios as worst case for droughts. The higher variability scenario can be used as a moderate scenario for multiyear events and to show the impact on variability of flows.

The findings from this chapter contribute to the recommendations detailed in Recommendation Sheet 2.9 in chapter 10 of this document.

4 Wetland Retention and its Enhancement

4.1 Introduction

The modification of rivers and river basins for flood prevention, hydroelectricity, navigation or agriculture, amongst others inevitably leads to a significant loss in biodiversity as well as severely disrupting the river's ability to provide important ecosystem services, such as water purification or floodwater retention. Three main water-resource developments on the Zambezi system are: Kariba Dam and Cahora Bassa Dam on the mainstream and the Kafue Gorge/Itezhi-tezhi Dam complex on the Kafue River, which is a major tributary of the Zambezi. These reservoirs have greatly contributed to the economic to the southern African region in terms of power generation fisheries, and tourism especially the Kariba and Cahora Bassa reservoirs. With regard to power generation, Kariba has an installed generation capacity of 1266MW, while Kafue and Cahora Bassa have 990MW and 2075MW respectively.

Wetlands may be defined as those areas where an excess of water is the dominant factor determining the nature of soil development and the types of animal and plant communities living at the soil surface (King, 2008). By definition, these are areas that would be significantly altered by a change in their flow/inundation regime. They include riverine floodplains, papyrus swamps, marshes, mangrove swamps and estuaries. Under the RAMSAR international wetland conservation treaty, wetlands are defined as follows:

- Article 1.1: "...wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres."
- Article 2.1: "[Wetlands] may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands".

For the purpose of this section wetlands are defined according to Ramsar definition, which is the most common and broad definition that has been adopted by many countries including southern African countries.

The Zambezi Basin has a number of wetlands which apart from flood retention have important ecosystem functions. These wetlands are integral to the health of the basin and transverse the whole basin from the source of the Zambezi River in north western Zambia to its delta in central Mozambique. Both humans and wildlife have historically depended on these wetlands besides their hydrological functions in regulating flows and attenuating floods. The effects of land use and water resource management practices on the wetlands have been enormous. In this section the wetlands of the basin are characterized before a discussion of options to enhance/restore their functions of these wetlands. This section also discusses the concept of ensuring environmental flows in the Zambezi River.

4.2 Identification and characterization of wetlands on the Zambezi Basin

In the Zambezi system, the principal types of wetlands are defined by Seyam *et al.* (2001) as:

- Riverine - all the floodplains along the river system, such as Barotse, Kafue, Luangwa and Shire
- Dambos - These tend to be relatively smaller wetlands that occur throughout the basin
- Fringe - at Kariba, Cahora Bassa and Itezhi-tezhi reservoirs and Lake Malawi. These are the areas that are wet on account of being on the shores of the three major lakes.

The major wetlands of the Zambezi river Basin are shown in Figure 4.1.

With regard to human utilization, large communities rely on riverine wetlands for subsistence agriculture and livelihoods. Table 4.1 lists the major wetlands in the Zambezi river Basin as well as their current usage and their current state of conservation.

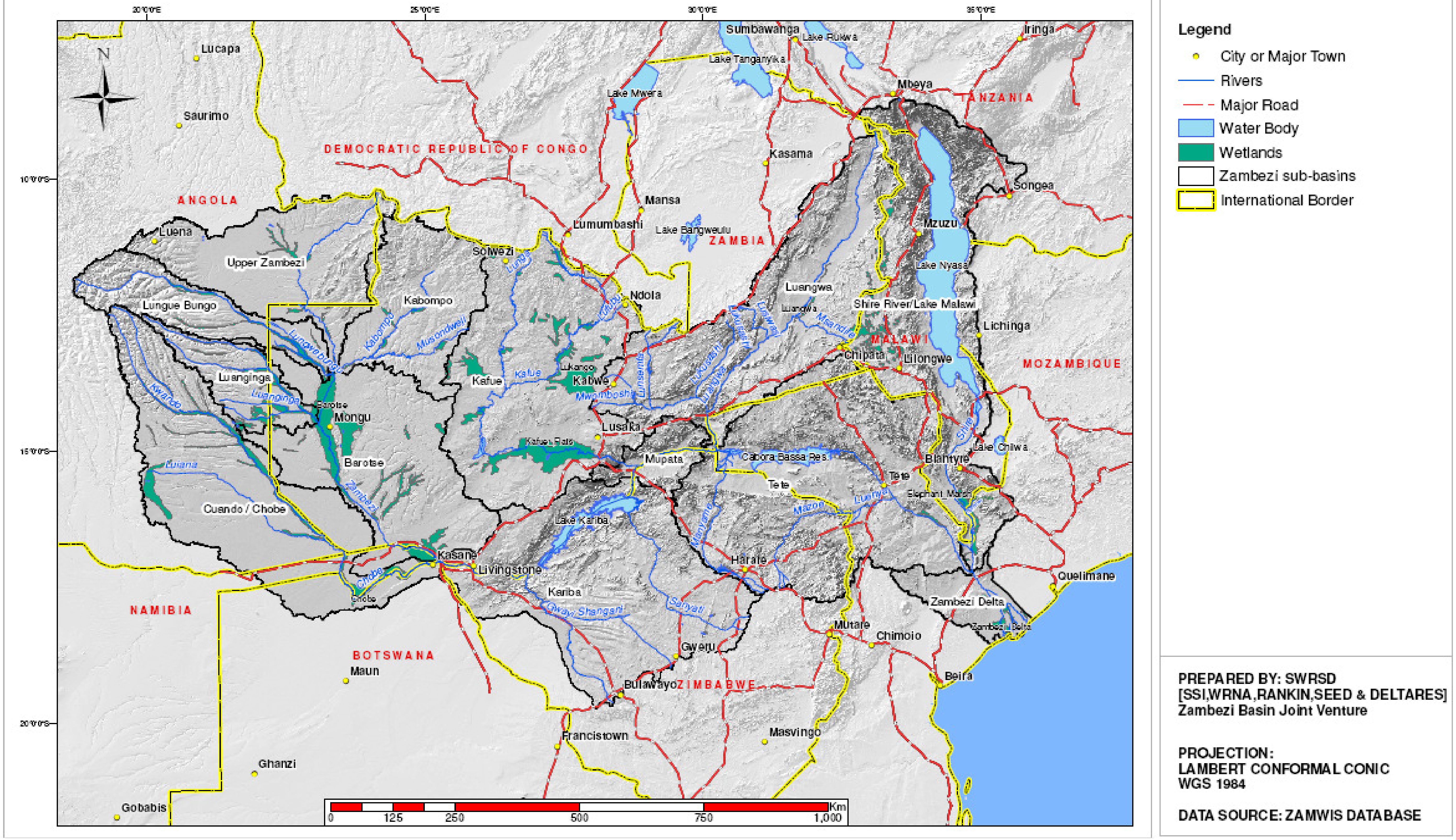
Table 4.1: Major freshwater wetlands of the Zambezi Basin

Wetland	Use	Conservation status
Kafue Flats	Fishery, grazing, wildlife, limited agriculture	Partly protected
Lukango	Fishery, grazing, transport	Unprotected
Barotse floodplain	Fishery, grazing, wildlife, limited agriculture	Partly protected
Liuwa floodplain	*	*
Linyanti-Chobe	Fishery, tourism, no subsistence use	Almost all protected
Cuando	*	*
Elephant Marsh	Fishery, grazing, agriculture	Unprotected
Luangwa	*	*
Busanga	Unexploited wildlife refuge	Completely protected
Luena	*	*
Lower Shire	*	*
Zambezi Delta	*	*
Key: *No data available		

The Luangwa River has a big influence on operations at Cahora Bassa and contributes about 70% of the floods for the reservoir. The Luangwa River is not regulated and the Luangwa wetlands are reportedly quite degraded. To halt further degradation there is need to institute a wetlands management program for maintenance of the integrity of the Luangwa wetlands.

The following wetlands are covered in this chapter:

- Barotse
- Chobe –Eastern Caprivi
- Kafue
- Lower Shire
- Zambezi delta



PREPARED BY: SWRSD
[SSI,WRNA,RANKIN,SEED & DELTARES]
Zambezi Basin Joint Venture

PROJECTION:
LAMBERT CONFORMAL CONIC
WGS 1984

DATA SOURCE: ZAMWIS DATABASE

SOUTHERN AFRICAN DEVELOPMENT COMMUNITY
SADC
TOWARDS A COMMON FUTURE

TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

FIG 4-1 MAJOR WETLANDS IN THE ZAMBEZI RIVER BASIN

giz

On behalf of:
Federal Republic of Germany
The Federal Government

UKaid
from the Department for International Development

Australian Government
Aid Program

(a) Barotse Flood Plain

The Barotse Flood plain in north western Zambia is located on an extensive totally flat area in western Zambia which receives large volumes of water from the Zambezi River and its tributaries. Because of the flat topography over this extensive area, the Zambezi River easily overflows its banks in the rainy season with large volumes of water flooding these Barotse plains.

The area extends over about 1.2 million hectares has been defined by Timberlake as extending from Lukulu to downstream of Senanga, and including the Liuwa Plain National Park, the Luena Flats, the Barotse Floodplain and the Lungwebungu River wetlands(Turpie *et al.*1999) Table 4.2 presents the main sub-catchments of the Barotse plains.

Table 4.2: Estimated area of the Barotse wetlands

Wetland	Area (ha)
Barotse Floodplain (main flood plain)	550 000
Lungwebungu wetlands	70 000
Luena Flats	110 000
Luanginga River	100 000
Liuwa Plains National Park	366 000
TOTAL	1 196 000

The flat topography of the plains reduces the velocity of the floodwaters, such that the Barotse floods only arrive in Lake Kariba about 10 weeks after their onset. The Barotse Floodplain was listed as a Ramsar site in 2007 (www.ramsar.org/sitelist.doc).

Within the Barotse plains area a number of nature and wildlife conservation areas have been demarcated as:

- Mamili National Park
- Liuwa Plain National Park
- Sioma Ngwezi National Park
- West Zambezi Game Management Area

A number of different habitats have been defined and demarcated for the Barotse plains. These are shown in the table 4.3 below. The areas in the table show that most of the Barotse plains fall into the floodplain savanna and wet grass areas accounting for 40% of the area each. The extent of different habitat types within the Barotse Floodplain is given in Table 4.3

Table 4.3: Approximate areal extent of different habitat types within the Barotse Floodplain

Habitat type	Percent coverage	Area (ha)
Palm savanna	2	11 000
Floodplain grassland	40	220 000
Wet grass	40	220 000
Reeds and sedges	10	55 000
River channel	8	44 000
TOTAL	100	550 000

(b) Chobe –Eastern Caprivi Wetlands

From Katima Mulilo in the west to Kazungula in the east, there are a series of inter-linked floodplains along the Zambezi River on the borders between Namibia, Zambia and Botswana.

The floodplain system in Eastern Caprivi extends over a gross area of approximately 370 000 hectares, linking the Cuando, Linyanti, Chobe and Zambezi Rivers. The main wetland areas are in the extreme eastern Caprivi, bounded by Botswana along the Chobe and also extends into Zambia. Within the gross areas of 370 000 ha, the actual wetland area is about 220 000 hectares, with the same range of habitats as the Barotse floodplain. The hectarages of these habitat types are shown in Table 4.4 and it can be seen that floodplain grassland accounts for 70% of the area, while wet grasses account for 15%. The Chobe-Caprivi floodplain lies downstream of the Barotse and relies on the Barotse waters for most of its flooding. Thus, the flooding of Chobe-Caprivi wetlands is often delayed until good summer rains have fallen in these areas upstream.

Table 4.4: Approximate areal extent of different habitat types within the Eastern Caprivi-Chobe

Habitat type	Percent coverage	Area (ha)
Palm savanna	2	4 400
Floodplain grassland	70	154 000
Wet grass	15	33 000
Reeds and sedges	8	17 600
River channel	5	11 000
TOTAL	100	220 000

(c) The Kafue Flats (wetlands)

The Kafue River is a major tributary of the Zambezi River, with its drainage basin lying entirely within Zambia. It is a source of portable water for 40% of Zambia and the major water source for its capital city of Lusaka. The Kafue Flats is a broad alluvial plain upstream of Kafue Gorge, and extending for a distance of about 250 km. It is 60 km wide, covering around 650 000 hectares. The retention time for water passing through the Flats is about two months. Before construction of the Itezhi-tezhi reservoir, seasonal runoff from the Kafue River and its tributaries inundated the Kafue Flats to create a mosaic of floodplain grassland and permanent lagoons. Water levels in the flats would start to rise in late November or early December, shortly after the onset of rains in the lower Kafue basin. Between December and February, runoff from local tributaries caused widespread shallow flooding and waterlogging of the flats (Beilfuss & dos Santos 2001). Peak runoff reached the upstream end of the Kafue Flats in March. The historical peak annual flood was about 500 m^3/s, with a 100-year flood of about 3000 m^3/s. Floodwaters spread slowly over the Flats for several months, inundating up to 5650 km^2 during very wet years. Downstream of the Kafue Flats, the Kafue River peaked in late May, well after the local rains had ended. The vast extent of shallow floodwaters across the Kafue Flats resulted in very high evaporative water losses, with an estimated average annual evaporation of 1784mm against an annual total rainfall of 739mm. Potential evaporation exceeds rainfall in all except the peak rainfall months. The net evaporation over the annual rainfall is about 1050 mm

Kafue Flats is one of the most biologically diverse ecosystems in the region comprising meandering river channels, lagoons, ox-bow lakes, remnant secondary channels, marshes, levees and flooded grasslands that support more than 400 bird species, a considerable number of fish species and substantial populations of mammals including the Kafue lechwe *Kobus leche kafuensis*. The Kafue Flats was listed as a Ramsar site in 1991 (www.ramsar.org/sitelist.doc).

(d) Lower Shire Wetlands

The Lower Shire wetland area extends from Kapuchira Falls near Blantyre, Malawi, to the confluence of the Shire with the Zambezi near Senna and Mutarara, Mozambique. It includes

Elephant Marsh and Ndinde Marsh, with additional minor wetland areas as shown in Table 4.5. Literature on the area is sparse and mostly outdated.

Table 4.5: Estimated area of the Lower Shire wetlands

Wetland	Area (ha)
Elephant Marsh	60 000
Bangula Marsh	17 000
Ndinde Marsh	80 000
Tributary marshes	5 000
TOTAL	162 000

Most of the wetlands are not well protected and appear to be shrinking because of dropping water levels in Lake Malawi, with only Ndinde Marsh being a reasonably intact ecosystem. Using the habitat classification that was used for Barotse, Caprivi and Kafue, and as shown in Table 4.6, the lower Shire wetlands are mainly made up of wet grasses (45%) and reeds and sedges (27%), with floodplain grassland only accounting for 20%. The Shire wetlands have less grassland than the Kafue, Barotse and Caprivi, possibly as a result of the fact that they tend to be waterlogged for longer periods of time and permanently in places.

Table 4.6: Approximate areal extent of different habitat types within the Lower Shire Wetlands

Habitat type	Percent coverage	Area (ha)
Palm savanna	2	3 240
Floodplain grassland	20	32 400
Wet grass	45	72 900
Reeds and sedges	27	43 740
River channel	6	9 720
TOTAL	100	162 000

With regard to hydrology, the lower Shire area receives summer rainfall, with flooding usually beginning late January or February. During periods of high runoff from the local catchments corresponding with floods in the Zambezi, the Shire River backs up from the Zambezi confluence to north of Elephant Marsh with widespread local flooding.

(e) Zambezi Delta

The Delta extends over a triangular area from Mopeia in Mozambique 120 km downstream to the coast, and between the Rio Cuacua in the north and the Mungari River in the south, covering 1.4 million hectares. It includes the 150 000 hectare Marromeu Buffalo Reserve, which is a proposed Ramsar international wetland site. The Delta as a whole used to support the same broad habitat types as the other wetlands described above as well as mangrove swamps. Table 4.7 shows the relative areal extents of the different habitat types. Prior to the construction of large dams upstream on the Zambezi, the original flooding pattern of the delta consisted of high waters in January to April and low waters October-November. This has been eradicated by upstream dams that now regulate 70% of the Basin. The Marromeu Complex was listed as a Ramsar wetland in 2004 (www.ramsar.org/sitelist.doc). Other important protected areas within the delta are:

- Marromeu Buffalo Reserve: a 150 000 hectare area of floodplain grasslands and a proposed Ramsar wetland
- Nhapakué Forest Reserve: a 17 000 hectare area that is outside the actual wetland

Table 4.7: Approximate original areal extent of different habitat types within the Zambezi Delta

Habitat type	Percent coverage	Area (ha)
Palm savanna	5	63 750
Floodplain grassland	40	510 000
Wet grass	25	318 750
Reeds and sedges	10	127 500
River channel	5	63 750
Mangroves	15	191 250
TOTAL	100	1 275 000

4.3 Quantification of lag and attenuation in the Barotse Flood Plains and Kafue Flats

The objective of this sub-task was to quantify the lag, attenuation and volume change of the flood wave as it passes through the Barotse floodplains, Chobe swamps and Kafue Flats. The Lukanga and Busanga wetlands that are also significantly larger in size were not considered in the analysis because their upstream catchments are smaller and thus have negligible effect on flood attenuation of the Zambezi basin.

The ZAMWIS database was used as the main source of data for this task. A flow gauge shape file that contained the locations of the flow gauges in the Zambezi basin was used to select the gauges that are located upstream and downstream of the wetlands in the basin. Some of the flow gauges had daily time series data available in the database. Hydrographs of the daily flows for upstream and downstream gauges with similar years were plotted on the same set of axes. The difference in time it takes for both hydrographs to peak was considered to be the lag or wetland attenuation period. The volume of daily average flows attenuated by the wetland was considered to be the area under the hydrographs where the inflow (upstream gauge) is greater than the outflow (downstream gauge). The findings for Barotse floodplains, Chobe swamps and Kafue Flats are shown in Table 4.8 and discussed in the following paragraphs.

Table 4.8: A Characterization of wetlands in the Zambezi River basin

Wetland name	Estimated wetland size km² (From ZAMWIS wetlands shapefile)	Upstream gauge	Downstream gauge	Distance between the gauges (km)	Hydrological years analysed	Upstream gauge peak period	Downstream gauge peak period	Attenuation period (days)	Reduction in Peak flow (m3/s)	Attenuated volume (million m3)
Chobe Swamps	1 600	Zambezi at Senanga (2400)	Zambezi at Nana's farm (3045)	176	1996/1997	05-May	18-May	13	41	2 143
Kafue Flats	7200	Kafue at Itetzhi-tezhi (4710)	Kafue at Kasaka (4977)	326	1964/1965	13-Feb	22-May	98	564	3 533
Beilfuss (2001)										
Barotse Floodplains	6 800	Zambezi at Lukulu (2030)	Zambezi at Senanga (2400)	242	1950-1999	Mid March	Mid April	30-45	600	
Kafue Flats	7200	Kafue at Itetzhi-tezhi (4710)	Kafue at Kasaka (4977)	326	1907-1969	March	May	100	30	

4.3.1 Barotse flood plains

The upstream gauge Lukulu (2030) and downstream gauge Senanga (2400) were selected to determine the attenuation period and volume of flow for Barotse floodplains. The gauges were found to be suitable in that they are geographically situated immediately upstream and downstream of the floodplain along the Zambezi River and thus were assumed to accurately capture the inflow and the outflow of the wetland. The total contributing catchment area between the inflow and outflow is 78007 km^2.

The GIS length estimation showed that the gauges are 242 km apart along the Zambezi River, and according to Beilfuss and dos Santos (2001) the floodplain grassland is more than 40 km wide bordered by sandy escarpment and attains a mean volume of 8.5 x 10^{9}m^3 at the height of the wet season. Beilfuss and dos Santos (2001) analyzed runoff at the Lukulu and Senanga gauges for the period 1950-1999 for their working paper on patterns of hydrological change in the Zambezi Delta (Mozambique). They found that the peak runoff that reaches the upstream gauge by February-March, following the period of peak rainfall, takes 4-6 weeks to pass through the Barotse Floodplain, and the peak discharge at the downstream gauge is often delayed until April or early May (refer to Figure 4.2). Their analysis also shows a mean peak reduction (on a monthly basis) of about 600 m^3/s due to evapo-transpiration and groundwater recharge. This is substantial given the significant contribution of runoff from the local Barotse catchment in addition to upstream inflow from the main stem Zambezi River.

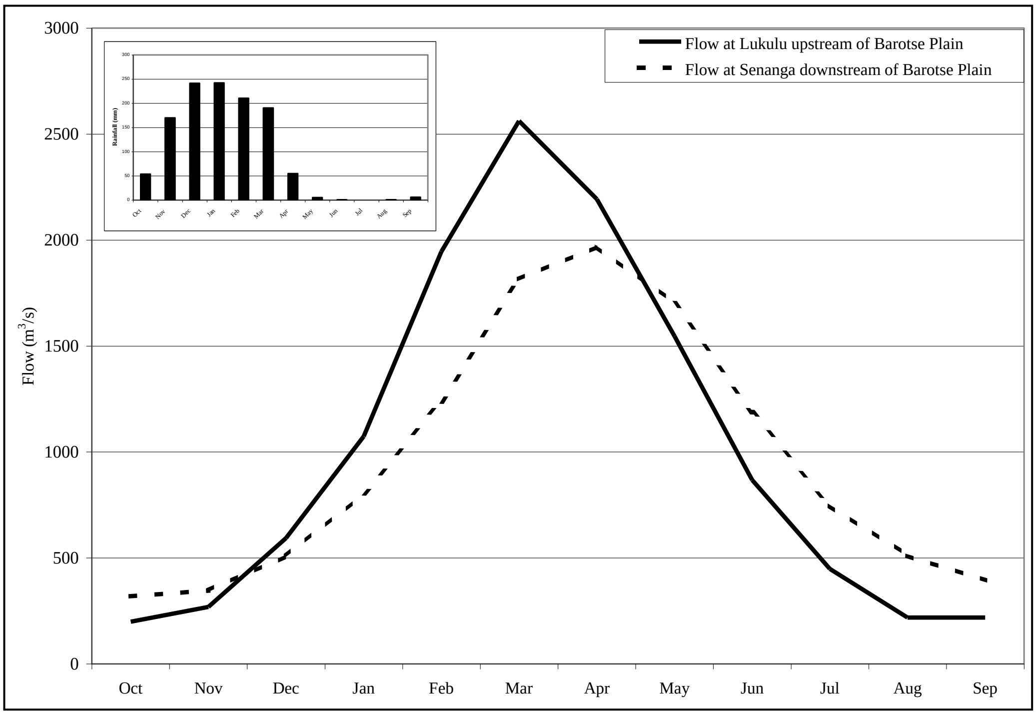


Figure 4.2: Barotse Floodplain, 1950-99, showing attenuation of peak runoff (from Beilfuss and dos Santos 2001).

Further analysis of the 1996/1997 hydrological year (i.e. October 1996-September 1997), a year during which the upper Zambezi River Basin experienced substantial flooding, was conducted. Two successive peaks were recorded at the upstream gauge as shown in Figure 4.2 but the downstream gauge reflected a smooth, single peak outflow. The higher flood peak on the downstream gauge giving a change in volume between the upstream and the downstream gauge of -5 136 10^{6}m^3 suggesting that substantial inflows occurred from the Luanginga and Luampo tributaries (combined catchment area of approximately 55 000 km^2) and other smaller streams. The contribution from rainfall falling directly on the wetland is also significant during the flood season as, even in an average year, rainfall usually exceeds evaporation in the period December to March.

Figure 4.1 and Figure 4.3 indicate that incoming floodwaters peaked at the upstream gauge on 15 April and peaked at the downstream gauge on 5 May, an attenuation period of about 20 days corresponding to a volume of 682 million m^3 respectively.

Table 4.9: Results for Barotse Floodplains analysis

Gauges	Contributing catchment area (km^2)	Total flood volume (10^{6}m^3)	Peak flow (m^3/s)	Attenuation volume (10^{6}m^3)
Inflow-Lukulu 2030	206 531	16 378	1 577	682
Outflow-Senanga 2400	284 538	21 514	1 748	
Difference	78 007	-5 136	-170	

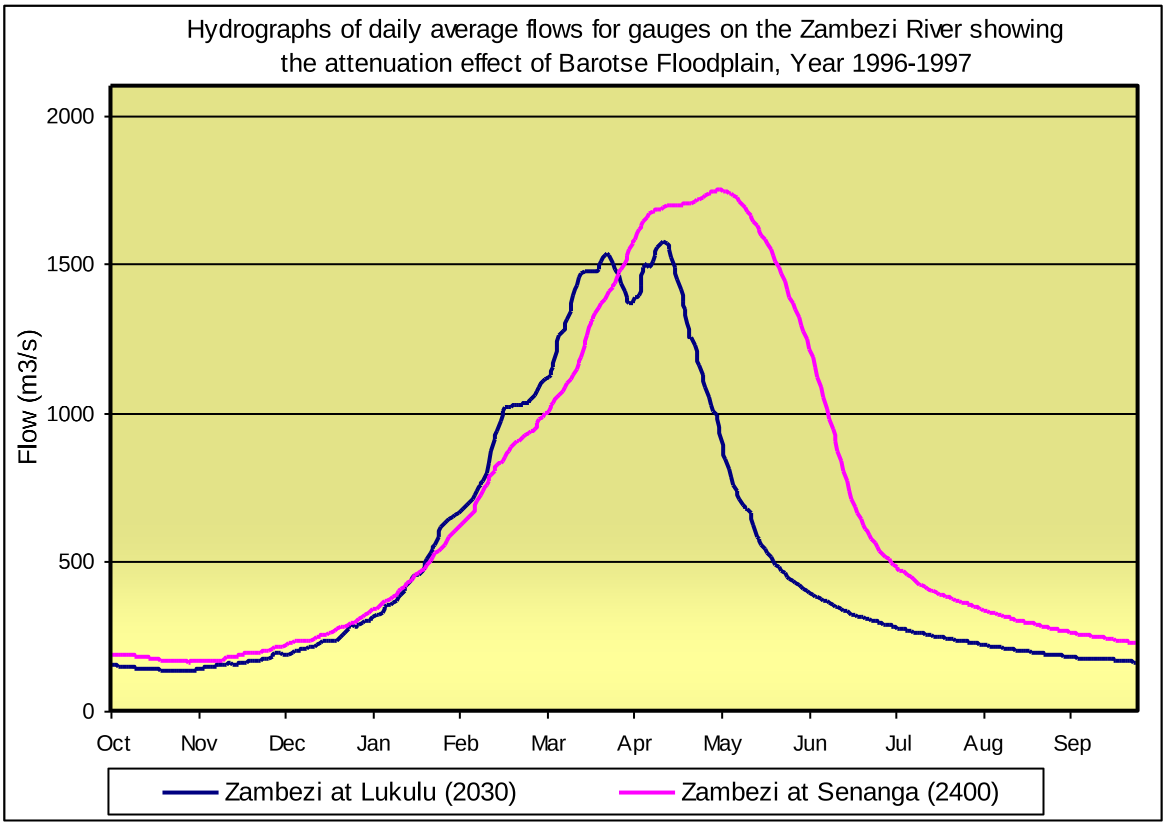


Figure 4.3: Hydrographs showing attenuation effect of Barotse Floodplains

These analyses clearly indicate that the Barotse Floodplains have a significant effect in attenuating Zambezi peak flows for several weeks or longer. Given the large contribution of the immediate catchment draining to the Barotse Floodplain, a deduction can be made that the Barotse Floodplain reduces the volume of peak runoff to the downstream Zambezi River. This volume varies from year to year. There is, however, a contradiction in that the graph of Beilfuss (Figure 4.1) shows a decrease in flow at Senanga while Figure 4.2 and Figure 4.4 (considering observed flows) show an increase in flow at Senanga (except for the last peak in Figure 4.4 where it is about the same). The periods analysed are different, with Beilfuss having examined flows for the 1950 to 1999 period, whereas Figures 4.2 and 4.4 covered periods 1996 to 1997 and 1994 to 1997 respectively. In Figure 4.4 the simulated modeled outflows tend to support the Beilfuss graph in Figure 4.1. This contradiction is explained by the fact that it is not known how much flow comes in from the Luanginga and Luampo tributaries between the two gauges. What is consistent between the simulations, the results from Beilfuss and observed inflow and outflow is the lag in peak flows.

A correlation analysis was carried out using daily streamflow at gauges Lukulu and Senanga for the Barotse wetland. The time lag with the highest correlation between the two discharge time series is the time lag for travel times. Missing values were excluded. Basically, with the correlation coefficient the flood wave shapes are compared with each other, while step-wise shifting one flood wave shape in time (a correlation coefficient of 0 shows a very poor match, 1 is a perfect match). The results are shown in Figure 4.4.

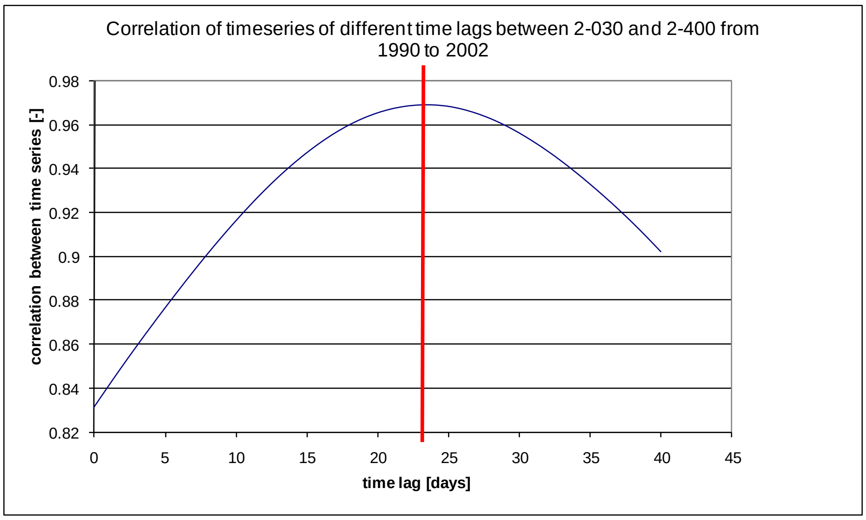


Figure 4.4: Correlation of streamflows for gauges 2030 and 2400 for the Barotse wetland

A monthly water balance was carried out on the Barotse wetland from 1994 to 1997 with data from the ZAMWIS database. The inflows to Barotse were taken from the Lukulu 2030 streamflow gauge and outflows from the Barotse streamflow gauge from Senanga 2400. Rainfall was taken from Senanga, Mongu and Kalabo and was averaged. Evaporation was taken from Beilfuss (2001). The WRSM2000 rainfall-runoff model was used to simulate the flow through a wetland. The wetland algorithm has been tested on the Kafue Flats and showed a good comparison between observed and simulated outflow. The main problem in modeling the Barotse wetland is the lack of knowledge concerning local inflow, i.e. the inflow to Barotse between Lukulu and Senanga. A constant factor was applied to the flow at Lukulu, based more or less on the ratio of catchment area. In reality this ratio will vary according to the distribution of rainfall over the upper Zambezi. This variation partly explains the differences between the observed and simulated hydrographs in Figure 4.5, as mentioned above. The model does, however, demonstrate in Figure 4.5 that local inflow generally exceeds net evaporation loss from the wetland, which is the reason that the total flow at Senanga is usually greater than at Lukulu. The results of simulations of inflow and outflow and wetland area are shown in Figures 4.5 and 4.6.

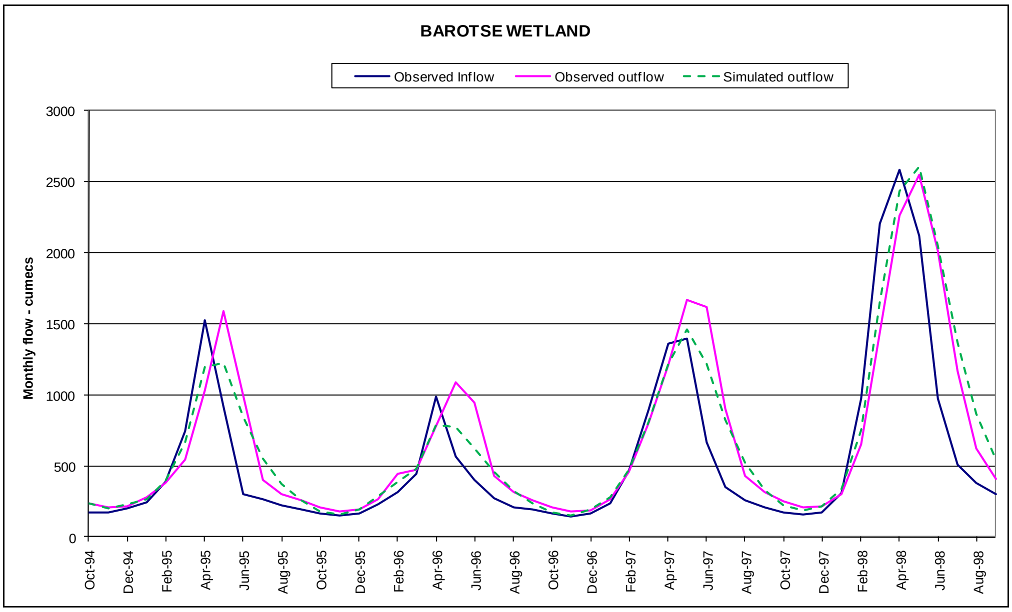


Figure 4.5: Observed inflow and outflow and simulated outflow for the Barotse wetland

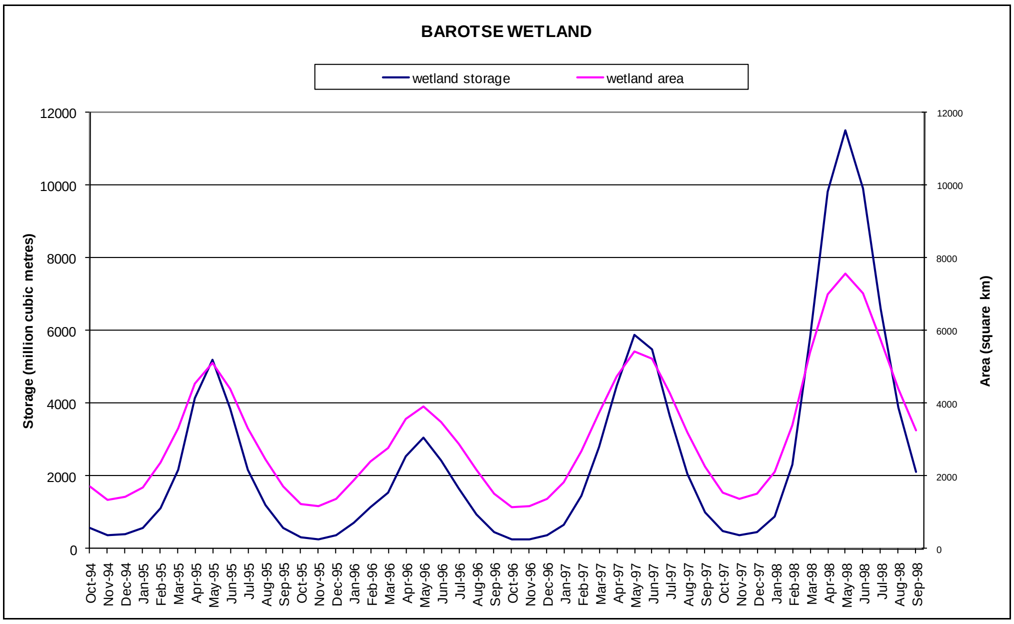


Figure 4.6: Storage and area for the Barotse wetland

4.3.2 Chobe swamps

The Chobe swamps are fed by both Chobe and Zambezi River but the available data was only suitable for attenuation analysis for the gauges along the Zambezi River. The upstream gauge Senanga (2400) and downstream gauge Nana's farm (3045) were selected to determine the attenuation period and volume of flow for the portion of Chobe swamps along the Zambezi River. The GIS estimated distance between the two stations was 176 km apart along the Zambezi River. The wetland area of 1600 km^2 is for the analysed portion of the swamp along the Zambezi River.

The Cuando River discharges into the upper end of the Chobe River floodplain, resulting in Chobe swamps that form an extensive 3000 km^2 wetland complex adjacent to and south of the main Zambezi channel, (Beilfuss and dos Santos, 2001).

The Senanga (2400) flow gauge is not located immediately upstream of the Chobe swamps but was chosen because there was not enough data for Sesheke (2700) flow gauge that represented the inflow into the wetland along the Zambezi River. The available data for Sesheke (2700) are water levels from 2000 to 2006, but there is no rating curve to enable the determination of attenuation volume of the wetland. The downstream gauge, Nana's farm (3045) is located downstream of the Chobe tributary.

The analysis was carried out for the hydrological year 1996/1997 (i.e. October 1996-September 1997) because that is the only year that there is available data for both gauges and the upper part of the basin had experienced some flooding during that period. The results are shown in Table 4.10. This length of historical data however limits the applicability of these results.

Table 4.10: Results for Chobe swamps analysis

Gauges	Total flood volume (10^6m^3)	Flood peak (m^3/s)	Attenuation volume (10^6m^3)
Inflow-Senanga 2400	21514	1748	2143
Outflow-Nana's farm 3045	20638	1706	
Difference	876	41	

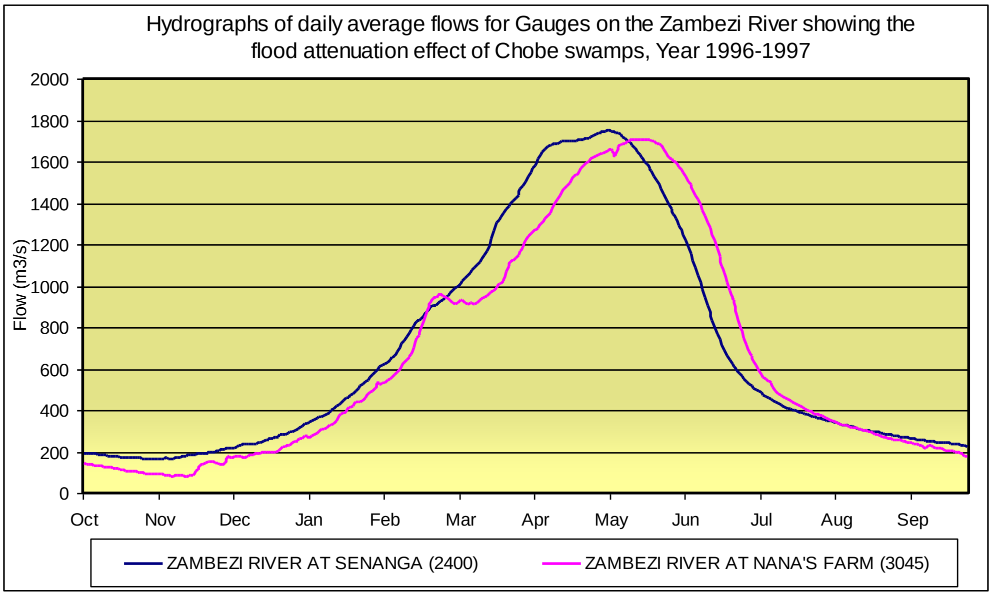


Figure 4.7: Hydrographs showing attenuation effect of Chobe Swamps

As shown in Figure 4.7, the analysis showed that the flood peaked at the upstream gauge on the 5th May 1997 and reached the downstream gauge on the 18th May 1997, thus the attenuation period and volume were found to be 13 days and 2143 10^6 m^3 respectively. It should be borne in mind, however, that part of the lag can be attributed to normal travel time between Senanga and Nana's Farm. The reduction in peak and the change in volume between the two gauges is 41 m^3/s and 876 10^6m^3 respectively. The decrease in flood peak is very little in comparison to measurements errors of flood peaks. The total attenuation volume is also little in comparison to the volume of the flood itself.

Beilfuss and dos Santos (2001) indicated that the Cuando River floodplains and Chobe swamps strongly attenuate peak runoff from the Cuando/Chobe catchment. During the early part of the flood season, the Chobe River flows in an easterly direction from the Chobe Swamps towards the main Zambezi River, and may contribute substantial runoff to Zambezi system. As Zambezi level rise, floodwaters spill from the Zambezi back into the Chobe swamps. The Chobe River reverses direction and flows to the northwest towards Lake Liambezi. Floodwaters spread over the dry plains and are lost through evaporation. Net evaporation from the Chobe swamps is more than 900 mm per annum. Overall, the contribution of Cuando River runoff to Zambezi River flow is counterbalanced by evaporation losses from Zambezi floodwaters that overflow into the Chobe floodplain, and net discharges to the Zambezi are negligible relative to runoff from headwaters region.

A correlation analysis was carried out using daily streamflow at gauges Senanga 2400 and Nana's Farm 3045 for the Chobe wetland and the same method applied to obtain Figure 4.3. The results are shown in Figure 4.8.

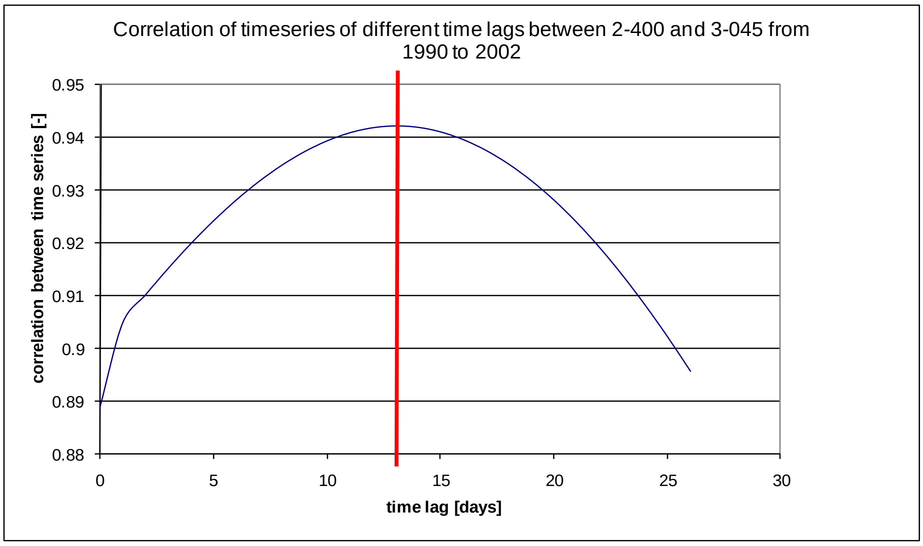


Figure 4.8: Correlation of streamflows for gauges 2400 and 3045 for the Chobe wetland

A monthly water balance was carried out on the Chobe wetland from 1994 to 1999 with data from the ZAMWIS database. The WRSM2000 rainfall-runoff model was used to simulate the flow through a wetland. The results of simulations of inflow and outflow and wetland area are shown in Figures 4.9 and 4.10.

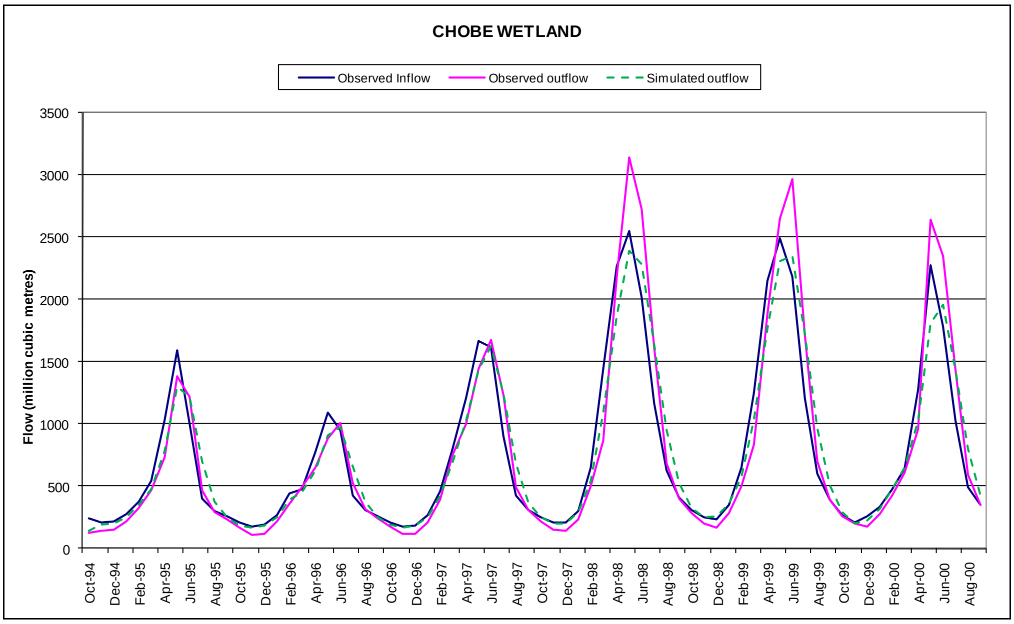


Figure 4.9: Observed inflow and outflow and simulated outflow for Chobe wetland

A good fit was obtained for the first 3 years but that the observed outflow is significantly higher than the simulated outflow for the last 3 years. This is likely to be the result of having to use the Senanga streamflow record which is only just downstream of the Barotse wetland and that there could have been more inflow between Senanga and Chobe during the last 3 years.

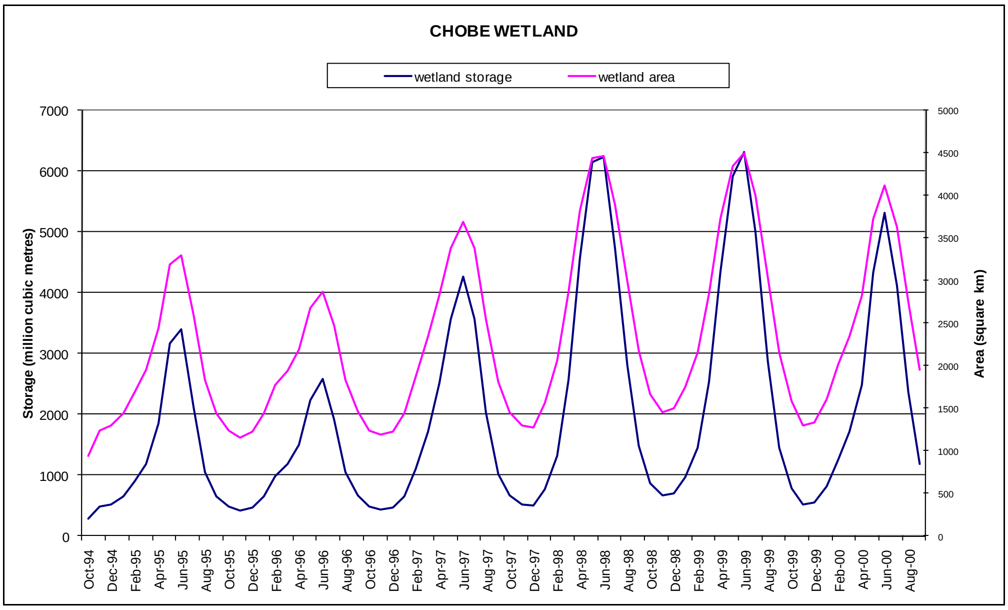


Figure 4.10: Storage and area of the Chobe wetland

4.3.3 Kafue flats

The upstream gauge Itezhi-tezhi (4710) and downstream gauge Kasaka (4977) were found to be suitable upstream and downstream gauges respectively, in that they are situated along the river to give an accurate indication of both the inflow and outflow of the wetland. The total contributing catchment area between the upstream and downstream gauges is 45299 km^2.

The GIS estimated length of the river between the two gauging stations is 326 km along the Kafue River. As was pointed out earlier, the Kafue Flats are an extensive floodplain area of about 60 km wide and 250 km long. Beilfuss and dos Santos (2001) assessed the effect of the Kafue Flats on Kafue River runoff, using a long term data set from 1907 to 1969 (Figure 4.11). Their results indicate that the Kafue Flats has a very substantial effect in reducing the timing and volume of peak runoff that ultimately enters the Zambezi River. Peak annual runoff typically reaches the upstream end of the Kafue Flats in March, with floodwaters spreading slowly over the flats for several months. Downstream of the Kafue Flats the Kafue River peaks in late May, after the end of the local rainy season. The average time of attenuation was nearly 100 days.

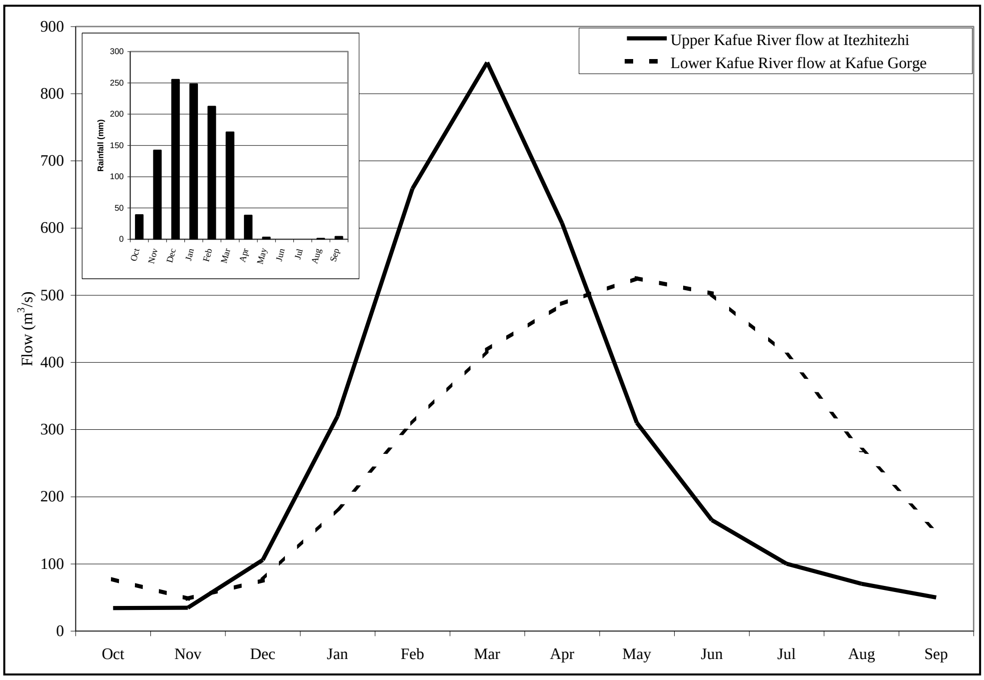


Figure 4.11: Kafue Flats, 1907-69, attenuation of peak runoff. (from Beilfuss and dos Santos 2001).

Further analysis was carried out for the hydrological year 1964/1965 (i.e. October 1964-September 1965) because that is one of the years that there is available data for both gauges and the flooding was experienced in the Middle Zambezi. Table 4.11 and Figure 4.12 below show the results of the analysis.

Table 4.11: Results for Kafue Flats analysis

Gauges	Contributing catchment area (km^2)	Total flood volume (10^6m^3)	Peak flow (m^3/s)	Attenuation volume (10^6m^3)
Itezhi-Tezhi 4710	105672	8004	916	3533
Kasaka (4977)	150971	6005	352	
Difference	45299	1999	564	

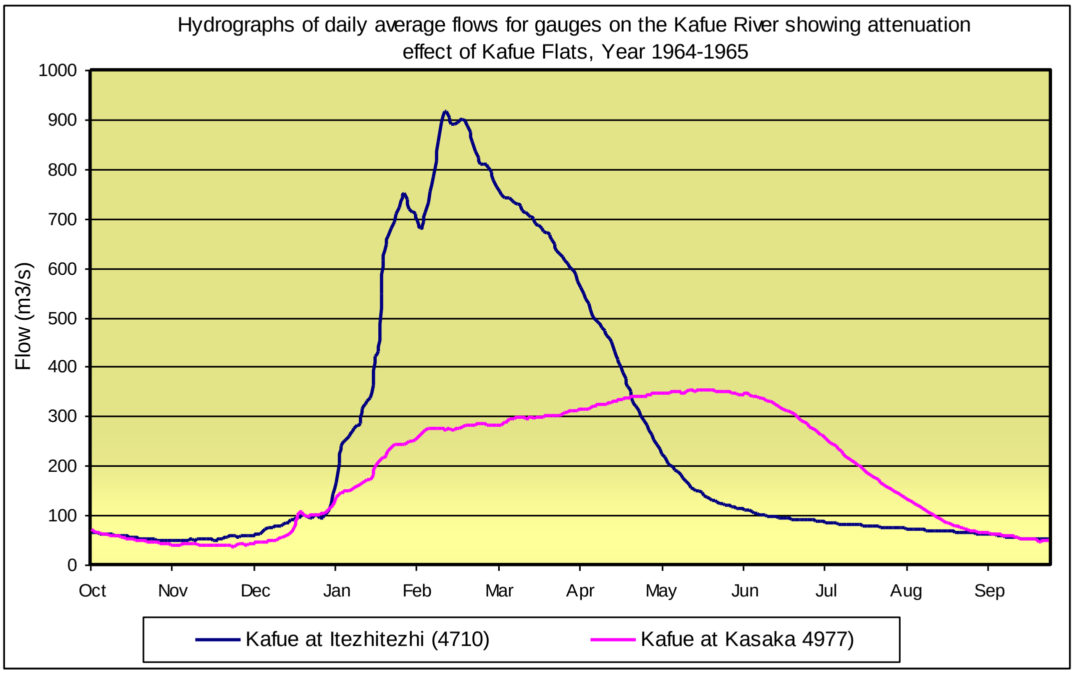


Figure 4.12: Hydrographs showing attenuation effect of Kafue Flats

As shown in Figure 4.12, the analysis showed that the flood peaks at the upstream gauge on the 13th February only reached the downstream gauge on 22nd May, thus the attenuation period and volume were found to be 98 days and 3533 10^6 m^3 respectively.

According to Beilfuss and dos Santos (2001), using the same gauging stations and data, they found that the peak runoff reached the upper Kafue Flats in March, and only peaked in late May at the downstream end of the wetland.

Both analyses show that the Kafue Flats have an attenuation effect of about three months, which is significantly larger than the other two wetlands in the River basin. They also show that the reduction in peak flow (as a percentage) much larger than for the other two wetlands. The attenuation volume is not larger than the other two wetlands in absolute terms. However, as a percentage of the flood volume, the differences are considerable.

A correlation analysis was carried out using daily streamflow at gauges Itezhi-Tezhi 4710 and Kasaka 4977 for the Kafue Flats wetland and the same method applied to obtain Figure 4.4. The results are shown in Figure 4.13.

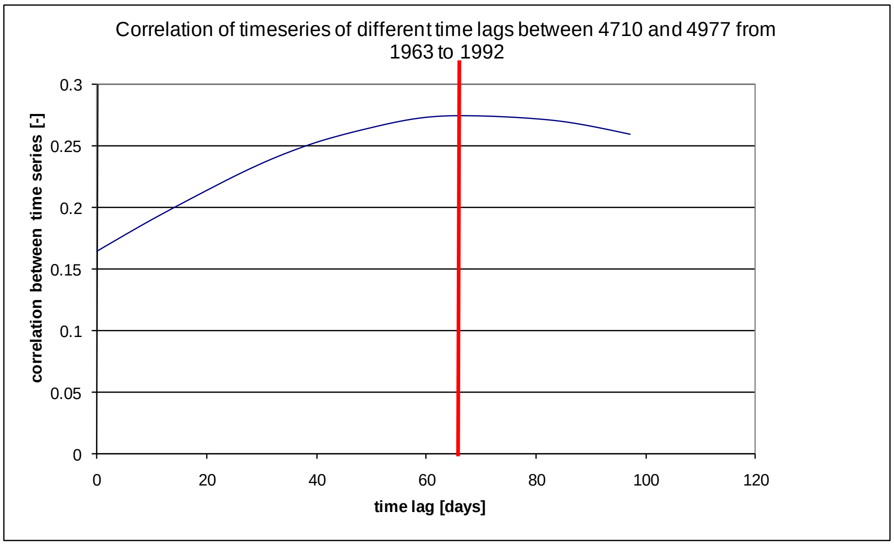


Figure 4.13: Correlation of streamflows for gauges 4710 and 4977 for the Kafue Flats wetland

A monthly water balance was carried out on the Kafue Flats wetland from 1983 to 1989 (after Itezhi-tezhi Dam was constructed in 1978) as well as 1963 to 1969 (before Itezhi-tezhi Dam was constructed) with data from the ZAMWIS database. The inflows to Kafue were taken from the Itezhi-tezhi streamflow 4710 gauge and outflows from the Kasaka 4977 streamflow gauge. For 1983 to 1989, rainfall was taken from Mumbwa – 2755 (about 70km north of the central part of the Kafue wetland) and Itezhi-tezhi - 2900 and averaged. For the earlier period from 1963 to 1969, for the 2998 station (about 70 kms north of Itezhi-tezhi Dam). Evaporation figures were taken from Mwelwa, (2004). The WRSM2000 rainfall-runoff model was used to simulate the flow through a wetland. The results of simulations of inflow and outflow and wetland area are shown in Figures 4.14 and 4.15.

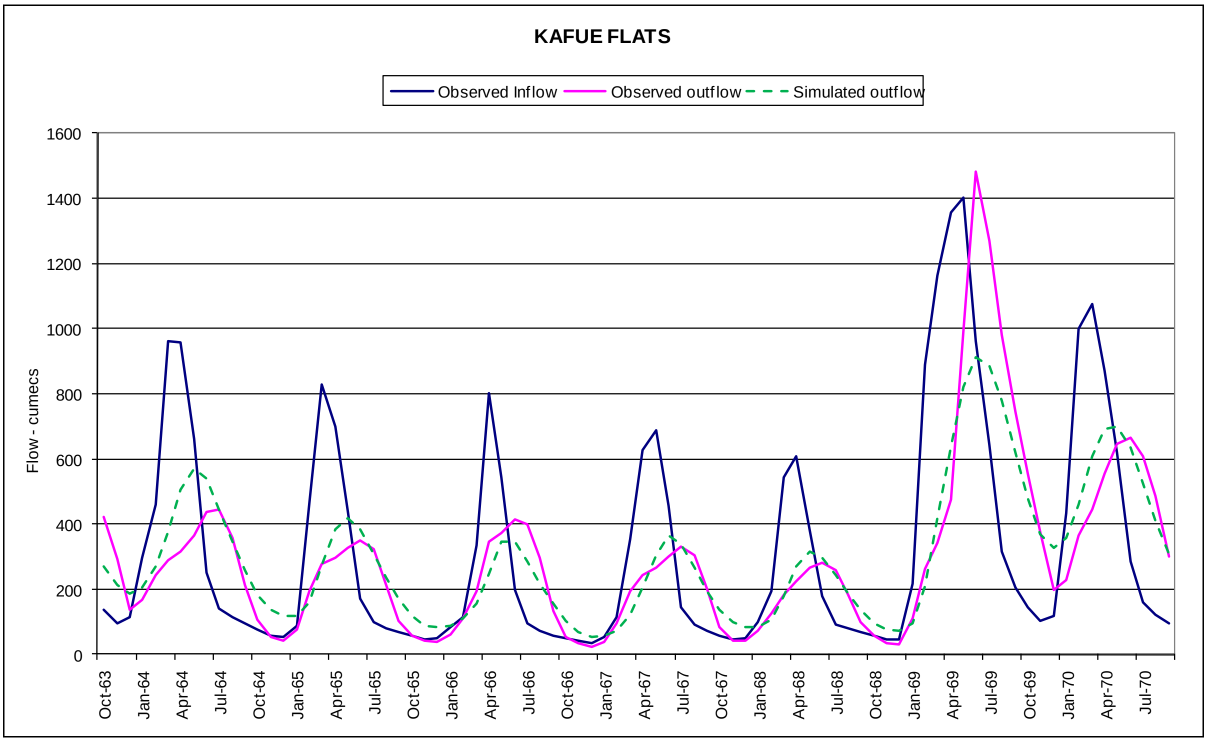


Figure 4.14: Observed inflow and outflow and simulated outflow for the Kafue Flats wetland (1963 to 1970)

The rather poor match between observed and simulated inflow data suggests that more detailed modeling and analysis needs to be done.

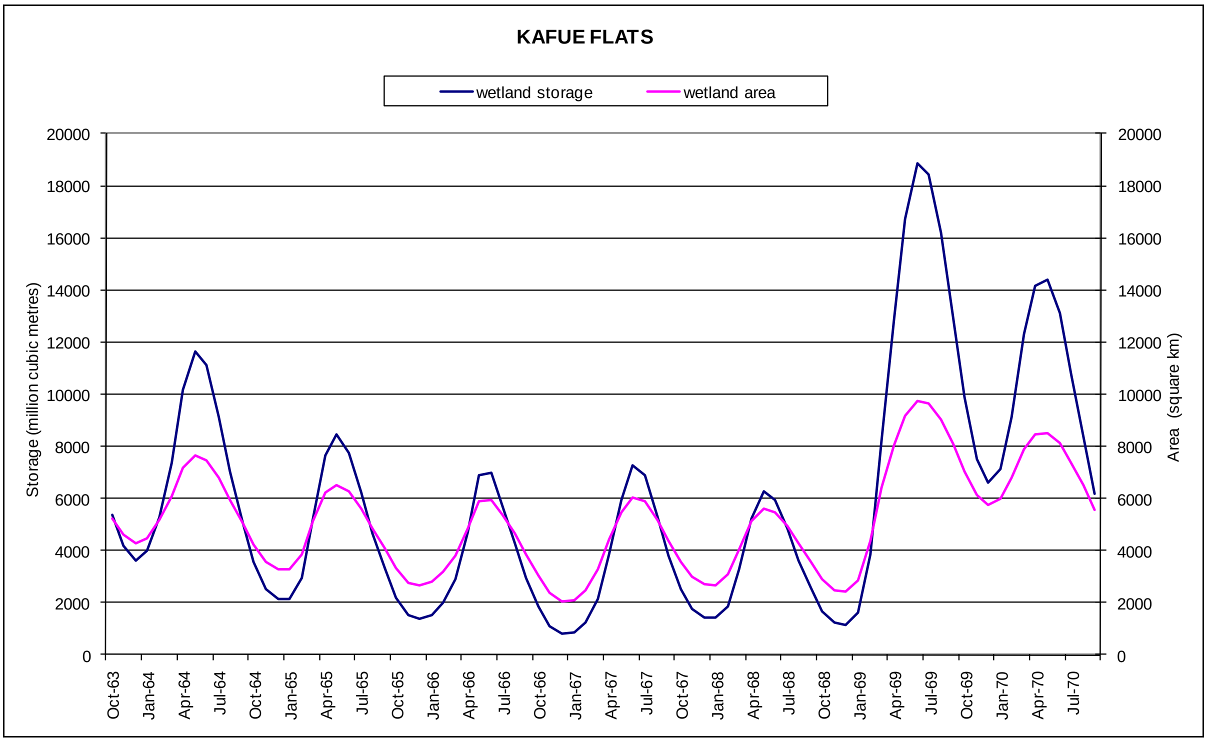


Figure 4.15: Storage and area of the Kafue Flats wetland

4.3.4 Estimation of Net Evaporation Losses of Wetlands

Beilfuss and dos Santos (2001) provide information on mean annual rainfall and potential evaporation on the three swamps as summarized in Table 4.12.

Table 4.12: Mean annual precipitation (MAP) and mean annual evaporation (MAE)

Wetland	Station	MAP (mm/a)	MAE (mm/a)	Source of MAE	Factor for Open water	Adjusted MAE (mm/a)
Barotse	Mongu	948	2306	A-pan	0.7(1)	1614
Chobe	Sesheke	948	1862	A-pan?	1.0(2)	1862
Kafue	Namwala	739	1784	Penman	1.0	1784

The rainfall and evaporation data presented by Beilfuss and dos Santos (2001) was used to estimate the mean annual net evaporation loss from each swamp by multiplying the net evaporation in each month by the assumed swamp area and summing the data to obtain the annual loss. The variation in swamp area was assumed to follow a sine curve, with a peak area in April and minimum area in October. The results of this exercise are summarized in Table 4.13. The data in the final column were derived from the Beilfuss and dos Santos report, 2001.

Table 4.13: Estimated mean annual net evaporation loss from wetlands

Wetland	Area km^2 (From ZAMWIS wetlands shapefile)	Net evaporation (mm/a)	Net evaporation Loss ($10^6m^3/a$)	Loss derived from hydrographs (10^6m^3) (see Table 1)*	Loss (10^6m^3) from Beilfuss and dos Santos (2001)
Barotse	6800	668	2265	682	1800
Chobe	1600	913	754	2143	n/a
Kafue	7200	1045	3700	3533	Negligible
NB * These losses are not directly comparable as they refer to the volumetric difference between the upstream and downstream hydrographs up to the cross-over point.					

The estimated net evaporation loss for Barotse compares well with the Beilfuss and dos Santos, 2001 value, as their lower figure can be ascribed to significant inflow from the Luanginga and Luampo tributaries

In the case of the Chobe Swamp, the loss derived from the hydrograph analysis is much lower than the calculated net evaporation loss. This is probably due to the inflow from the Chobe River, which has not been taken into account, especially considering that the Chobe river changes flow direction in the course of the season in response to flood levels in the Zambezi river.

The calculated net evaporation loss for the Kafue Swamp is very much greater than calculated and, in fact, Beilfuss and dos Santos indicate that a mean annual outflow approximately equals to the inflow, resulting a negligible net loss. This suggests that (a) the tributary inflow is sufficient to balance the net evaporation loss or (b) the area of 7200 km^2 is an overestimate, or both.

The ZAMWIS database seems to use total floodplain areas which might result in an upper estimate of net evaporation losses. Aduah (2007) gives flooded areas for Kafue Flats derived by remote sensing, which for the highest flood measured in 2001 does not exceed 2000km^2.

4.4 Option to enhance wetland retention

4.4.1 Simulated Impact of Climate Change on Wetlands Behaviour

A discussion of the potential impact of climate change on the water resources for the basin was carried out in chapter 3, and four scenarios were selected and analysed based on flow trends observed at Victoria Falls by Tumbare (2008):

- Scenario 1:- Dry sequence : 1908 – 1950 (42 years);
- Scenario 2:- Wet sequence : 1950 -1983 (32 years);
- Scenario 3:- Dry sequence : 1983 – 1999 (15 years) and
- Scenario 4:- Mixed sequence : 1999 – 2007 (15 years)

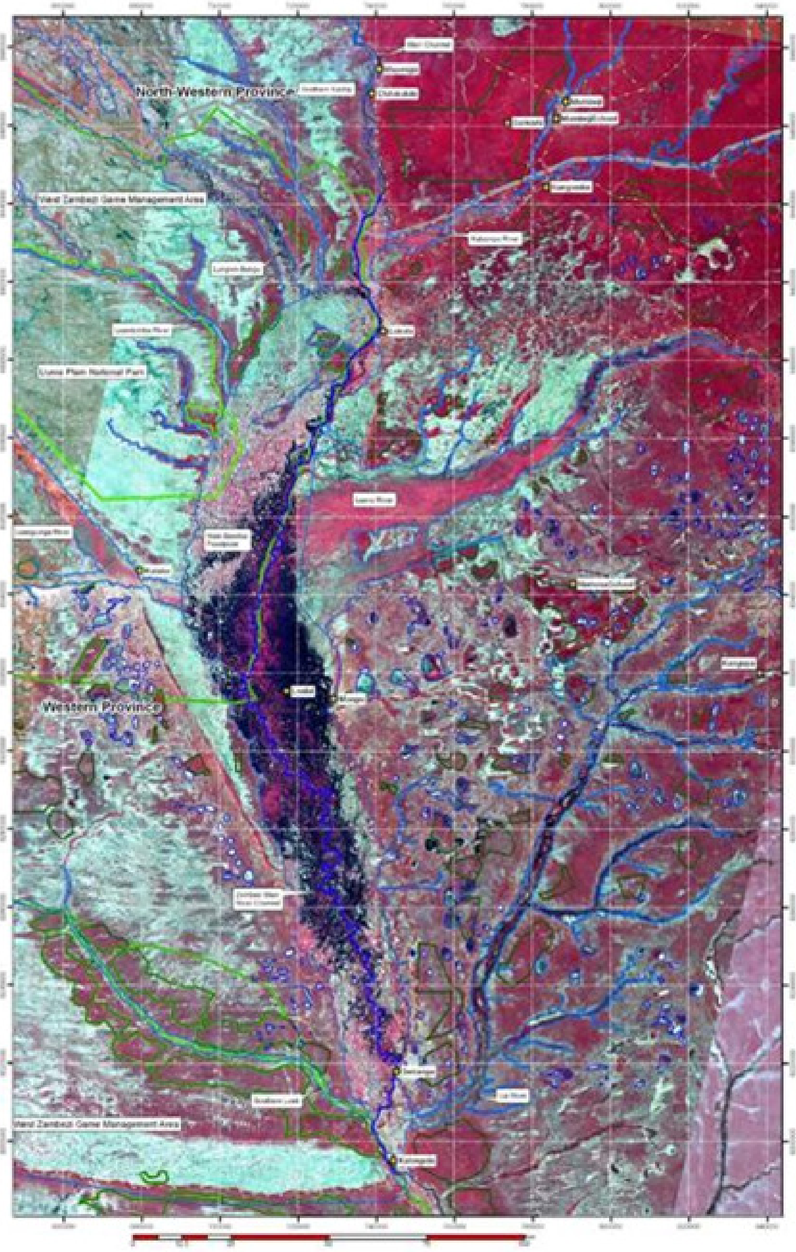
The dry season condition for parts of the Kafue main stem and Barotse floodplains are shown in Figure 4.16 (June 2010) and Figure 4.17 (July 2010) respectively. The year 2010 falls within a wet sequence. The behavior of wetlands during dry and wet periods can be studied using a combination of time series of satellite images and time series of ground based observations including flows and groundwater levels. Figure 4.17 uses satellite images taken during March of 1995 (dry year) and 2009 (wet year) to demonstrate how the wetland signatures and hence wetland behavior changes as the flow changes. The storage available can be determined by analysis of the wetland conditions and modeling.

Figure 4.16: Kafue River main stem and flood plains-16 June 2010

07.13.2010 09:51

Figure 4.17: Barotse flood plains - 13 July 2010

The Barotse flood plain during selected dry and wet years



Dry year - 1995

Wet year - 2009

Legend:

- ⊕ Settlement
- MainChannel
- Road
- ▢ Aeolian Pan
- River Delineation
- ▢ Protected Forest
- ▢ Other Protected Area
- Provincial Boundary

IMAGE DATA
False Color Composite Mosaic Satellite Image
Satellites Landsat 5 and Landsat 7
Projection: Universal Transverse Mercator (UTM)
Ellipsoid: WGS 84
Zone: 34 South

All Features extracted from the satellite imagery have been done so using a combination of manual and automated feature extraction techniques and vegetation indices. They are therefore affected by inaccuracies that arise from using such techniques. These satellite images have been selected as the best cloud free images that show wetland during times of inundation during a dry period.

IMAGE NOTES:
These images are represented in visible and near infrared band false color composites (FCCs). The FCC images show areas of active chlorophyll in bright red. Thus blood red colors represent woodland areas and grey/green and which areas grassland/bare ground. In some areas these are caused by human settlement. Clouds will also show as white. Pink tones show wetland grass areas where some chlorophyll activity is occurring.

Open/standing waster is black in appearance and burn scars, dry season only are dark green. Some visual recognition of shapes is required to distinguish between elements. These maps are made of 6 separate Landsat images and as such are different color tones per panel.

Schematic map images & notes source : Imagen Consulting, 2010

Date:28/03/2011

PREPARED BY: SWRSD
[SSI, WRNA, RANKIN, SEED & DELTARES]
Zambezi Basin Joint Venture

TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

FIG 4-18 THE BAROTSE FLOOD PLAIN DURING SELECTED DRY & WET PERIODS.

SOUTHERN AFRICAN DEVELOPMENT COMMUNITY
SADC
TOWARDS A COMMON FUTURE
giz
On behalf of:
Federal Republic of Germany
The Federal Government
UKaid
from the Department for International Development
Australian Government
Aid Program

The analysis of historical climatic data and cyclicity carried out in chapter 3 also suggests that extreme flooding incidences are likely to occur more frequently in future but there is no certainty on their duration and frequency as these cannot be easily handled by existing GCMs. In summary, general expected conditions from the climate change scenarios are as follows:

Parameter change	Level of change
Rainfall decline	10-15% by 2050
Evaporation	10-25% by 2050
Increase in temperature	0.3-0.6% per decade
Runoff decrease	26%- 40%
Extreme flooding (cyclones)	Uncertain

Based on these climate change predictions, the hydrological situations of the wetlands in the Zambezi basin are expected to become drier, with the water table in all the wetlands being expected to drop below the soil surface, which will result in a drop in peak floods and overall runoff. Due to the increase in temperatures, there will be concomitant increases in evaporation and transpiration from the wetlands. This will, in turn, result in a reduction in the extent of permanently flooded areas. It has already been observed that since 1960 the inundated area of the wetlands has reduced by 18% in the Zambezi Delta (Beilfuss, 2001), although this has partly been caused by the damming of the Zambezi river and resultant attenuation of flooding.

4.4.2 Options available to mitigate identified risks

The analysis that has been carried out has established that the there is a potential adverse impact of climate change on wetlands and overall availability of runoff on the Zambezi system. However, the analysis was not conclusive and there is need to be further investigations. The rather gloomy prognosis on the future of wetlands in the face of climate change, however, can be mitigated by improving the management of the wetlands themselves and by judicious releases of water from the major dams in line with recommended operating rules to ensure environmental flows. Since all the dams that were constructed in the basin were for hydropower generation, the release of water to ensure environmental flows may not always be consistent with preferred operating rules of these dams for maximum hydropower generation, and may sacrifice some generation capacity. Where a shortfall in energy is created as a result of provision for environmental flows, alternative sources of energy could be considered.

4.5 Options for wetland retention capacity enhancement

Wetlands function as natural sponges that trap and slowly release surface water, and potential flood waters. Trees, root mats, and other wetland vegetation slow the speed of flood waters and distribute them more slowly over the floodplain. This combined water storage and braking action lowers flood heights and reduces erosion. This capability is mainly due to the wetland plants that hold the soil together, absorb the energy of waves and break up the flow of stream or river currents. Preserving and restoring wetlands, together with other water retention, can often provide the level of flood control otherwise provided by expensive dredge operations and levees. In this section, the options possible options for enhancing these beneficial effects of wetlands in the Zambezi basin are discussed.

4.5.1 Methods of Enhancing Wetland Retention Capacity

Wetland water retention capacity can be enhanced in several ways to improve wetland function, and prevent undesirable floods. Wetlands retention function has been used in a number of cases to delay flooding downstream of rivers. Enhancing retention capacity is usually done by enlarging the flooded areas, by leveling out the flooded area or constructing artificial impoundments that would delay floods proceeding downstream. On small wetlands this has been achieved by increasing the wetland vegetation areas (planting and removing encroaching terrestrial plants).

The following methods given by International Fund for Agricultural development (IFAD) may be applied in enhancing wetland retention capacity:

- Intercepting run-off (through contour trenches or bunds),
- Contour trenches are created to divert run-off from flashing down the main channels to spread out into an existing wetland. According to KISSAN Kerala Operations Centre trenches are dug along contour lines upstream of the wetland to intercept runoff. This additional water increases the retention capacity in the wetland.
- spreading run-off (through infiltration ponds or recharge basin, percolation tanks, inundation canals or flood-water spreading),
- The practice is used to manage storm water runoff, prevent flooding and downstream erosion, and improve water quality in an adjacent river, stream, lake or bay. It is essentially a shallow artificial pond that is designed to infiltrate storm water though permeable soils into the groundwater aquifer. Infiltration basins do not discharge to a surface water body under most storm conditions, but are designed with overflow structures (pipes, weirs, etc.) that operate during flood conditions. It also involves spreading the water flow through an established wetland.
- Recharging aquifers through river banks, by modification of river channels (subsurface, sand or recharge dams).This can be done by spreading water over the land in pits, furrows, or ditches, or to erect small dams in stream channels to detain and deflect surface runoff, thereby allowing longer retention periods USGS (2010).
- Recharging aquifers through shallow wells or injection through deep wells. This is achieved by constructing recharge wells and injecting water directly into an aquifer (USGS, 2010).

Various livelihood activities take place on the major wetlands of the Zambezi River basin. Management of human land use and grazing can enhance the role of the wetlands

4.5.2 Feasibility of enhancing wetlands on the Zambezi basin

In theory, the structural methods listed above can be used for enhancing wetland storage. However, they are obviously only suitable for small wetlands and of no practical value to the large wetlands of the Zambezi basin.

Furthermore, a host of factors that include depth, size, evaporation rates, vegetation conditions and sorptive capacity of the soils influence the retention capacity of wetland. Detailed studies would be necessary to understand the factors and how they interact in the above wetlands in establishing the current capacity.

Having given the above reasons, it should be noted that there are other possible interventions for improvement of retention capacity that are carried out as 'restoration and rehabilitation" of degraded wetlands. These interventions have attained variable success in particular with regard to the hydrological regime. So far it is not known to what extent these interventions have succeeded in attaining the original state or desired state. On the other hand restoration work for successional marsh and reed swamps has been recorded as successful. It still has to be emphasised that this has been done on small size wetlands.

The anticipated costs for "enhancing the wetlands and maintenance" would be enormous making the whole exercise financially unviable. Information on costs in literature is only on artificial wetlands created for treating waste water. And it has been reported that the costs compare favourably with those of traditional/conventional treatment facilities.

The management intervention mentioned as the last point in the preceding section may be more effective hence its further investigation is recommended.

4.5.3 Recommendations

From the three wetlands analysed, only Kafue Flats gives a considerable reduction of peak flow. Attenuation volume effects are comparatively little percentage-wise to the volume of floods, for Barotse and Chobe. For Kafue Flats the absolute attenuation volume is the smallest, but the relative effect on the flood is the highest. Evaporation losses for Barotse and Kafue Floodplains are probably considerable in absolute volume. Both floodplains seem to be compensated by inflow from tributaries directly into the wetlands.

The floods from the Barotse and Chobe take 30 to 40 days to travel to the Victoria Falls, however in periods following a drought season the floods take almost 90 days before they arrive in the falls areas. It is therefore recommended that instead of flood retention 'enhancement' dam releases be operated in synchrony with the flooding of wetlands so that releases are done much earlier to accommodate huge floods and that way huge and sudden impacts downstream can be averted. The Kafue system floods should be managed in conjunction with the releases from the Cahora Bassa. The storage characteristics of the wetlands can be determined using satellite images and ground based observations and modeling. This is important for dam management and disaster management.

The Luangwa has a big influence on Cahora Bassa and contributes 70% of the floods for the reservoir. Luangwa River is not regulated and there are no significant wetlands on the Luangwa. Other options to for regulating Luangwa for flood control should be studied.

The findings from this chapter contribute to the recommendations detailed in Recommendation Sheets 2.6 and 2.10.

5 Regulation of Existing Large Reservoirs

5.1 Introduction

The main Dam Operators of the Zambezi River Basin are as follows:

Table 5.1: Main Dam Operators

Dam Operator	Dams
Zambezi River Authority (ZRA)	Kariba
Hidroeléctrica Cahora Bassa (HCB)	Cahora Bassa
Zambia Electricity Supply Company (ZESCO)	Kafue and Itezhi-Tezhi
Zimbabwe National Water authority (ZINWA)	Dams on Zambezi tributaries in Zimbabwe
Electricity Corporation of Malawi (ESCOM)	Barrages and diversion weirs/dams in Malawi
Various individual operators	Small and medium size dams

Table 5.2 shows that that the major storage infrastructure on the Zambezi except for Kariba will fill up every year on average. These dams cannot capture and store large floods and on average they will spill every year. It *is* known that despite a century of river regulation and flood protection works, large floods are a fact of life in the Zambezi system. The high coefficient of variation on MAR shows why the management of flood flows is important for these dams to pass on large floods safely. It is important to schedule the start of releases and to set the discharge rate in advance so as to prevent the head of water behind the dam wall from rising to a level where extreme damage can occur. Cahora Bassa and Kafue Gorge have to pass on most of the flood releases from upstream dams and decisions on releases from upstream dams are therefore of interest to the operators of these dams.

Table 5.2: Storage Versus Runoff for major reservoirs on the Zambezi River System

Storage Facility	Gross storage capacity (km^3)	Live storage capacity (km^3)	Mean Annual Runoff (m^3/sec)	CV of MAR	**Live storage capacity/MAR**	Cumulative MAR/Basin MAR (%)
Kariba dam	185.6	64.8	1276	0.4	**1.6**	33%
Itezhi Tezhi	5.7	5	336.5	0.5	**0.5**	8%
Kafue Gorge	1.2	0.9	408.5	0.5	**0.1**	9%
Cahora Bassa	72.2	51.7	2494	0.4	**0.7**	76%

To date management decisions on operation of these dams have not referred to or considered other water users in the basin. Furthermore, there has been little, if any, consideration for provision of water for environmental requirements. The negative impacts of lack of coordinated management are already being experienced. As the water resources of the Zambezi River Basin are developed this situation may get worse. Consequently, there will be greater need for cooperation and liaison with regard to water resources management in the future. Dam operations need to take into account of the requirements of all users in the basin. Operating objectives need to be defined to guide the operations and ensure optimal and mutual benefit for all users while ensuring protection of the environment. This will enable operators to define operating rules which specify the amount of water to be released/abstracted/stored over a given period. In these operating rules, the storage at the time of making the decision and probability of occurrence of certain inflow being received, and losses from the reservoir, need to be taken into account. Historical precipitation, inflow, evaporation and storage can be used as a general guide in interpreting the results for decision making but these are limitations because of the climate patterns as discussed in Chapter 3 of this document .High variability in precipitation and hence inflow as well as evaporation from the reservoir and changing water demands and climate change are major challenges mean that the operating rules cannot be static, they should be periodically reviewed and updated.

This Chapter considers the existing situation and develops scenarios to address identified challenges. Their analysis informs the recommendations on new modes of dam operation for improved management of releases.

5.2 Situation assessment

5.2.1 Description of present and past rules and modes of dam operation

5.2.1.1 Kariba Dam

Operational Objectives

The main operational objectives for the Kariba Dam, currently, are to ensure **dam safety** and **maximization of hydropower production**. This is interpreted/implemented as follows by the Dam Operator:

> Sufficient capacity is reserved at the beginning of the rainy season to store peak flows (floods) and to avoid peak discharges through the floodgates. Opening floodgates is extremely inconvenient for four main reasons: for power generation the rise of the tail water level associated with the opening of one floodgate reduces the net head by about 5m, and thereafter by 3m for every additional gate opened; secondly for dam safety reasons, the vibrations caused by very high discharges through the floodgates should be avoided; thirdly extremely high releases may endanger the population living downstream and create operational problems at the Cahora Bassa Dam; and fourthly the plunge pool, which is the energy dissipater for the spilling waters, is currently only stable with three gates open. Opening more than three gates for prolonged periods may cause further erosion of the plunge pool necessitating very expensive rehabilitation/maintenance works.

There are **other objectives**, related to human activities, fish production, eco-tourism and to environmental protection of wildlife areas around as well as downstream of the reservoir. However these objectives are not included in the current operating rule.

Description of the Operating Rule

The existing and old dam safety rule curves for the Kariba Dam are shown in Figure 5.1. The existing rule was formulated to be able to release the design flood without operating all the six flood gates in order to safeguard the dam wall. The rule curve specifies the desired maximum storage values in every month of the year. According to the existing rule curve, the storage level should drop from the full supply level (FSL) between November and February in anticipation of receipt of Barotse flood waters, and then the rules prescribe for the level to gradually rise, reaching the FSL again in May. The spare storage created between November and February is intended to be sufficient to hold the design flood.

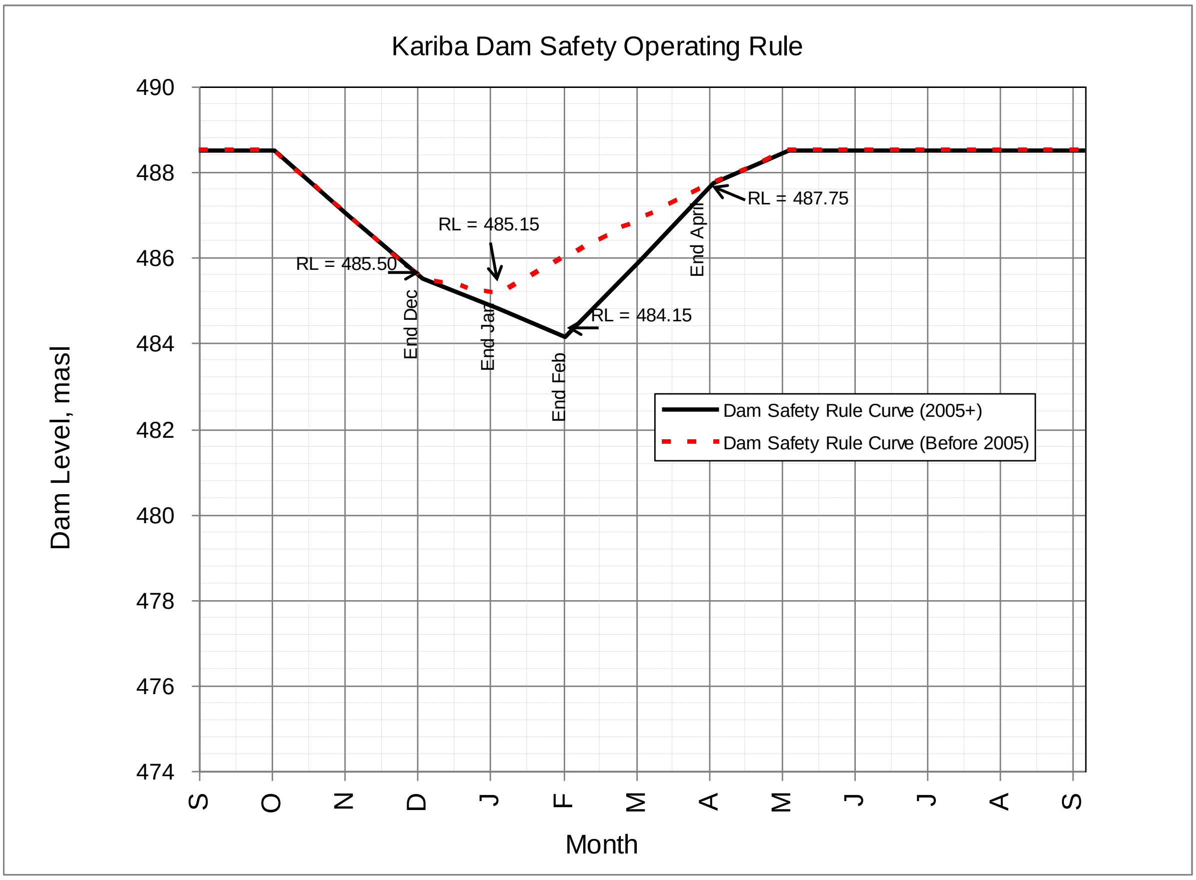


Figure 5.1: Kariba Dam – Old and new dam safety rule curves

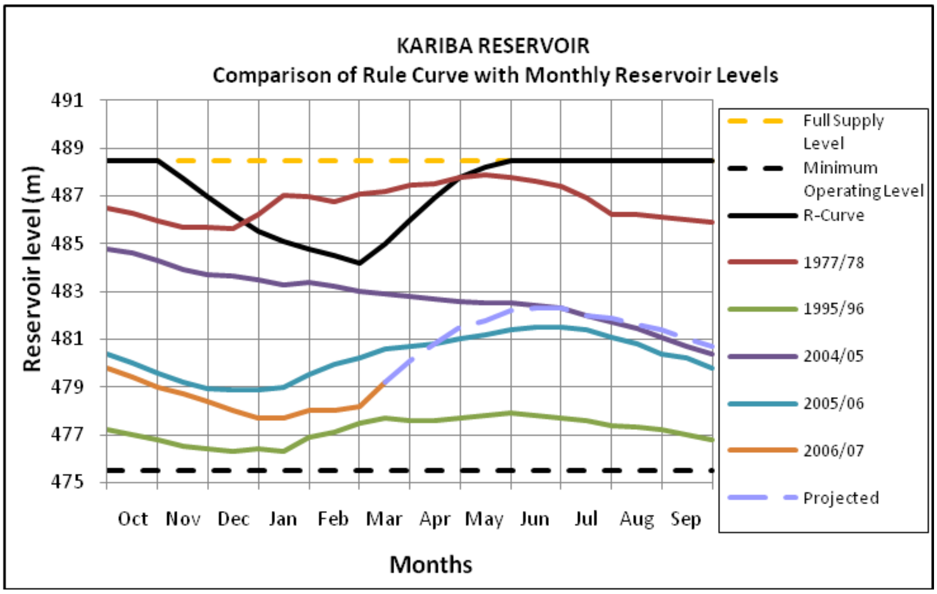


Figure 5.2: Kariba Dam – Dams safety rule curve and recent historical operations

Figure 5.2 shows the rule curve superimposed on historical time series of the reservoir storage levels. The graphs show that except for the 1977/78 and 2000/01 seasons, Kariba Dam is being operated well below the maximum permissible levels.

5.2.1.2 Cahora Bassa

Figure 5.3 shows Cahora Bassa dam with two floods open (April 2010) and the resulting flow downstream of the dam wall.

Figure 5.3: Cahora Bassa Dam April 29, 2010

(a) Existing Design Flood Rule Curve

Operational Objectives

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 maximal hydropower production.

Description of the Operating Rule

The releases from the 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 327.0m. 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 Table 5.3 and Figure 5.4

Table 5.3: Design Flood Rule Curve (end-of-month levels)

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Level	326.0	323.0	320.8	321.4	324.7	328.4	329.0	329.0	328.0	326.0	326.0	326.0

(Source: Hidroelectrica de Cahora Bassa)

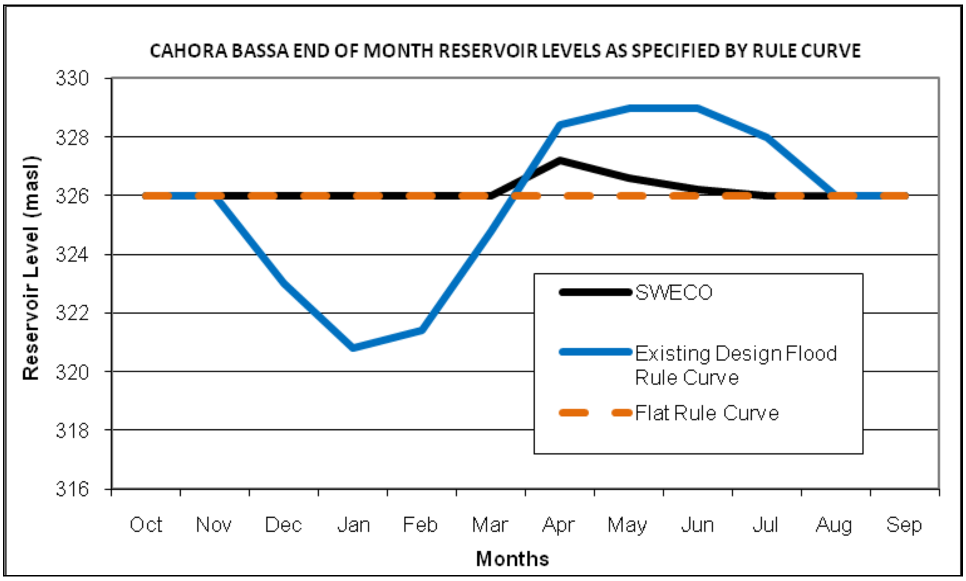


Figure 5.4: Cahora Bassa Dam Rule Curves

(b) SWECO Proposed Operating Rule (1982)

Operational Objectives

The objective of the SWECO proposals is to incorporate environmental flow releases with minimal impact on hydropower production and dam safety.

Description of the Operating Rule

SWECO(1982) proposed the release of freshets (i.e. environmental flow releases) from Cahora Bassa to coincide with high flows from downstream tributaries. It was estimated that a release during February of 7 x 10^9 m^3 (i.e. 2 894 m^3/s) in excess of power generation needs would create the desired flood peak of 9 000 m^3/s at Dona Ana on the lower reaches of the river towards the delta. The SWECO flood rule curve creates storage during the months of December to June as compensation for the release of freshets in February. This rule was never implemented because of the intensified civil war in Mozambique.

5.2.1.3 Kafue Gorge & Itezhi-Tezhi Reservoir Operating Rules

(a) SWECO Operating Rules (1978 to 1994)

Operational Objectives

Upon completion in 1978, the Kafue Gorge and Itezhi-tezhi dams used operating rules developed by SWECO. These rules were aimed at maintaining maximum storage levels for both reservoirs in order to maximize hydropower production.

Description of the Operating Rules

The operating rules for Itezhi-tezhi allowed for environmental flow releases (i.e. freshet) for the specific purpose of flooding the downstream Kafue Flats for the benefit of fisheries. The operating rule specified a minimum flow of $40m^3/s$ and a discharge of at least $300m^3/s$ over four weeks usually in March. It is not clear however to what extent these freshets were released in the past and what benefits have been realized.

(b) SADC Operating Rules (1994 to 2004)

Operational Objectives

In 1991, Zambia experienced a severe drought which resulted in low water levels in both reservoirs and resulted in power failures. It was found that this situation could have been avoided if other operating rules for the two dams had been implemented. A SADC project was then initiated to avert such power failures in dry years.

In terms of flood dynamics, the new rules were found to be an improvement, as a larger area is flooded in the wet season while on the other hand a larger area falls dry in the dry season. However, the regime was still far from mimicking natural flows and did not allow for a freshet release in the wet season.

Description of the Operating Rule

The operating rules developed during the SADC project consist of lower rule curves, indicating minimum target water levels for the two reservoirs.

The lower rule curve for Itezhi-tezhi indicates the minimum level at any moment in time that should be exceeded to maintain safe energy generation at the Kafue Gorge. The lower rule curve for Kasaka (Kafue Gorge) allows for limited depletion of the water level in the downstream part bearing in mind the requirements of safe power generation. The rule curves are presented in Figure 5.5 and Figure 5.6.

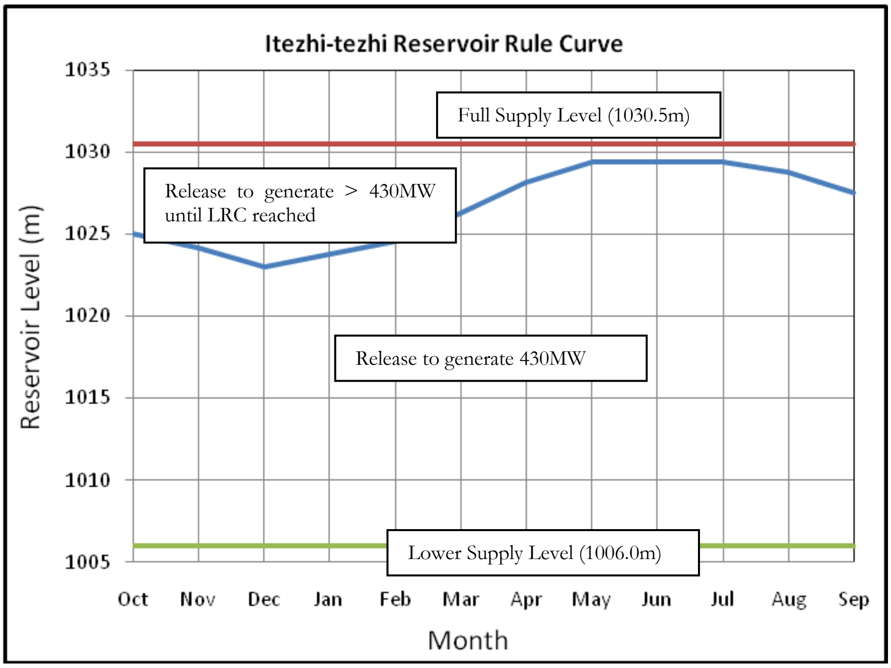


Figure 5.5: Itezhi-tezhi Hydropower Rule Curve

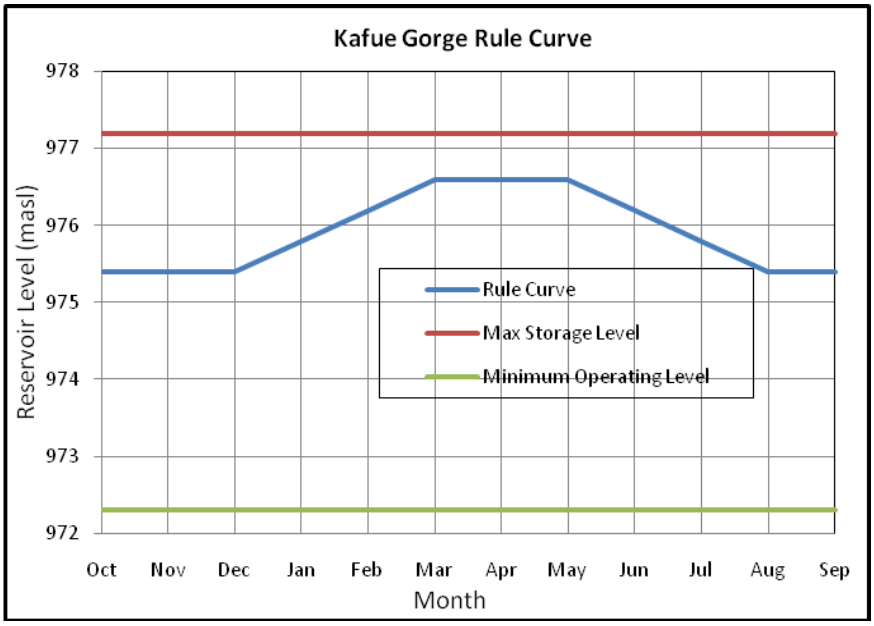


Figure 5.6: Kafue Gorge Hydropower Rule Curve

(c) Kafue decision support system (KAFRIBA – DHV, 2004)

In 1999, the WWF initiated dialogue with the Zambian Government, ZESCO, MWED, and other stakeholders to restore a more natural flow pattern to water releases from Itezhi-tezhi Dam. A proposal was made to fine tune the SADC operating rules with a view to achieving better congruence with the ecological requirements. The improvements were aimed at:

- Better timing of the beginning of the freshet,
- Increasing the flood volume, and
- Increasing the flood recession area

(d) Itezhi-tezhi Operation

Operational Objectives

Operation of the Itezhi-tezhi reservoir for the benefit of the Kafue Flats entails implementation of scheduled releases (the freshet) which has the right shape to mimic the natural state. The freshet which was selected has extensive flooding and smooth flooding and recession.

Description of the Operating Rule

The description of the freshet and how it is released is as follows:

The **volume of the freshet** is not a fixed discharge but is linked to the hydrological situation. The freshet has different **start times** to mimic the natural phenomenon of *wet*, *average* and *dry* seasons. The *wet* freshet starts in the months January or February. The *average* starts in February or March. The *dry* freshet starts in March. The decision to **release a freshet** is taken by the operator using the decision support system according to the following steps:

Step 1: Select the month (January, February, or March)
Step 2: On a monthly basis, operator runs KAFRIBA with releases from Itezhi-tezhi according to the indicated freshet (wet freshet in January, wet or average freshet in February and average or dry freshet in March)

Step 3: The KAFRIBA model forecasts the water levels in the Itezhi-tezhi reservoir.

Step 4: When the forecasted water level in the Itezhi-tezhi reservoir ends on or above the lower rule curve, the freshet can be released. When the forecasted water level ends under the lower rule curve, the operator should try a smaller freshet as indicated.

Step 5: When the smallest allowed freshet does not give a satisfactory water level in the Itezhi-tezhi reservoir, the operator decides not to release the freshet, and goes through the process again one week late.

Typical hydrographs for the freshet releases are shown in Figure 5.7.

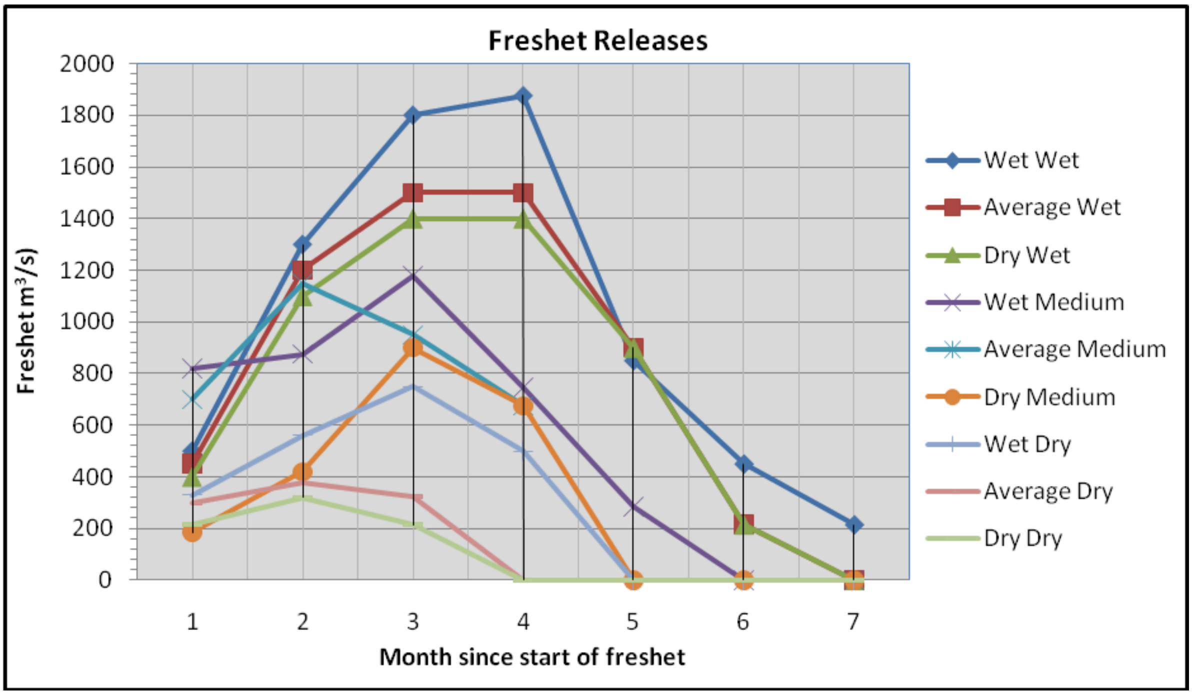


Figure 5.7: Freshet volumes, timing and variability according to the hydrological situation

(e) Kafue Gorge Operation

Operational Objectives

The operational objectives of the Kafue Gorge are intended to maintain a high water level for hydropower generation, increase the flood recession area, and maintain a minimum water level during dry seasons in order to reduce evaporation.

Description of the Operating Rule

The aforementioned operational objectives are achieved as follows:

- Minimize releases from Itezhi-tezhi in the dry season to less than the water rights of 55m^3/s as the requirements for large water consumers can still be obtained from Kafue Gorge Reservoir. This will save water in the Itezhi-tezhi reservoir which can be used for the freshet in the coming year.
- Minimize the stock volume in the Kafue Gorge reservoir in the dry season thus saving water by minimizing evaporation. A timely release from Itezhi-tezhi will prevent any shortages in the Kafue Gorge reservoir.

- Lower water levels from 975.4 to 974.0 m + ND will expose an additional area of some 200 to 400 km^2 by flood recession
- In dry years when only a minor or no freshet at all can be released at Itezhi-tezhi, lowering the Kafue Gorge level in April and May is even more important. An artificial recession must be realized in this way.
- Incorporate the operation rules with a strategy for the freshet period. The freshet period also links to the flood recession period. A gradual lowering of the water levels in the Kafue Gorge reservoir after the freshet period should be part of the freshet strategy.

For the rule curve at Kasaka the following water levels (at the beginning of the month) are recommended:

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Level	974.4	974.8	975.4	975.8	976.2	976.6	977.0	976.2	975.8	975.2	974.6	974.4

For the Kafue Gorge reservoir the rule curves are not being followed in current practice, but levels are being maintained at a constantly high level whenever possible.

5.2.2 Assessment of status of existing models and their applicability of on this study

An understanding of the time step and spatial extent of events in a river basin are important in flood modeling studies. The Zambezi river basin experiences flash floods (arising from high intensity low duration rainfall) typically associated with tropical storms as well as large floods typically associated with cyclone events. The latter are usually over a relatively small catchments but the amplitude of the flood at a point in the basin or sub-basin can be quite large depending on the number of catchments that simultaneously discharge to that point. The duration of the floods may vary from a matter of minutes, hours to days. Floods associated with cyclones are usually over a large area and may last several days or weeks. Thus the time step for floods is over hours, days and weeks. Flood modeling involves analysis of hydrographs.

The following models were identified for possible application on this study:

- HEC-3 Reservoir Operation Model developed by NIRAS-BRL for the World Bank
- The WEAP model available in the ZAMWIS database
- The ZRA flow forecasting model
- The Hugo Model

The HEC3 was incomplete and there was a complete description of the set up was not available, therefore could not be applied on this study. The WEAP model is for a water balance assessment and the time-step is not suitable for flood studies. It is also a work in progress. Updating and configuring these models to address the objective of management of flood and environmental flows would require detailed studies. The ZRA has developed regression equation (wet season) and an exponential decay equation (dry season) to estimate flow at Vitoria. Falls. The wet season equation uses observed flow at upstream gauge stations namely Chavuma, Matongo Platform, Watopa and Kalabo whereas the dry season equation uses the flow observed during the previous month as input These algorithms are limited to estimating inflows into Kariba but not clear how the inflow from the Kariba sub-basin is incorporated into the lake water balance. The Hugo model is a simple water balance spreadsheet model for estimating hydropower and environmental releases developed by Hugh Williams. It has been applied on a study for HCB to estimate the capacity of turbines for the Cahora Bassa North and the impact of conjunctive operation of Cahora Bassa and Mpanda Nkuwa on overall power output from both plants. There has been very limited application of this model beyond its developer.

Hydrological and statistical analysis was conducted using spreadsheets and the HDAM Graphs developed by WRNA to inform this study. About 99% of the graphs presented in this report are from this software.

5.3 Analysis of historical dam operations from the flood protection and environment point of view

This section documents historical occurrence of floods in the Zambezi Basin and the problems that have experienced in the past on dam operation with regards to floods. The impact of historical floods on the settlements/livelihoods and the environment is assessed from available literature. The time-line of flood events is superimposed on historical flows/releases to assess the how dam operations could contribute to flood protection and improved environmental management.

5.3.1 Large floods prior to Zambezi regulation

Descriptions of major flooding events dating back to 1830 are common in the oral histories of the people of the Zambezi delta region. Liesegang and Chidiamassamba (1997) report written records of extreme floods dating back to 1648. Three historical floods are particularly noteworthy.

In 1939, the delta reached its highest water levels in recorded history. The flood was generated by extreme runoff from the Middle and Lower Zambezi Valley, as peak runoff from the Zambezi headwaters region was only about 3016 m^3/s (below the long-term mean). Heavy runoff from the Middle Zambezi was sustained over most of February and March and the 2-month flood volume (25×10^9 m^3) was one of the highest on record. In the Lower Zambezi, flows at Mutarara peaked at 18,700 m^3/s (4th highest discharge on record), and remained above 12,000 m^3/s for 27 days. Downstream of Mutarara the Shire Valley generated the heaviest rainfall and runoff in cultural memory (Mandala 1990) as Lake Malawi reached the highest water levels in recorded history[1]. The resulting flood in the delta region overtopped the dikes that were built in 1926 to protect the sugar estates at Marromeu and Luabo, and inundated most of the 1.2 million ha. delta. The dikes were overtopped again in 1940 and 1944, during what was probably the wettest period in the twentieth century.

The most prolonged flooding on record occurred in 1952, with heavy runoff generated from each of the Zambezi sub-basins. The flood, known locally as *Cheia M'bomane* ("the flood that destroyed everything"), caused extensive damage to houses and crops on the delta plains (Liesegang and Chidiamassamba 1997). Floods began building up in December and by February the Upper Zambezi reached its sixth highest flood peak on record, the Gwembe Valley was contributing its fourth highest flows on record, and the Luangwa Valley and remaining Middle

---

[1] The highest recorded discharge at Chiromo (the lowest downstream gauging station) was 2142 m^3/s in April 1984, suggesting a maximum inflow of approximately 2705 m^3/s to the Zambezi River. Inflows from the Shire during the 1939 flood must have exceeded 4500 m^3/s (a statistical 1:1000 year flood) to surpass the 1952 flood stage at Marromeu.

Zambezi catchments were generating the highest flows on record. On February 17, Zambezi discharge at Mutarara reached 22,300 m^3/s, the second highest on record. Flooding in the Lower Zambezi was prolonged by heavy runoff from the Shire Valley, as discharges from Lake Malawi remained near record highs and a maximum discharge of more than 1900 m^3/s was reported from the Ruo tributary, a statistical 1:100 year flood (Halcrow and Partners 1954). Water levels remained above flood stage for 130 days, and above the catastrophic flooding level of 7.9 m (nearly 13,000 m^3/s) for a remarkable 37 days until early March. For the fourth time since 1926, the dikes protecting Marromeu and Luabo were overtopped. Maximum water levels in the Zambezi Delta reached 8.0 m, just shy of the highest on record, on four occasions over this period.

In 1958, the final year before Kariba Dam began regulating Zambezi flows, the delta again experienced extreme flooding. Known as the *Cheia N'sasira (*"the flood that forced people to live on top of termite mounds"), the flood was triggered by the highest runoff ever recorded in the Zambezi headwaters region. Reeve and Edmonds (1966) noted that a low pressure system developed over Southern Angola during the dry season and moist Congo Air arrived over the northern watershed in September, much earlier than usual. The low-pressure area persisted for months, moving across the headwaters region from north to south and generating a belt of intense rain that moved slowly down the catchment. The prolonged, early rainfall produced an exceptionally large flood above the Barotse Plain[2] that quickly exceeded the storage capacity of the floodplain and passed downstream, where it was augmented by very heavy rain between Senanga and Livingstone. The Zambezi peaked about 4-5 weeks earlier than usual, reaching a record peak discharge of 11,800 m^3/s at Livingstone on March 8 at the same time that the rivers of the Gwembe Valley catchments were in peak flood. This resulted in a phenomenal peak of 16-17,000 m^3/s in Kariba Gorge. The total volume of runoff during the three month flooding period exceeded 61 x 10^9 m^3, just shy of the estimated 1:10,000 year design flood (65 x 10^9 m^3) for the dam under construction. The floods scoured through the partially completed dam wall, causing extensive structural damage. Downstream of Kariba, near-record runoff from the remaining middle Zambezi catchment also contributed to the flooding, and peak discharge at Muturara (22,500 m^3/s) was the highest on record. Water levels in the delta reached near-record levels, and exceeded catastrophic flood levels for 26 days. Large numbers of Cape buffalo and waterbuck were purportedly drowned by these large floods (Tinley 1994).

5.3.2 Large floods under Zambezi regulation

After the completion in 1959 of Kariba Dam, with a storage capacity of almost 185.5km^3 or 4.6 times the mean annual incremental catchment runoff to Kariba, large flooding events in the Zambezi Delta region were greatly curtailed. The 1969 flood was not remarkable in terms of the peak water levels in the delta (about 7.39 m), but is noteworthy because water levels remained above flood stage for 222 days from early January until mid-August. Local villagers refer to this strange dry season flood as the *Cheia Nabwariri* ("water coming from the ground"). The unusual pattern of flooding was the result of prolonged releases from Kariba Reservoir. Kariba received a near-record inflow volume of 79 x 10^9 m^3 – comparable to inflows to Kariba Gorge during the 1958 flood season – including the third highest recorded flood discharge from the headwaters region (8204 m^3/s). Unlike the 1958 floods, however, most of this inflow volume was stored by

---

[2] Although runoff the Zambezi headwaters region was the highest on record in, rainfall was only about 17% higher than the long-term mean. Runoff was disproportionately high because the heaviest rains were centered along the main river channel and there was an unusually short time of concentration over the catchment as a whole.

the reservoir and floodwaters were subsequently discharged through the Kariba's sluice gates during the dry season to draw down reservoir levels according to the Design Flood Rule Curve. Kariba thus operated to significantly reduce peak flooding in the Zambezi Delta, but greatly prolonged the total duration of flooding. Several other years during which runoff from the Zambezi headwaters was among the highest on record, including 1961 (6032 m^3/s), 1962 (5425 m^3/s), 1966 (5233 m^3/s), 1968 (5340 m^3/s), and 1970 (4783 m^3/s), also resulted in relatively insignificant floods at Marromeu due to Kariba regulation.

Since the construction of Cahora Bassa Dam in 1975, large flooding events have resulted in extensive social and economic damage. Many of these costs can be attributed to the encroachment of people onto lowland areas of the Zambezi floodplains that had never been historically occupied before Kariba regulation. In 1978, flooding on the lower Zambezi caused an estimated USD62 million worth of damage and necessitating flood relief operations costing about USD40 million. As noted by RPT (1980), "this was the first flood since completion of Cahora Bassa, and dispelled the widely held belief that the dam would finally bring flooding under full control." The flood resulted from a combination of emergency releases from Cahora Bassa Dam and heavy runoff from lower Zambezi tributaries. During 1978, prolonged rainfall in Kariba catchment produced some of the highest inflows to Kariba Reservoir on record and the Zambezi River Authority opened four of the six sluice gates at Kariba to prevent overtopping of the dam. Maximum discharge reached 7300 m^3/s. Downstream, heavy runoff from the Luangwa catchment more than doubled the Zambezi flows below Kariba, and Cahora Bassa inflows steadily increased to a peak of 17,900 m^3/s. During this period, Cahora Bassa operated with only 3-4 sluice gates open, but in late March water levels neared design capacity, and reservoir managers opened the remaining sluice gates in rapid succession. On March 30 reservoir levels reached 327.9 m, and Cahora Bassa released a peak discharge of 14,900 m^3/s with all eight sluice gates and the emergency spillway gate open. Peak discharge downstream at Mutarara surged to 19,500 m^3/s, and water levels at Marromeu spiked to 7.92 m. Many floodplain residents were unable to evacuate to higher ground in time, and forty-five people died during floods. More than 100,00 people were displaced[3]. Subsequent studies by RPT (1980) showed that if the reservoir had released water in January and February, gradually stepping up the outflow to 7000 m^3/s, releases would have been significantly less than actually occurred (reaching a maximum of 10, 163 m^3/s during early part of April) with adequate time to evacuate the most flood-prone areas.

In 1989, runoff from the Upper Zambezi was not sufficient to force Kariba to spill floodwaters, but heavy runoff from the Luangwa Valley generated a peak inflow of 14,436 m^3/s to Cahora Bassa Reservoir. Cahora Bassa operated to attenuate inflows and reduce the magnitude of downstream flooding, but during peak flooding reservoir levels approached design capacity and outflows were rapidly stepped up from one sluice gate on February 6 to five sluice gates on February 12, reaching a maximum discharge of 7,938 m^3/ (Vaz 1989). Combined with heavy runoff from the plateau region[4], runoff in the Zambezi Delta region surged to 11,000 m^3/s. Although this peak discharge was less than the mean annual peak discharge prior to Kariba regulation (about 11,500), the flood caused widespread damage to settlements that had

---

[3] The 1978 floods are known locally as the *Cheia Maldeia* ("the flood that forces us to leave our homes and move to communal villagers"). The Government of Mozambique required flood victims to resettle into communal farming areas on higher ground to administer aid during the floods, and to promote agricultural development in subsequent years.

[4] Estimated contribution from Luia River, for example, included peaks of 3875 m^3/s on Feb 7 and 3865 on March 8, and remained above 3000 m^3/s from March 8-12.

encroached back to the delta floodplains. The flood is known locally as *Cheia Cassussa*, remembered locally because flood levels rose so rapidly there was no time to escape[5].
In 1997, flooding in the Zambezi Delta reached its highest level since 1978 with a peak of 7.61 m at Marromeu. Flooding was generated almost entirely within the Lower Zambezi catchment. Maximum runoff from the Zambezi headwaters region was only 1758 m^3/s, one of the lowest peaks in the 75-year historic record, and Kariba did not spill. Inflows to Cahora Bassa from the Luangwa Valley rose sharply from less than 4000 m^3/s on February 9 to a peak of 12,170 m^3/s on February 15, but then fell again below 4000 by February 25. Cahora Bassa captured most of this brief surge, and maximum discharge from the dam was only 2000 m^3/s. Runoff from the Shire Valley was the highest since the 1950s. Overall, the flood peak was not remarkable – only the sixteenth highest on record – but the flooding ripped through new settlements on the Zambezi banks and is known as the *Cheia N'selusso* ("flood of ill-fortune"). The media portrayed the flood as catastrophic and international evacuation efforts were widely televised.

The recent 2001 floods in the Zambezi Delta were the most prolonged since construction of Cahora Bassa Dam. Very heavy rainfall in the Zambezi headwaters region resulted in substantial inflows to Kariba Dam, which spilled floodwaters for first time since 1981. Two gates were operated, discharging a steady 3800m^3/s in addition to turbine outflows. Rainfall in the Middle Zambezi catchment was also heavy, and inflows to Cahora Bassa peaked at 13,978 m^3/s on February 22 and again at 11,379 m^3/s on March 15. Discharges from Cahora Bassa were stepped up to 9000 m^3/s on March 7-8 through five sluice gates. Downstream the Luia and Revuboe Rivers discharged a steady 2000-3500 m^3/s, the Luenha contributed 1000-1500 m^3/s, and heavy rains in the Shire Valley (that left 5 people dead and 22,454 people homeless) generated runoff from the Shire basin comparable to the 1997 floods. Water levels at Marromeu climbed above flood stage on January 20, and reached a maximum of 7.69 m on March 9. The navy began evacuating people from the delta region in January using rubber boats and later helicopters, but many people refused to leave their homes. Overall, eighty-one people died and more than 155,000 people were displaced by the floods (Hanlon 2001). Although tragic the damage could have been considerably worse if Hurricane Elise, which struck the central Mozambique a year earlier, had hit the delta region during peak flooding and forced Cahora Bassa authorities to open more sluice gates. In fact, although the media frequently reported this flood as one of the biggest in history, floods of this magnitude have occurred at least once every 10 years on average over the past 75 years. The estimated maximum discharge, about 13,500 m^3/s, was far less than occurred during past flooding events.

Although the 2001 flood was not remarkable relative to previous extreme floods in the lower Zambezi, the impact of this first major flood since the Mozambican civil war on delta wildlife was notable. Aerial reconnaissance surveys conducted during and after peak flood inundation in the Zambezi (*pers. obs.*) revealed large numbers of Cape buffalo stranded and starving in deepwater areas, while helicopters pilots on rescue missions reported large numbers of drowned buffalo carcasses. Subsequent surveys (Dutton *et al.* 2003) revealed 40% mortality of the buffalo population, predominately calves. Dutton suggests that past extreme floods likely also resulted in high mortality of buffalo in the delta, but that the buffalo herds that remain in the delta today are particularly vulnerable to extreme flooding because they concentrated in the wettest, most remote part of the Buffalo Reserve to escape persecution during the war.

The timeline of major flood events and interventions by operators is shown in Table 5.4.

---

[5] Because there was no hydropower transmission capability at Cahora Bassa turbine discharge was only 75 m^3/s throughout the flooding period rather than 1400-1600 m^3/s, resulting in a sharper increase in reservoir water levels.

Table 5.4: Timeline of flooding events in the Zambezi Basin and their socio-economic impacts

Year	Location	Description	Socio-Economic Impacts	Interventions by dam operators
1958	Middle Zambezi	Flood waters from upper and middle Zambezi tributaries upstream of the new dam rushing through partly constructed dam wall and around circular coffer dam.	At least 86 project workers were killed, including 18 who were buried in wet concrete. Existing suspension bridge and work done on the dam wall eroded away.	
1969	Zambezi Delta	Water levels remained above flood stage for 222 days from early January until mid-August as a result of prolonged releases from Kariba Reservoir.		Floodwaters discharged through sluice gates during the dry season to draw down reservoir levels
1978	Lower Zambezi	The flood resulted from a combination of emergency releases from Cahora Bassa Dam and heavy runoff from lower Zambezi tributaries.	Many floodplain residents were unable to evacuate to higher ground in time, and forty-five people died during floods. More than 100,000 people were displaced[6]. Damage was estimated at USD62 million, necessitating flood relief operations costing about USD40 million.	Sluice gates were opened in rapid succession.
1989	Lower Zambezi	Heavy runoff from the Luangwa Valley generated a peak inflow of 14,436 m^3/s **into Cahora Bassa**, but during peak flooding reservoir levels approached design capacity and outflows were rapidly stepped up from one sluice gate to five sluice gates.	The flood caused widespread damage to settlements that had encroached back to the delta floodplains without giving time for escape.	Outflows were rapidly stepped up by opening gates (from one sluice gate to five sluice gates)
1997	Lower Shire River Valley	Flash floods	Extensive damage to roads, bridges, houses as well as crops and livestock. 4 people drowned. 400,000 people affected	
2000	Most of the Zambezi Basin	Prolonged and exceptionally heavy rains compounded by cyclone Eline caused flooding throughout Southern Africa. Mozambique was the most affected.	Loss of lives, extensive damage to roads, bridges, crops, and communication lines. Outbreak of diseases. More than 200,000 people affected.	
2003	Villages near Lake Malawi	Rising water levels in Lake Malawi submerged nearby villages	Houses collapsed. 107 families displaced	
2006	Lower Shire valley	Heavy rains caused flooding	Destruction of houses and outbreak of diseases (cholera). 37,431 households were affected. 1,794 houses destroyed	

From Table 5.5 it is evident that while the major flooding events on the delta are linked to high flows at Vitoria Falls and Mutarara, the worst flood at Morromeu did not coincide with the worst floods at Mutarara or Victoria Falls. This is because of the impact of the other tributaries in the Middle and Lower Zambezi. ARA Zambeze pointed out that large floods were experienced during the years 2001, 2008 and 2009/2010, around 12,000 m^3/s passed Caia (ARA Zambeze, 2010).

---

[6] The 1978 floods are known locally as the *Cheia Maldeia* ("the flood that forces us to leave our homes and move to communal villagers"). The Government of Mozambique required flood victims to resettle into communal farming areas on higher ground to administer aid during the floods, and to promote agricultural development in subsequent years.

Table 5.5: Ranking annual maximum flood stages recorded at selected points on the Zambezi River System

Year	Marromeu maximum water level (m amsl)	Rank	Muturara maximum discharge (m^3/s)	Rank	Victoria Falls maximum discharge (m^3/s)	Rank
1939	8.01	1	18,700	4	3,016	42
1952	8.00	2	22,300	2	6,084	6
1958	**7.97**	**3**	**22,500**	**1**	**11,800**	**1**
1944	7.97	4	18,200	5	2,724	46
1978	**7.92**	**5**	**19,500**	**3**	**6,297**	**5**
1940	7.91	6	13,200	8	5,035	18
1926	(7.85)	7	-	-	4,497	23
1963	7.85	8	13,200	8	7,011	4
1948	7.85	9	12,600	9	6,074	7
1955	7.77	10	12,300	10	3,753	29
1974	7.73	11	-	-	2,992	-
2001	7.69	12	13,500	7	-	-
1943	7.67	13	11,000	12	2,030	-
1957	7.64	14	12,300	10	9,312	-
1956	7.62	15	12,000	11	5,590	-
1997	**7.61**	**16**	**-**	**-**	**1,758**	**-**

5.3.3 Changes in flow patterns with regulation

The flood events in Table 5.6 were superimposed on the graph of inflow and outflow of Lake Kariba as shown in Figure 5.8. The following is apparent from the graph.

(a) During relatively wet years (1961 to 1981) **the pattern of wet season discharges followed that of inflows**.

(b) During relatively dry years (1982 to 1997) **the pattern of wet and dry season discharges ranged between** 350 to 1000 cum/sec on average.

(c) In the third year of the period (1998 to 2000 in which average peak inflow was around 3000cum/sec) discharge pattern for wet years was adopted.

(d) Outflows from Kariba were maintained above 350 cum/sec on average.

The floods of 1974, 1978, and 2001 were identified with high outflows from Kariba dam, but the floods of 1989 and 1997 were not related to high discharges from this dam. In addition some significantly high releases such as those in 1975 do not seem to appear in the history of flood impacts.

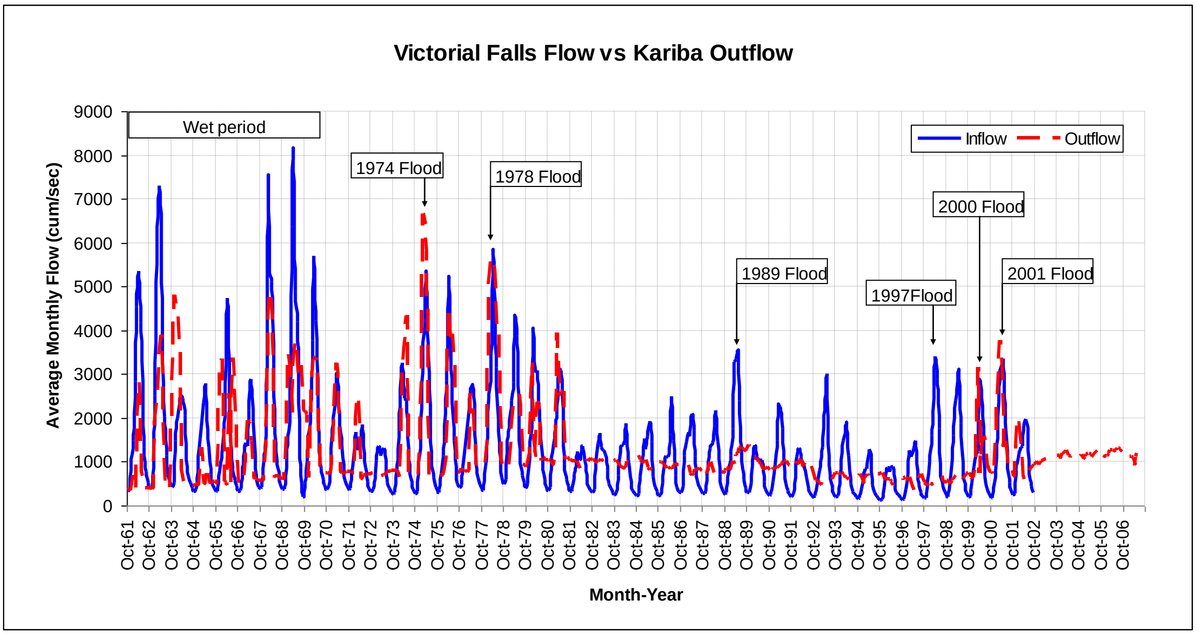


Figure 5.8: Lake Kariba - Inflows and Outflows

Figure 5.9 shows the time-line of flood events superimposed on historical flows/releases for Kafue Gorge. It is evident that the floods of 1974, 1978, 1989 and 2001 were related to releases from this dam. However some significantly high releases such as those in 1975, 1976 and 1981 do not seem to appear in the history of floods on the Zambezi River system.

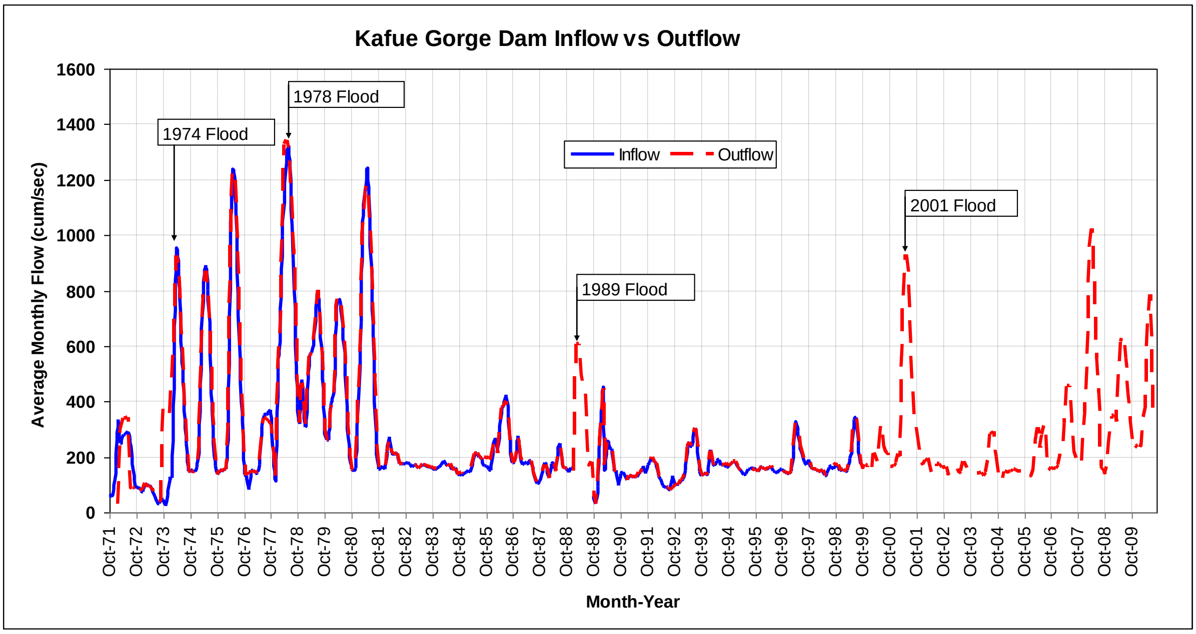


Figure 5.9: Kafue Gorge - Inflows and Outflows

Flow data from period beginning 1961 shows that that Kariba dam reduces extremely high low frequency floods (through attenuation) and changes the pattern of flows below 1000m^3/sec as shown in Figure 5.10.

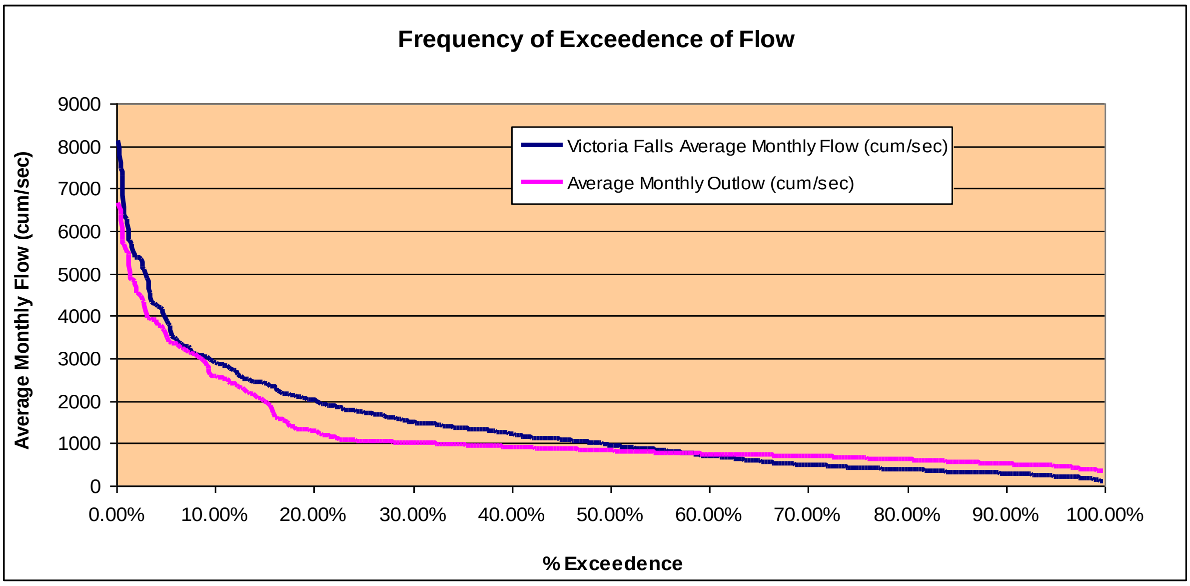


Figure 5.10: Comparison frequency of exceedence of flows for Victoria Falls and Kariba outflows

Most small and medium-sized floods are modified by the Kariba. Dam management practices attenuate (essentially capturing) the unregulated small to medium floods including the 1:5 and 1:10 year flood events. While they also alter the basic hydrological characteristics of larger flood events, they cannot fully control them due to insufficient storage capacity. They do not have sufficient storage capacity to hold the great floods that periodically move through the Zambezi system, as occurred in 2001.

The pattern of historical outflow for Kafue Gorge matches the inflow as shown in Figure 5.11.

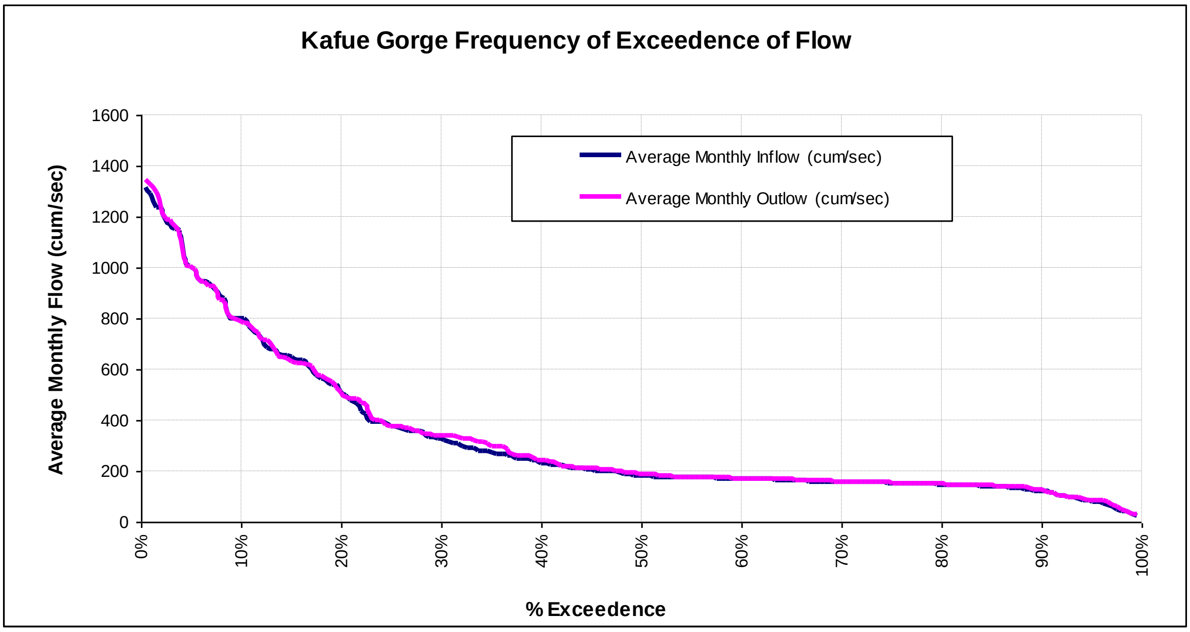


Figure 5.11: Kafue Gorge - comparison frequency of exceedence of inflow and outflow

Figure 5.12 (Beilfuss and Dos Santos 2001) shows the historical distribution of mean monthly inflows to Cahora Bassa Gorge during the period 1907-58, as a function of runoff from various inflow sources-the Upper Zambezi, the Gwembe Valley (inflows upstream from Kariba Dam). Runoff from the Luangwa River, Gwembe Valley catchment, and smaller tributaries of the middle Zambezi contributed to early wet-season Zambezi flood stages in the gorge. Zambezi discharges rose sharply with the onset of the rainy season, and peaked in March with a mean monthly runoff of 5948 m3/s. Runoff from Upper Zambezi catchment sustained peak flood discharges in March-April, and controlled the dry season recession of floodwaters. Mean monthly runoff at the end of the dry season in October-November dropped to 522 m3/s. Runoff from the Kafue River, the largest catchment in the Middle Zambezi, was naturally attenuated by the vast Kafue Flats and did not have a significant effect on the shape of the inflow hydrograph for Cahora Bassa relative to the other sources of runoff.

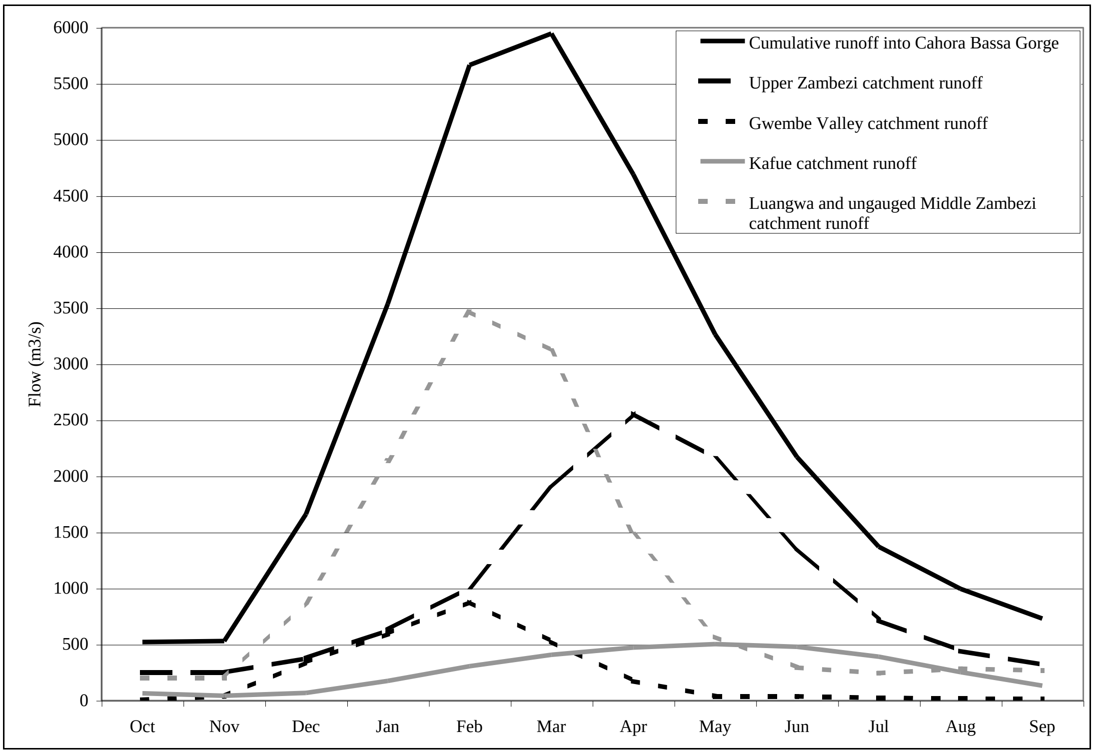


Figure 5.12: Hydrographs of mean monthly runoff to the Cahora Bassa Gorge catchment, 1907-58

The recent distribution of mean monthly inflows to Cahora Bassa Reservoir is shown for the period 1974-04 in Figure 5.13 (Beilfuss and Dos Santos 2001). Inflows now occur as a function of Kariba Reservoir outflows, Kafue Gorge Reservoir outflows, and remaining Middle Zambezi catchment inflows below the Kafue confluence. The increased significance of unregulated runoff from the Luangwa River relative to historical conditions is evident. Despite the regulation of more than 78% of the catchment above Cahora Bassa Reservoir, high volume flood discharges from the Luangwa and other tributaries of the Middle Zambezi below Kariba/Kafue maintain the basic shape of the inflow hydrograph relative to pre-regulation conditions.

The relative magnitude of maximum and minimum flows has changed substantially. Mean monthly flows over the flooding season from January-May are 36% lower than occurred during the period prior to Zambezi regulation. The recession limb of the inflow hydrograph during the dry season is flattened by hydropower releases from Kariba and Kafue Gorge Dams, with dry season flows dipping only slightly below 1000 m3/s, an 88% increase relative to pre-regulation conditions.

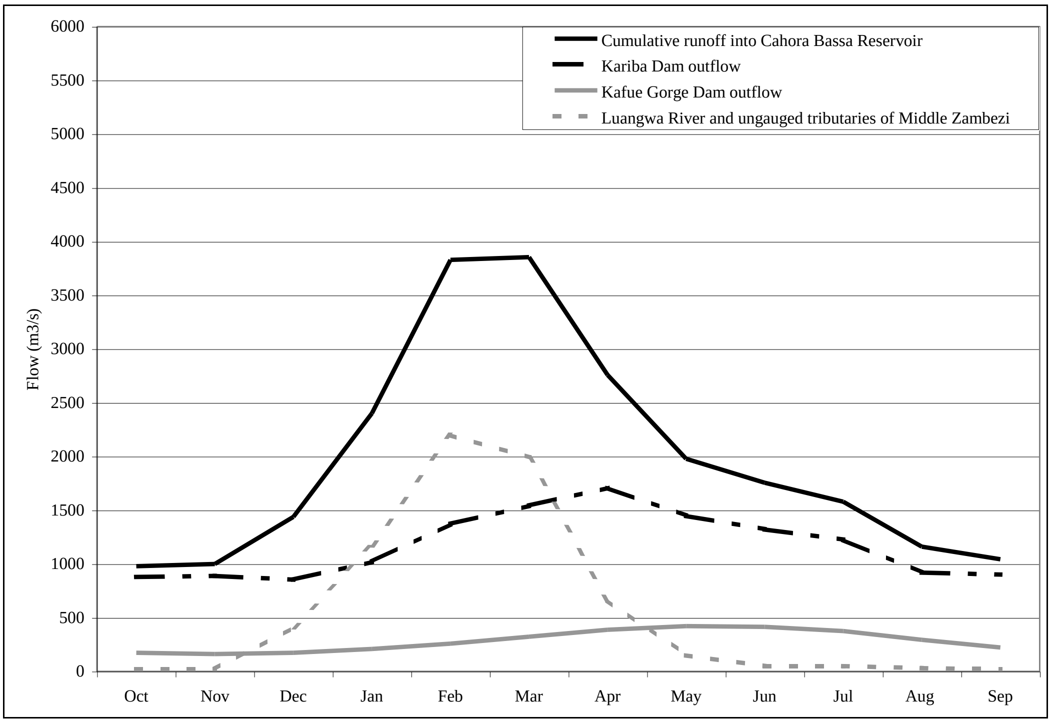


Figure 5.13: Hydrographs of mean monthly runoff from Cahora Bassa Gorge catchment, 1976-04

Figure 5.14 (Beilfuss and Dos Santos 2001) compares mean inflows and outflows at Cahora Bassa over the period since dam construction. The dam has clearly operated to significantly reduce mean monthly flood season flows and increase mean monthly dry season flows relative to inflows, in addition to hydrological changes brought in by the operation of Kariba and Kafue Gorge Dams upstream. The highest mean monthly discharges occur in December (several months before the historical peak flood) and July (mid-dry season). Downstream flow contribution from the unregulated plateau tributaries and Shire River help to offset these effects and result in higher variation in mean monthly flows at Mutarara during the rainy season.

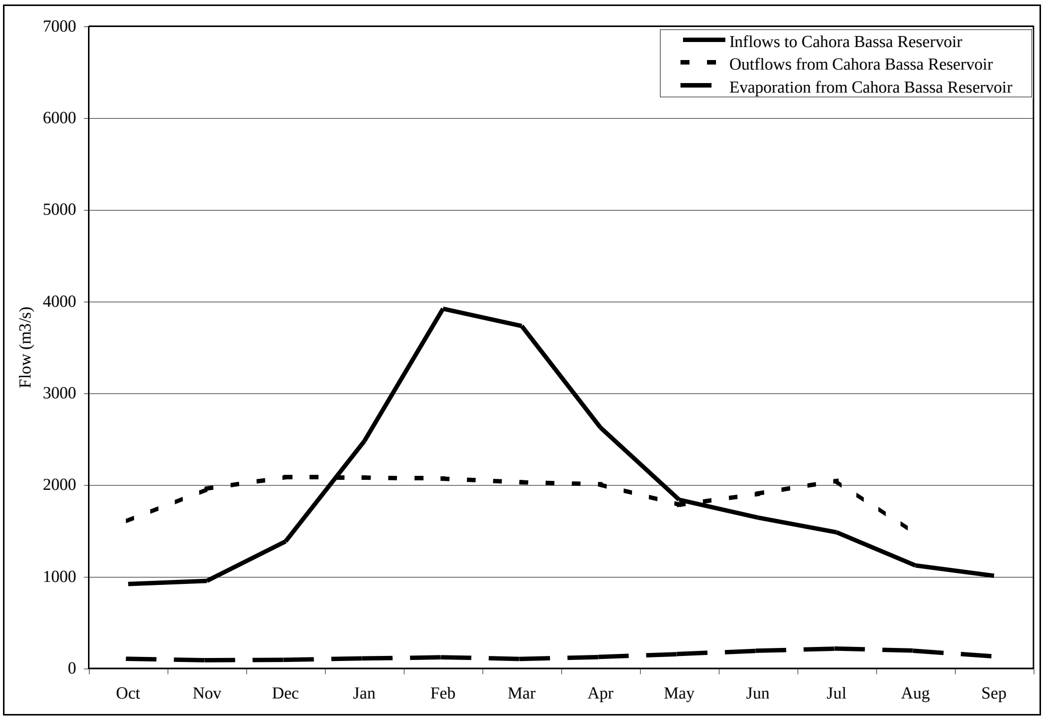


Figure 5.14: Hydrographs of mean monthly inflows and outflows at Cahora Bassa Reservoir, 1976-04

Figure 5.15 (Beilfuss and Dos Santos 2001) shows the changes in the magnitude of mean monthly flows at Muturara. has been a 32% reduction in the mean annual flow between 1930-59 and 1976-04. Part of this reduction may be due to evaporative water loss in Kariba, Kafue Gorge, and Cahora Bassa Reservoirs (perhaps 20%), but most is due to the generally drier climatic cycle in the 1980s-1990s, compared to the 1930s-1950s. The changing climatic patterns discussed in section 3.2.2 show that existing studies have do not provide quantitative data on impacts of climate change.

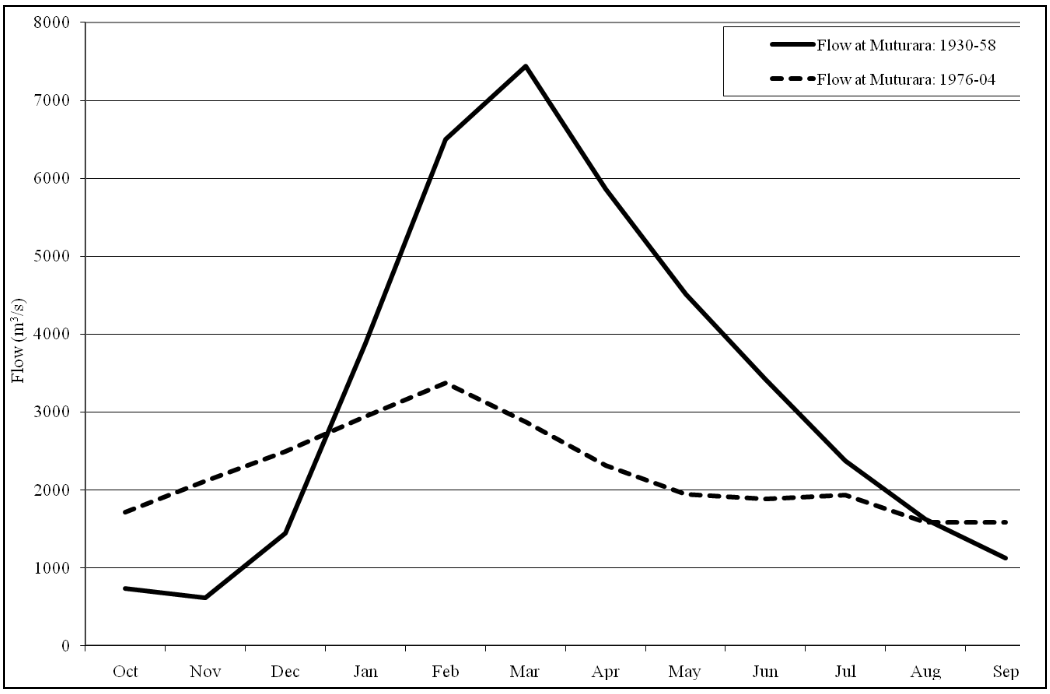


Figure 5.15: Hydrographs of mean monthly runoff for Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-04).

5.4 Description and concepts and purpose of environmental flows

A primary challenge in water resource development is designing and operating infrastructure projects in order to maximize financial returns, provide social benefits while preventing deleterious effects to the natural ecosystem. The construction, filling and operation of dams can cause a myriad of changes to river ecosystems, but many of these impacts can be avoided, minimized or mitigated through proper planning, careful design and judicious operational management. It is now standard practice, worldwide, to evaluate environmental impacts in new dam proposals. Unfortunately, many of these environmental assessments are limited in geographical scope to the immediate vicinity of a dam, especially during the construction process. However, evidence from dam developments around the world suggest that more widespread and long-lasting ecological impacts can be expected a long way downstream of dams.

Among the many environmental and social concerns involved in building or operating a dam, it is particularly important to maintain adequate environmental flow conditions downstream of dams. The term ‘environmental flow’ refers to a variable water flow regime that has been designed and implemented—such as through intentional releases of water from a dam into a downstream reach of a river—in an effort to support desired ecological conditions and ecosystem services. Environmental flows are one tool in mitigating the impacts of hydropower dams, and thus each project should consider the range and appropriate combination of environmental management tools available.

The Brisbane Declaration of 2007 defined "Environmental flows" or (E-flows) as the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems. E-flows are based on Environmental Flow Requirement (EFR), where the latter defined as water required in a river to maintain a desired condition (which should be as close to the natural condition of the river as possible). "Prescribed flows" are not necessarily EFRs and may not represent or simulate natural river pulses. "Environmental flow management provides the environmental flows needed to sustain freshwater and estuarine ecosystems in coexistence with agriculture, industry, and cities (Brisbane Declaration, 2007). The goal of environmental flow management is to restore and maintain the socially valued benefits of healthy, resilient freshwater ecosystems through participatory decision making informed by sound science. Ground-water and floodplain management are integral to environmental flow management.

The objectives of environmental flow management vary widely based on the specific river basin ecosystems. In some instances, the purpose of environmental flow management is limited to restoring the population of a particular fish species; while in other cases, a more holistic goal would have been adopted, such as maintaining river health and ecosystem services.

A recent trend is to specify objectives for environmental flow management using a scaled measure of the desired health of the overall river ecosystem, sometimes referred to as ecological management classes. From a scientific perspective, an ecosystem management approach is preferable to a species-focused approach. From a social perspective, a choice among multiple levels of ecosystem protection provides flexibility in balancing dam-related benefits and ecosystem-related benefits. In applying this approach, it is also important to clearly define objectives for ecosystem service and biodiversity protection for each river being affected

A number of important principles that direct environmental flows and include:

- that environmental flow decisions should be based on sound scientific knowledge;
- that water resource developments should be ecologically sustainable;
- that allocations should be reviewed five years after they are issued;
- that allocations should be made with room for adjustment as necessary; and
- that methods for determining environmental flows (for given broad geographic areas or types of environment) should be as consistent as possible throughout the country.

5.4.1 Ecological assumptions and limitations underlying environmental flows

A number of gaps limit the implementation of environmental flows. These are:

(a) Legislation and policy

- There is a general lack of specific reference under most legislation to the provision of environmental flows.
- There is a lack of knowledge of the effects of altering freshwater flows to estuaries, and there is also a high level of uncertainty associated with determining adequate and appropriate environmental flows.

(b) Process frameworks and methods

- There are serious data limitations, especially where long-term monitoring programs have not been implemented.
- There are serious methodological challenges (e.g. modeling river hydrodynamics and sediment dynamics is technically difficult).
- The absence of available data on ecological and underlying physical processes has a large influence on the methods that could be adopted and the likely outcomes of any given study, most of which rely on expert panels and qualitative risk based assessments.
- There is no accepted standard framework for assessing environmental flow needs globally.
- Biophysical knowledge gaps limit the ability to assess ecological response to different development scenarios.

(c) Community engagement and involvement

- The use of expert panels and stakeholder representative committees for making decisions regarding setting environmental flow trade-offs and rules is common. These panels and committees will remain important given the limited availability of scientific information regarding environmental flow needs of estuaries. However, anecdotal information is not a substitute for good science.

5.4.2 Benefits and costs of environmental flows for socio-economic and ecological river basin management goals

Environmental flows result in better water resources management in river basins. Environmental flows contribute to the maintenance of ecosystems such as rivers, wetlands, estuaries and near coast marine systems, which provide a great variety ecosystem of goods and services. Aquatic ecosystems need water and other inputs such as debris and sediment to stay healthy. Depriving a river or a groundwater system of these flows damages the entire ecosystem, and also threatens the people and communities who depend on it.

Food security can be enhanced by environmental flows, where amount of water for agriculture is increased. Fish stocks also increase and this has a direct positive impact on commercial and subsistence farming; and particularly on the poor who have few assets and rely on common property resources such as rivers and wetlands.

Loss of biodiversity can be halted by environmental flows. This in turn may result in increased revenue earning option from tourism and recreation. Furthermore, environmental flows help reduce public health risks caused by reduced river flows due to less available drinking water and more concentrated pollution. The mere increase in water quantity may also reduce water related conflicts, as competing users will have adequate water resources to satisfy their needs.

According to IUCN (2003), 'an understanding of the transition in the costs and benefits is vital to identify the types of resources and finance required to implement an environmental flow regime'. Table 5.6 from the same source lists the costs and benefits that result from implementing environmental flows.

Table 5.6: Costs and benefits of a transition to environmental flows

Cost / Benefit	
Stranded Costs (financial only)	• Remaining financial costs of debt or other finance obtained to build the original facilities that regulated the river in the first place
Direct Costs (financial and economic)	• Capital investments in modification of structures, water delivery systems, etc • Operational and maintenance cost of modifying system to facilitate environmental flows • Capital or operational and maintenance costs of environmental mitigation (where environmental enhancement has occurred after developing water resources) • Resettlement costs (where settlement has occurred in areas now to be inundated)
Opportunity Costs (financial and economic)	• Net benefits foregone in relation to power, irrigation, water supply, flood control, recreational and other uses
Transaction Costs (financial and economic)	• Costs of developing environmental flow regimes and setting targets for specific rivers and facilities • Costs of legislation and litigation • Costs of developing new mechanisms and institutions necessary to implement environmental flow regimes
Cost-Savings (financial and economic)	• Reductions in operational and maintenance costs • Reductions in mitigation expenditures
Direct Benefits (financial, but mostly economic)	• Net benefits of commercial and non-commercial (subsistence) agriculture, timber, recreation, and fisheries • Improvements in water quality • Improvements in aquatic habitat and biodiversity • Reduction in water-borne disease risks • Reduction of previous social impacts
External Impacts (+ or -) (financial, but mostly economic)	• Impacts on third parties (i.e. those not directly using the water or amenities provided by the dam or other facility) • Impacts on ecosystem and biodiversity (as adjusted to the existing infrastructure)
Source: Dyson, M., Bergkamp, G., Scanlon, J. (eds) (2003)	

5.4.3 Global examples of environmental flows for integrated river basin management

Table 5.7 adapted from IUCN (2003), gives examples of river basins where environmental flows have been applied.

Table 5.7: Examples of application of Environmental Flows

Project	Measure / Characteristics
Norris Dam, USA	This 81 metre high hydropower dam is on a tributary to the Tennessee river. In 1995 the Tennessee Valley Authority completed studies to improve downstream flow releases. Measures adopted included: • installation of two auto-venting power turbines to oxygenate water passing through the turbines, reportedly increasing DO levels by 91%; each unit cost about USD 2.5 million to install; and • Construction of a re-regulating weir three km downstream of the dam (USD 3.5 million) to further boost dissolved oxygen levels, and serve as a pool to release water when the dams was not generating

Project	Measure / Characteristics
	power. This maintained flows according to the EFR schedule regardless of intermittent hydropower releases.
Priest Rapids and Wanapum Dams, USA	Two hydropower projects on the Columbia river system (2,000 MW). The Grant County Public Utility worked with local NGO's and civil society to develop an adaptive management plan to improve downstream releases. The agreements: • changed the reservoir operation to "spill" during summer and spring fish migrations to about half the river flow at that period (on average), rather than passing through power turbines (which would already be at capacity); • reduced power output of 20% on an annual basis; and • required an investment of USD 200 million in fisheries protection measures.
Arrow Rock Dam, USA	The Arrow Rock dam built in the early 1900's has valves at three levels to control water releases from the dam. All have exceeded their design life. Three valves that control flow through lower conduits were out of service, inhibiting flood releases and the ability to meet minimum flow releases when the reservoir was partially drawn down. In 2000, a multi-stakeholder assessment of the rehabilitation options and associated environment impacts recommended: • replacing lower row of outlet valves in the dam structure (ensign valves) with clamshell gates, and enlarging valves in the mid and upper levels; and • renovating the dam, at a capital cost estimated at USD 14.6 million.
Stave Falls Replacement Project, Canada	In the mid-1990's, British Columbia introduced a requirement for water use plans (WUPs) to define operating strategies for all licensed dams. Regulations require operators to engage local communities in dialogue about options, tradeoffs and priorities. A Consultative Committee (CC) was established for the existing Stave Falls dam and power station replacement project. The CC set eight objectives to balance downstream releases from the reservoir, including: industry use of the reservoir; downstream flood protection; hydropower generation; reservoir recreation activities; heritage protection for the First Nations people; wildlife, fish and aquatic biodiversity protection; and maximum flexibility to respond to future changes in operation policy. Other features of the project included: • agreement on a new release strategy to maintain downstream water level stability (supporting viability of fish populations, increasing spawning and rearing capacity, and reducing stranding), and to ensure periodic flooding of riparian areas; • other measures to the reduce risk of exposure to elevated levels of total gas pressure; • a CC recommendation to adopt immediately an operating strategy, with an interim review after five years, and a full review after 10 years; and • estimated implementation costs for the plan of an estimated USD 200,000 per year in avoided power revenue.
Source: Dyson, M., Bergkamp, G., Scanlon, J. (eds) (2003)	

Other examples of river basins where environmental flows have been applied are the Pangani Basin, Tanzania; SAVA River Basin in Croatia; and Mekong River Basin in Thailand.

5.5 Summary of impact of historical releases on flow requirements for the environment

Kariba dam and Cahora Bassa dams have, since their construction, visited some negative impacts on the downstream biotic environment and socio-economy. Kafue dam and the Itezhi-Tezhi have also affected flows in the Kafue River. Following studies carried out by WWF in 2003, the Zambia Electricity Cooperation (ZESCO) and the Ministry of Energy and Water Development (MEWD) (Schelle and Pitlock, 2005) have implemented environmental flows on Kafue River. The operation rules of the Ithezi-Tezhi and Kafue Gorge dams were changed to provide a more natural flooding regime. A new management strategy consisting of artificial floods was developed and is now being implemented. The strategy is based on rainfall-runoff models for predicting future inflows.

The impact of the Cahora Bassa dam studied by Beilfuss *et al* (2000) and refined by Klassen. Klassen also looked at the possibility of releasing flow from the Kariba dam. Both studies indicated that the existing spillways capacities of Kariba and Cahora Bassa dams can be better utilised to manage releases and for improved downstream conditions. The studies also concluded that an increase in the spillway capacity of the Cahora Bassa dam helps in avoiding rapid drawdown of the reservoir.

The current situation in the Zambezi below Kariba is of a more or less constant flow provided through the release of water from the turbines at Kariba and Cahora Bassa. Excess water is only released through the spillway gates on an unscheduled basis when the dams fill up or ahead of flooding. These constant flood experienced downstream of the Cahora Bassa in particular are below the bankfull discharges throughout most of the year. There is a clear absence of a low flow season; and instead there is a sudden and unexpected flood late in the dry season when the Cahora Bassa reservoir is partly emptied to allow for sufficient flood storage.

These changes in hydrology have triggered major changes in the downstream environment and have necessitated the downstream population to adjust to these new conditions. Both the environment and the downstream population are negatively affected. Proposals for environmental flows have been made through several studies including Beilfuss' (2001) and the World Commission on Dams study but there have not been implemented yet.

Some of the major environmental impacts arising from the failure to provide for environmental flows in the past are summarised in table 5.8.

Table 5.8: Historical Impacts of dam releases on floods

Period	Location	Impact of Dam Regulation	Comment
After the construction of Kariba Dam	Mana Pools floodplain	Frequent floods of long duration replaced by rare floods of short duration	Floodplain species adapted to frequent floods of long duration might be replaced by species adapted to rare floods of short duration. (Dunham 1989a, 1989b).
1978	Zambezi delta	Discharges from both Kariba and Cahora Bassa were hastily increased over a two-week period to more than 14,700m³/s. Extensive property damage and loss of life.	Coordinated management between Kariba and Cahora Bassa Dam has significantly improved since that time Novela (1989) demonstrated that different patterns of water release could have been made to reduce downstream

Period	Location	Impact of Dam Regulation	Comment
			flooding.
1989	Zambezi delta	Cahora Bassa dam and the downstream tributaries contributed to the flood.	
1997	Zambezi delta	According to De Vries *et al* the floods of 1997 were the result of near-record rainfall in the Lower Zambezi Valley above Tete. Discharges from Cahora Bassa contributed to the floods.	
During the initial filling of Cahora Bassa Reservoir	Zambezi delta	No releases were made. Salt water intrusion occurred up to 70 km inland from the coast.	
2001	Zambezi delta	Cahora Bassa releases contributed to the floods. Maximum inflows occurred on February 22 but outflow was only 4739 m^3/s. Releases were then stepped up over a series of days reaching the peak discharge on March 7. Emergency flood releases were done from Kariba released to emergency. Middle Zambezi below Kariba Dam was also discharging high flows. While Cahora Bassa and Kariba dams experienced a gradual rise and recession of floodwaters over several months, flooding in the delta was characterized by a rapid rise and rapid recession	
2003		Flooding decreased due to Kariba regulation.	

5.5.1 Impact of environmental flows on fisheries

Perhaps the most significant impact of reduced large floods is on freshwater fisheries. The yield and production of riverine fisheries is highly dependent on the magnitude of flood season flows (*e.g.,* Bayley (1991)). The annual spread of floodwaters creates nearly optimal conditions for fish breeding and feeding activity (Welcome 1979). Flooding stimulates the production of food sources (including insects, worms, and mollusks) and the growth of emergent vegetation that provides both food and shelter. Many fish species "anticipate" these conditions by migrating laterally from the river channel to the floodplain to spawn just before or during the rise of floodwaters (Jackson 1986). During the floods, feeding is most intense and most fish reach peak condition. The number of surviving fry is directly proportional to the extent of inundation, as is the survival and growth of adult fish (Welcome 1979). When floods fail, fish are confined to the river channel which offers minimal vegetation cover and fewer food sources, leading to fish being stranded in the floodplain before they can reach sufficient size to avoid predation (Bayley 1995).

Fish are the most important source of protein in most Zambezi basin floodplains, especially during times of food shortage. In the Zambezi Delta, for example, fishermen concentrated in large numbers on the Zambezi floodplains, with seasonal fishing camps spread throughout the area between the main Zambezi channel and Mungari River tributary (Mr. Paul Dutton *pers. comm*). The annual months of low flows enabled a high catch of fish per-unit-effort because fishers were able to wade into the river using simple gill nets and baskets. SWECO (1983) estimated a total floodplain harvest of about 10,000 tons per annum under historical flooding conditions. Over the past three decades, riverine and near-shore coastal fisheries have replaced the floodplain fishery in the delta. The catch-per-unit-effort in the main stem Zambezi is low due to high dry season flows, and most of the fishing camps are now found in the coastal waters of Chinde district. The change in volume and value of catches in unknown, but recently DNFFB

(1998) and Turpie *et al.* (1998) estimated the total catch at one of main fishing camps (Chinde) at only 645 tons per annum. Similar declines are reported for the subsistence fishery of the Kafue Flats following river regulation (Hayward 1984, Subramanium 1992). After the extensive delta flooding of 2001, however, fishing camps were re-established on the floodplains for the first time since 1978 and fish harvests were the highest in terms of total catch and biomass in twenty years, with local markets at Marromeu and other places far as Malawi (Mr. Simoes Fombe *pers. comm.*).

5.5.2 Impact of environmental flows on the prawn industry

The reproductive success of prawns is also closely linked to annual flood flows (Garcia and Le Reste 1981). Studies have shown there is a high degree of correlation between Zambezi runoff patterns and the abundance of shrimp at the Zambezi mouth (Da Silva 1986, Gammelsrod 1996, Hoguane 1997). Almost half of the shrimp caught are of the species *Penaeus indicus*, which has a life cycle of one year. Spawning takes place at sea, but the larvae and juveniles require brackish water as nursery areas and must migrate against the current to reach the protected mangrove swamps. Because shrimp are inefficient swimmers, low dry season flows enable them to migrate inshore on tidal currents. High flood season flows, in turn, lower the salinity in the mangrove swamps, and trigger juveniles to move from the mangrove zone to the ocean to reproduce. Flood flows also spread nutrient-rich river water along the coastal bank to stimulate prawn recruitment.

The prawn fishery off the delta coast, which began in 1965, is one of the most important sources of foreign currency in Mozambique. The catch rate of the shrimp is reported to be decreasing at an alarming rate since the early 1980s (Gammelsrod 1992b). Hoguane (1997) estimated that the regulation of the Zambezi River is leading to a loss of USD 10-20 million per annum and Gammelsrod (1992a) predicted that catch rates would increase by 20% with increased flood flows and decreased dry season flows.

5.5.3 Impact of environmental flows on wildlife

The reduction in annual peak flooding has affected patterns of wildlife grazing and threatened the long-term carrying capacity of the vast delta floodplains. Tinley (1977) described the migratory and local movements of wild ungulates in the delta as an opportunistic response to the availability of suitable food resources and water. The close proximity of different vegetation communities with different soil moisture conditions allows ungulate species to meet their year-round life requirements through a rotation grazing patterns in response to natural flood cycles. When floods fail to appear, the system is disrupted. Woody vegetation and thickets invade grasslands, and drought resistant grassland species replace wetland species of higher nutrient content (Beilfuss 2001). The elimination of large floods facilitates year-round grazing on the open plains, and the stressed vegetation is further displaced by less palatable upland species. Similar patterns have been shown for the Kafue Flats (Rees 1978c&e) and middle Zambezi floodplains (Attwell 1970, Dunham 1994, Nilsson and Dynesius 1994) following river regulation. Cape buffalo are highly susceptible to starvation and high mortality when their pastures dry out early in the dry season, especially when uncontrolled fires sweep across the delta (Tinley 1977). Hippo (the only truly aquatic mammal species in the delta) and waterbuck are also vulnerable to poor forage conditions in the wet floodplains.

5.5.4 Impact of environmental flows on agriculture

The timing of the annual flood is critical for floodplain agricultural practices in the lower Zambezi system (Negrão 1995). Planting occurs on the heavy alluvial soils as floodwaters recede and crops are harvested prior to the next flooding cycle. Scudder (1972) observed that the extreme irregularity in Middle Zambezi flows below Kariba Dam has had terrible consequences for floodplain agriculture, with crops alternatively flooded out and desiccated. In the delta region, flood recession agriculture is similarly constrained by the timing of water releases from Cahora Bassa Dam. Occasional out-of-season drawdown releases from Cahora Bassa have wiped out crops along the length of the main stem Zambezi River and along the Catarina, Chinde, and Mucelo distributaries. Turpie *et al.* (1998) estimated the total value of subsistence agriculture in the delta at USD5.3 million per annum, a significant value in an area of chronic food insecurity (Schmidt 1997).

The findings from this section contribute to the recommendations detailed in Recommendation Sheets 2.4 and 2.7 in Chapter 10.

5.6 Conceptualization of new modes for dam operation to incorporate prescribed floods

In this section the desired scenarios for flood protection, provision for ecological flows and other uses are determined and used to derive possible modes of operating the dams.

5.6.1 Operating rule scenarios for flood protection

The review of historical flood events shows the following from a flood protection point of view:

(a) floodplain farmers have resettled close to the main-stem Zambezi to cultivate crops in the narrow band of alluvium that is inundated each year. The near elimination of medium-sized flooding events has resulted in famers moving deeper into the flood pain under the perception that the large dams can control large floods. This has contributed to increased flood damage when large floods occur, such as the 1978 (RPT 1979) and 2001 floods (Hanlon 2001). Floodplain agriculture is also practiced on some of the tributaries of the Zambezi river and it is affected by water levels (see Figure 5.16).

(b) the record of reservoir outflows versus inflows dispels the notion that the frequency of floods and magnitude of flows have increased because of dam operations. The timing of releases and lack of appropriate responses have increased the risk of flooding and the social and economic severity of large flooding events. Even floods that are moderate by historical standards such as the 1989 and 1997 floods (about 10,000 m^3/s at Mutarara) resulted in extensive flood damage (Vaz 1989, De Vries *et al.*1997, Beilfuss 2001).

(c) Some of the serious flooding emanated from tributaries which do not have large dams.

Point (a) suggests a change in perception which can be addressed through education, awareness, regulation and enforcement. This is the concept of "living with floods". The second point suggests improving timing of releases and monitoring response. The third point suggests that new dams be constructed on the unregulated tributaries.

Figure 5.16: Zambezi tributaries floodplain farming August 3, 2010

"New" modes of dam management can be developed from flood protection point of view to address (b) unfortunately the existing major reservoirs do not have enough storage capacity to attenuate large floods as pointed out at the beginning of this Chapter. In addition the existing spillways are for dam safety, to release of floods to safeguard dam walls and not for flood control. Therefore the window to manage releases from Kariba and Kafue dams to protect dam walls combined with high flows from unregulated tributaries is also very narrow. However, the following new modes can be considered:

(i) Managing releases to allow evacuation from flood plain (e.g. a stepped flood release pattern). The rising and recession patterns would follow an acceptable hydrograph.
(ii) Managing releases to provided early warning (e.g. an early release within an acceptable range of flow) to warn downstream riparian communities of the onset of flooding.
(iii) Adopting a downstream to upstream dam draw-down sequence (e.g. downstream dams draw down first and provide storage space for floods) to allows dams immediately upstream of floodplains to capture floods. Draw down levels should minimize loss in generation capacity. Operate upstream dams for optimum generation. Use additional power from upstream dams to replace lost power generation of downstream dams.
(iv) Implementing new infrastructure on the unregulated rivers interventions to manage floods. While (i), (ii) and (iii) present attempts to regulate releases by reservoir operation each of the sub-basins of the Zambezi, including the lower Zambezi Valley, is capable of generating significant flooding events in the delta region, independent of runoff elsewhere in the catchment. Thus that flood protection downstream of the major dams cannot be addressed from existing dam operations alone.
(v) Providing accurate early warning information, monitoring implementation of mitigation actions, evaluating and implementing impact of interventions (implementing the flood management cycle). Information dissemination could be through radio broadcasts and local newscasts for all communities downstream of the dam. Nodes of information dissemination could be established in each community.

5.6.2 Operating rule scenarios to incorporate prescribed floods

The importance of regular, annual environmental flow releases aimed at restoring ecological functions and diversity, alleviating poverty, meeting community aspirations, and satisfying national development objectives in the Zambezi River basin has been described for several decades (e.g., Tinley 1975; SWECO 1982; Beilfuss 2001; Beilfuss and Davies 2000; Davies 1997; Beilfuss and Brown 2010; others). However, the role of large flooding events (*floods capable of inundating vast areas of the Zambezi River floodplains*) in maintaining economic productivity and ecological processes is poorly understood. Large flooding events often cause tremendous hardship for floodplain communities—displacing people from their homes, destroying food supplies, drowning livestock, but the floods also deposit nutrient-rich sediments, flush accumulated salts, and recharge groundwater supplies that maintain agricultural systems in the long-run. Large floods may drown buffalo calves and other wildlife species that are unable to escape rising water levels, but they also improve conditions for wildlife by removing woody invaders from the floodplain grasslands, reducing dry season fires, flushing aquatic macrophytes from waterways, or dispersing seed to the floodplain margin. In this context the value of even a single large flooding event may take years or even decades to assess, if ever, especially given that the benefits and costs of large flooding events also change with changing patterns of settlement, rural development, and social custom.

Klassen (2003) indicates that it is possible to release environmental flows in the Zambezi Basin with the existing dams but with modification of the spillways. In principle there are two types of facilities which can be used to release environmental flows: - spillways and bottom outlets.

Bottom outlets are placed near the bottom of a dam wall and are always gated. They are included in a dam either to cope with floods during dam construction or to facilitate the management of the reservoir thereafter. Bottom gates allow for drawing down the water level much more than spillways placed higher in the dam body because of the higher head available. When bottom outlets are present, it is possible to release not only flow but also sediment, allowing for sediment management in the reservoir. Spillways are constructed either at the crest of the dam at some distance from the channel (overflow) or as openings underwater in the wall in the channel. Spillways for Kariba and Cahora Bassa are both openings under water but neither Kariba nor Cahora Bassa have bottom outlets. It would therefore be impossible to release sediments from the reservoirs. Downstream tributaries carry fine sediments to the main stem of the Zambezi River, but deposition of these fine sediments on the floodplains can only happen when the floods in the tributaries coincide with floods in the main stem of the Zambezi River.

Scudder & Acreman (1996) in Beilfuss (2001) states that the first prescribed flood releases within the Zambezi basin were first considered in 1971 in the Kafue River catchment when Itezhi-Tezhi Dam was designed and constructed with the capacity to generate a prescribed flood of 300 m^3/s during a four week period in March for the maintenance of agricultural and biological productivity in the Kafue Flats. In order to counter, to some extent, the effects of the upstream dam on the Flats, extra storage was built into Itezhi-Tezhi specifically for releasing floods onto the Flats. SWECO (1983) proposed prescribed flood releases to improve conditions in the lower Zambezi Valley. They proposed an environmental flow release from Cahora Bassa (freshet) to coincide with high flows from downstream tributaries. As was pointed out earlier, and according to Beilfuss (2001), SWECO estimated that a release of 7x109 m^3 during February, in excess of power generation needs, would create a desired flood peak of 9000 m^3/s in the Zambezi Delta region. While noting that the volume of water released in a freshet was less than the volume of a naturally occurring flood (and therefore different in effect from a natural flood), they predicted that flood releases would benefit natural vegetation, agricultural productivity, and the carrying capacity of grasslands by reducing soil salinisation. They also predicted that the short-duration release would reduce the growth of invasive aquatic macrophytes in river channels. SWECO noted that the benefits of freshets would be most pronounced during dry years, especially during periods of consecutive dry years. (Li-EDF-KP Joint Venture consultants 2001) in Beilfuss (2008) reported that despite the enormous potential of prescribed flood releases, the SWECO recommendations were ignored by Hidroeléctrica de Cahora Bassa (the Portuguese corporation charged with the management of the dam) and the Ministry of Public Works and Transport (the Mozambique government body charged with the management of water resources) even though the power station required negligible amounts of water between 1981-98 because the transmission lines were destroyed and the station was on a 'care and maintenance basis only'.

Beilfuss (2001) recommends a water management program for the lower Zambezi system that consists of integrated flood release strategy involving the coordinated management of Kariba and Cahora Bassa Dams. He notes, however, that Kariba Dam was designed without any consideration for prescribed flood releases, although its six sluice gates have the a maximum discharge capacity of 9515 m^3/s. The discharge capacity of each of the eight sluice gates at Cahora Bassa is approximately 1650 m^3/s and unlike the Kariba Dam, prescribed flood releases from Cahora Bassa Dam are achievable as its eight sluice gates located 111 meters below the crest of, significantly lower on the dam wall than at Kariba. They are also below the average operating level of the reservoir. (Olivier 1977 in Beilfuss, 2001).

Assessment for the Environmental Flow Requirements for the Marromeu Complex of the Zambezi Delta has been done with the aim to use available data and expert opinion to:

- establish the relationship between hydrological conditions (past, present, and future) and different water-related users and concerns in the Marromeu Complex.
- identify potential conflicts/trade-offs among users/concerns in the Marromeu Complex with respect to flow requirements.
- explore the potential for the improvement in the condition of the Marromeu Complex through incorporation of environmental flow releases into Cahora Bassa Dam, chiefly in terms of:
    - reduction in dry season low flows;
    - provision of a regular annual flood; and,
    - possible regulation of large floods (1:5 year return period or larger).
- identify key knowledge gaps and data requirements that would need to be addressed prior to any formal Environmental Flow Assessment (EFA) for the Zambezi River and Delta.

Table 5.9 summarises the major historical impacts of floods on the environment.

Table 5.9: Summary of environmental concerns from historical floods

Flow situation	Location	Environmental Impact	Comments from a dam operation point of view
Unpredictable changes in occurrence and duration of annual flooding	Zambezi delta	Downstream people and ecosystems unable to rapidly adjust to incremental, unpredictable increases in discharge. Miss-timed flooding. Wattled Crane pairs may not be induced to initiate nesting. Unanticipated water level rises can drown nests and food sources.	The occurrence and duration of annual flooding is unpredictable
Reduction in frequency and duration of annual flooding	Zambezi delta	Changes in composition and vigor of vegetation communities on floodplains. These changes have important implications for the wildlife on the delta. Pattern of short-duration flooding is not sufficient, salts in delta	Large floods are passed on with a reduction in peak flow, however small to medium floods

Flow situation	Location	Environmental Impact	Comments from a dam operation point of view
		substrate not flushed out causing salinization of the upper soil layers (Beilfuss 2001). Saline soils occur progressively closer to the main river channels over time, and eventually only soils in the immediate vicinity of the rivers remain productive.	are captured to provide required storage. The flow frequency - duration pattern is no longer natural.
Reduction in large floods		Negative impacts on small-scale agriculture, estuarine ecology & coastal fisheries, freshwater fisheries, livestock, large mammals, water birds, floodplain vegetation & invasive species, natural resource availability, water quality, water supply (groundwater recharge)	Large floods are passed on with a reduction in peak flow. Timing of emergency releases can be better managed.
Changes to timing of annual flood	Zambezi delta	Key life cycle phases of many floodplain wildlife species are also intimately linked to the timing of annual floods. For example the Wattled Cranes are "triggered" to nest after peak flooding. They nest in deep, open water after the major flood peak, to ensure that nests are protected from predators and wildfires but not drowned by further rising floodwaters. As floodwaters slowly recede, they raise their single chick on the pulse of exposed plant and insect life (Konrad 1981). Wattled Cranes have abandoned areas subject to erratic flooding. Breeding occurs only in the floodplains adjacent to the Cheringoma escarpment, which still receives unregulated floodwaters (Beilfuss 2000, Bento in press).	Timing of emergency releases can be better managed.
	Kafue Flats	On the Kafue Flats, Douthwaite (1974) observed that whereas 40% of Wattled Crane pairs attempt to breed in a year of normal flooding conditions, only 3% of all pairs breed in a year of negligible flooding conditions due to drought.	
Rapid flood recession	Zambezi delta	Rapid water level drawdown in the floodplains may expose nests to wildfires and predators and limit food availability.	A avoid rapid flood recession

The mean values for hydrological indicators describing spatial changes in Zambezi flow patterns above and below Cahora Bassa Dam are given in Table 5.10 for the period 1976-04.

Table 5.10: Ecologically-sensitive indicators for the Zambezi River hydrological condition, comparing Cahora Bassa inflows and outflows for the period 1976-04. The magnitude and percent of deviation are given for the means and coefficients of variation for each parameter

Indicator	Inflows Mean	Outflows Mean	Dev Mag	%	Inflows CV	Outflows CV	Dev Mag	%
Annual and monthly flow condition								
Mean annual runoff (m^3/s)	1863	1866	3	0.2	0.95	0.77	-0.18	-18.9
Mean October runoff	947	1635	688	72.7	0.47	0.52	0.05	10.6
Mean November runoff	1023	1915	892	87.2	0.48	0.64	0.16	33.3
Mean December runoff	1396	2057	661	47.3	0.56	0.65	0.09	16.1
Mean January runoff	2515	2114	-401	-15.9	0.56	0.61	0.05	8.9
Mean February runoff	3769	2183	-1586	-42.1	0.69	0.67	-0.02	-2.9
Mean March runoff	3649	2137	-1512	-41.4	0.78	1.02	0.24	30.8
Mean April runoff	2338	1876	-462	-19.8	0.85	1.02	0.17	20.0
Mean May runoff	1702	1770	68	4.0	0.86	0.88	0.02	2.3
Mean June runoff	1523	1786	263	17.3	0.74	0.85	0.11	14.9
Mean July runoff	1381	1852	471	34.1	0.72	0.75	0.03	4.2
Mean August runoff	1163	1532	369	31.7	0.48	0.46	-0.02	-4.2
Mean September runoff	1043	1547	504	48.3	0.46	0.45	-0.01	-2.2
Magnitude and timing of annual extreme daily flows								
Maximum annual 1-day flood flow (m^3/s)	7308	4398	-2910	-39.8	0.51	0.71	0.2	39.2
Minimum annual 1-day low flow (m^3/s)	295	623	328	111.2	0.84	0.59	-0.25	-29.8
Timing of maximum annual 1-day flood flow (Julian date)	145	124	-21	-14.5	0.15	0.75	0.6	400.0

Indicator	Inflows Mean	Outflows Mean	Dev Mag	%	Inflows CV	Outflows CV	Dev Mag	%
Timing of minimum annual 1-day low flow (Julian date)	182	191	9	4.9	0.79	0.58	-0.21	-26.6
Flood season river condition								
Timing of onset of flood flows* (date)	86	76	-10	-12	0.46	0.54	0.08	17
Duration of flood flows* (days)	42	31	-11	-26	1.19	1.57	0.38	32
Volume of flood flows *(km^3)	2248	1670	-578	-26	2.65	2.64	-0.01	-1
Frequency of flood pulses* (events per year)	9.3	1.4	-7.9	-85	0.92	1.41	0.49	53
Dry season river condition								
Timing of onset of low flows* (date)	55	116	61	111	1.94	0.61	-1.33	-67
Duration of low flows* (days)	56	42	-14	-25	1.21	1.69	0.48	37
Minimum annual 7-day low flow (m^3/s)	716	863	147	20.5	0.30	0.36	0.06	20.0
Daily river fluctuations								
No. of rises	180	166	-14	-7.8	0.08	0.11	0.03	37.5
No. of falls	175	178	3	1.7	0.11	0.12	0.01	9.1
Means of + diffs btw daily	424	113	-311	-73.3	0.58	0.60	0.02	3.4
Means of – diffs btw daily	421	104	-317	-75.3	0.51	0.59	0.08	15.7
*Based on the 75th percentile (3600 m^3/s) and 25th percentile (m^3/s), respectively, of the natural flow series at Cahora Bassa gorge.								

The mean values for key hydrological indicators describing temporal changes in Zambezi flow patterns at Mutarara between 1930-58 and 1976-04 are given in Table 5.11.

Table 5.11: Ecologically-sensitive indicators for the Zambezi River hydrological condition at Muturara, comparing parameters for the periods 1930-58 and 1976-04. The magnitude and percent of deviation are given for the means and coefficients of variation for each parameter

Indicator	1930-58 Mean	1976-04 Mean	Dev Mag	%	1930-58 CV	1976-04 CV	Dev Mag	%
Annual and monthly flow condition								
Mean annual runoff (m^3/s)	3293	2227	-1066	-32	0.44	0.65	0.21	48
Mean October runoff	736	1686	950	129	0.45	0.50	0.05	11
Mean November runoff	617	1991	1374	223	0.47	0.62	0.15	32
Mean December runoff	1440	2379	939	65	0.85	0.60	-0.25	-29
Mean January runoff	3886	2873	-1013	-26	0.58	0.49	-0.09	-16
Mean February runoff	6496	3335	-3161	-49	0.54	0.55	0.01	2
Mean March runoff	7436	2988	-4448	-60	0.49	0.87	0.38	78
Mean April runoff	5859	2378	-3481	-59	0.37	0.86	0.49	132
Mean May runoff	4509	1991	-2518	-56	0.27	0.80	0.53	196
Mean June runoff	3418	1919	-1499	-44	0.28	0.80	0.52	186
Mean July runoff	2372	1957	-415	-17	0.29	0.71	0.42	145
Mean August runoff	1623	1618	-5	0	0.32	0.43	0.11	34
Mean September runoff	1125	1608	483	43	0.38	0.44	0.06	16
Magnitude and timing of annual extreme daily flows								
Maximum annual 1-day flood flow (m^3/s)	11519	5957	-5562	-48	0.38	0.55	0.17	45
Minimum annual 1-day low flow (m^3/s)	501	775	274	55	0.41	0.45	0.04	10
Timing of maximum annual 1-day flood flow (date)	150	136	-14	-9	0.14	0.29	0.15	107
Timing of minimum annual 1-day low flow (date)	318	190	-128	-40	0.04	0.71	0.67	1675
Flood season river condition								
Timing of onset of flood flows* (Julian date)	114	90	-24	-21	0.17	0.43	0.26	153

Indicator	1930-58 Mean	1976-04 Mean	Dev Mag	%	1930-58 CV	1976-04 CV	Dev Mag	%
Duration of flood flows* (days)	93	27	-66	-71	0.43	1.55	1.12	260
Volume of flood flows* (km^3)	6595	1517	-5078	-77	0.82	2.87	2.05	250
Frequency of flood pulses* (events per year)	2.3	1.8	-0.5	-22	0.49	1.11	0.62	127
Dry season river condition								
Timing of onset of low flows* (date)	351	160	-191	-54	0.08	0.68	0.6	750
Duration of low flows* (days)	92	69	-23	-25	0.41	1.28	0.87	212
Minimum annual 7-day low flow (m^3/s)	516	988	472	91	0.41	0.36	-0.05	-12
Daily river fluctuations								
No. of rises	85	157	72	85	0.14	0.17	0.03	21
No. of falls	209	198	-11	-5	0.16	0.12	-0.04	-25
Means of + diffs btw daily	244	147	-97	-40	0.42	0.47	0.05	12
Means of – diffs btw daily	97	120	23	24	0.36	0.52	0.16	44
*Based on the 75th percentile (4500 m3/s) and 25th percentile (1100 m3/s), respectively, of the pre-dam flow series at Dona Ana (1930-1958)								

Other flows which can be considered in operating rules to maintain the downstream ecology are presented in Table 5.12.

Table 5.12: Flows for maintenance of downstream ecosystems functioning

Flow category	Ecosystem link
Dry-season low flows	Maintain flow characteristics for survival of aquatic species. Flow conditions can trigger emergence of some insect species
Wet-season low flows	Maintain wet bank vegetation and fast-flow habitat
Intra-annual flood 1	Trigger fish spawning in mid-dry season, flush out poor-quality water
Intra-annual flood 2	Trigger fish spawning in early dry season, flush out poor-quality water
Intra-annual flood 3	ort sediments by size, maintain physical heterogeneity, flush riffles, scour cobbles
Intra-annual flood 4	Sort sediments by size, maintain physical heterogeneity, flush tree seedlings from edge of active channel
1:2 yr flood	Maintain tree line on banks, scour out sediments in active channel
1:5 yr flood	Maintain lower part of tree/shrub vegetation zone on banks, deposit sediments in riparian zone
1:10 yr flood	Maintain channel, reset physical habitat, maintain middle part of tree/shrub zone
^{3}1:20 yr flood	Maintain channel, reset physical habitat, maintain top part of tree/shrub zone
KING, J.M. & BROWN, C.A. 2006. Environmental flows: striking the balance between development and resource protection. Ecology and Society 11(2): 26 (online).	

5.6.3 Recommended rules for the protection of the environment

The following considerations for operating rules to rehabilitate the downstream ecology are suggested:

- Restoring the difference between wet and dry season low flows as much as possible (i.e. wet season low flows should be higher than dry season low flows). Managing dam releases patterns to reflect natural wet and dry seasons for example high downstream flows in the wet season, and no floods in the dry season. Maintaining the seasonality of different magnitude flows for example preserving pattern of natural low flows within the dry season. Changing seasonality and magnitude of flows can leave aquatic animals and plants stranded; wash away vulnerable stages of fish and invertebrates, and leave banks and floodplains dry at times when they should be inundated. Productivity of the complete ecosystem will decline and some species may become locally extinct. The challenge is to identify and agree on significant ecosystems.

- Making a flood release as early as possible in the natural flood season, 'piggy-backed' on natural floods from tributaries or on pre-arranged releases from other dams to maximise their effects and to reduce the amount needed from any one dam. This would assist in flushing out the pollution, bilharzia snails, and mosquitoes and resets the river for wet season conditions. If too late, it starts up a process that is insufficiently fulfilled when the dry season starts. Providing specific flood releases (of size and timing to drive ecosystem health for example floods released from dams can be timed to augment each other thereby providing much needed (but naturally rare) larger floods. These are generally called prescribed floods.
- Releasing single long flood pulse as early as possible in the flood season on the main stem; on tributaries with flashy hydrographs single floods should be released in their entirety and others captured in their entirety, with one of the first floods of the flood season released.
- Recognising/forecasting dry and wet years (or dry and wet cycles of years), and amending operating rules accordingly so that the river, as well as people, go through years of drought and wet years. There should not be one set of rules for all years as there will be more flow in wet than in dry cycles/years as demonstrated by the flow categories in section 5.6.2.
- Varying releases at a daily, or at least weekly, level, linked to the flow pattern of an un-impacted headwater reach and in accordance with the wet/dry year arrangement. The rate of change of releases should be no greater than the natural rate of change in flow in that river. Hydro-electric power dams should not create unnatural surges of water or unnatural de-watering of the downstream river.
- Using outflow gates at different levels to mix and match water quality and temperature of released water, in order to approximate that of inflowing water as much as possible.
- Monitoring should focus on whether or not the agreed pattern of flows is being released and achieving the predicted river condition. Such monitoring could be funded from the dam sales of water or HEP, and should include a facility of adaptive management respond to monitoring results.
- Allowing for release of sediments from new dams on unregulated tributaries.
- Providing for movement of plants and animals along the river system with new dams.

5.6.4 Operating rule scenarios to incorporate other uses such as agriculture

The review of impact of historical floods on other uses discussed in this chapter is summarized in Table 5.13:

"New" concepts of operating rule scenarios can be developed that consider the requirements of other users. However the most serious risk to flooding is the lack of appreciation that floods have not disappeared with the construction of the major dams.

Table 5.13: Summary of impacts of historical floods on other water uses

Flow situation	Location	Impacts on other water uses/users	Comments from a dam operation point of view
Reduction of flood peaks	Zambezi Delta	Negative impacts on availability of sediments for small-scale agriculture, coastal fisheries, freshwater fisheries and livestock	Estimates of flood peaks for sediment transport and

Flow situation	Location	Impacts on other water uses/users	Comments from a dam operation point of view
			deposition are required.
Drying of flood plains	Middle and Lower Zambezi	Silt-free waters from reservoirs deepen the river bed and prevent flood waters from breaking banks and feeding much needed water on the flood plain. Previously remote, wet and harsh landscape becomes accessible leading to uncontrolled hunting and poaching and a subsequent reduction in population of wildlife. Drier flood plains have reduced the amount of diverse herbaceous wetland species and allow for woody savanna invasion. Remaining herbivores cannot control plant growth.	Implementation of releases to simulate uncontrolled river flow to restore the conditions for ecosystems in the flood plain. Bigger floods to meet flow requirements for wetlands and flood plains.
Reduction in nutrient rich sediment load coupled with reduces flood peaks	Zambezi Delta	Salt water intrusion from the ocean has increased decreasing the delta's productivity (e.g. prawn catches down 60%), size (40% reduction in mangroves areas) and health. Adult prawns lay their eggs at sea. These develop into larvae which in the dry season, when the river flow is weak they are pushed by the stronger ocean tides into the mangroves and other fresh water areas of the delta. With higher levels of nutrients than in the marine habitat, this environment supports strong growth to adult prawns. During the flood season the stronger river flow pushes the adult prawns into the sea where they lay eggs and restart the cycle.	The cycle requires fertile and natural mangroves. River flow should be maintained close to natural. Highest prawn catches in the last 20 years were recorded in the 2000 and 2001 floods. Maintain supply of nutrient-rich sediment from the Luia River, the Shire River and the Cheringoma Plateau.
		Reduction in papyrus wood used in local construction due to continued reduction in nutrients in the delta waters.	
Unpredictable flood regime	Lower Zambezi	The lower summer flow and lack of routine flooding has promoted permanent settlement in riverbanks, consolidated sandbars, and floodplain areas that were formerly only seasonally occupied. As a result of this the fatalities of the 2000 – 2001 floods were quite severe.	Raise public awareness and improve education on occurrence, flood risks and mitigation.
		Agriculture and food security – Cahora Bassa dry season releases provide for hydroelectric power irrigation of sugarcane and river transport (large ferry boats). Often these releases affect dry season flood plain agriculture from the dry season by taking place two to three weeks before the harvest is due.	Consider local livelihood practices in managing dam releases.

The negative impacts could be mitigated by operating existing dams considering the following "new" scenarios:

(a) Adjusting flood release patterns to accommodating the harvest period for floodplain agriculture

(b) Adjusting flood release pattern to maintain floodplain

(c) Providing specific flood releases (of size and timing to drive ecosystem health for example floods released from dams can be timed to augment each other thereby providing much needed (but naturally rare) larger floods. These are generally called prescribed floods. These floods are required for management of salt intrusion.

(d) Provide adequate flow for navigation

(e) Provide adequate water for plantation irrigation

5.6.5 Operating objectives to inform synchronization of dam management in the Zambezi River system

The operation of existing dams on the Zambezi River System places high priority on dam safety and provision of water for hydropower generation. This study has shown the need to incorporate flood protection, environmental requirements and other use which contribute to improvement of socio-economic conditions. However each of these other water uses has different links to the water resource system which need to be kept in balance through a multi-objective procedure. This would provide an answer on how dam management can incorporate the other uses. The dam safety and hydropower objectives are currently dominant. Table 5.14 includes six new objectives identified on this study. Synchronisation allows objectives for a river reach to be set to support the objectives for another river reach. Monitoring and review are prerequisites for ensuring that the whole system is kept in balance.

Table 5.14: Water resource system operating requirements

Objective	Description
Objective 1	Dam Safety: Manage releases to avoid the reservoir reaching unsafe levels. Provide adequate capacity to safely storing and pass the design flood.
Objective 2	Hydropower: Provide adequate head and firm yield for electricity generation. Failure of Hydropower has severe socio-economic consequences beyond the Zambezi basin riparians.
Objective 3	Flood management: Avoid loss of life and reduce socio-economic impacts.
Objective 4	Environmental management: Maintain flow characteristics. Provide quantity and quality of water required to maintain ecosystems and enable them to provide sustainable services and good quality water
Objective 5	Dry season floodplain agriculture: Accommodate harvest period in release management
Objective 6	Plantation irrigation: Provide adequate yield for crop production
Objective 7	Navigation: Provide adequate flow for large ferry boats
Objective 8	Other water users: These can also have their own sets of priorities according social considerations such as elimination of poverty and economic benefits.

Objectives as listed in table 5.14 allow stakeholders to take a holistic approach to the debate on operational rules and to understand how decisions are made during floods and droughts.

5.7 Consideration of multi-year operating rules

The existing and historical operating rules presented in section 5.2.1 of this report consider a one year window. This makes it difficult to review and communicate possible risks for the forthcoming season or that of past ones. Section 3.3 of this report identified duration of annual flow cycles identified from existing literature

.

The ranked historical annual flows at Victoria Falls were divided into quarters (“very wet”, “wet”, “dry” and “very dry”) and re-ordered sequentially. Consecutive years from any quartile which do not exceed a period of 2 years where discarded except for the period 1974/75 to 1978/79, a “very wet period” which was broken by one “wet” season and the 1992/93 a “dry” season which was between “very dry” periods . This was considered relevant from a dam operation point of view. The results in Table 5.15 show that the longest period where years from one quartile are consecutive is 5years. These years come from the “very dry quartile”. Consecutive years in the “very wet quartile” occupy a maximum period of 3years. Operating rules which consider a period of 5 years can provide good illustrative examples for both “very wet”, “wet”, “dry” and “very dry” periods. However in actual practice it may be prudent to consider periods of say 10 to 20 years can cover combinations of periods “wetness” or “dryness” which may be necessary to inform the different modes of operation. These findings are corroborated by section 3.6 of this report which identifies 1960-1980 as a wet period and 1990 to 1966 as a critical dry period which approximates a 1:100 year drought.

Table 5.15: Assessment of quartiles for consecutive wet and dry year (Period 1907 to 2001)

Year	Rank	%Exceedence	Count (Years)	Description of Quartile
1955/56	7	8.0%	1	Very Wet
1956/57	15	17.2%	2	
1957/58	1	1.1%	3	
1960/61	18	20.7%	4	
1961/62	8	9.2%	1	Very Wet
1962/63	3	3.4%	2	
1967/68	6	6.9%	3	
1968/69	2	2.3%	4	
1969/70	13	14.9%	1	Very Wet
1974/75	11	12.6%	2	
1975/76	14	16.1%	3	
1976/77	34	39.1%	1	Wet
1977/78	4	4.6%	1	Very Wet
1978/79	16	18.4%	2	
1981/82	76	87.4%	1	Very Dry
1982/83	75	86.2%	2	
1983/84	72	82.8%	3	
1984/85	68	78.2%	4	
1985/86	67	77.0%	5	
1989/90	82	94.3%	1	Very Dry
1990/91	66	75.9%	2	
1991/92	83	95.4%	3	
1992/93	57	65.5%	1	Dry
1993/94	80	92.0%	1	Very Dry
1994/95	85	97.7%	2	
1995/96	86	98.9%	3	
1996/97	81	93.1%	4	

The inflows into the major lakes on the Zambezi vary significantly from season to season. Figure 5.17 shows that for Lake Kariba the highest inflow variability occurs during the period February to May. **This highlights the complexity of operating large dams on the Zambezi river system.**

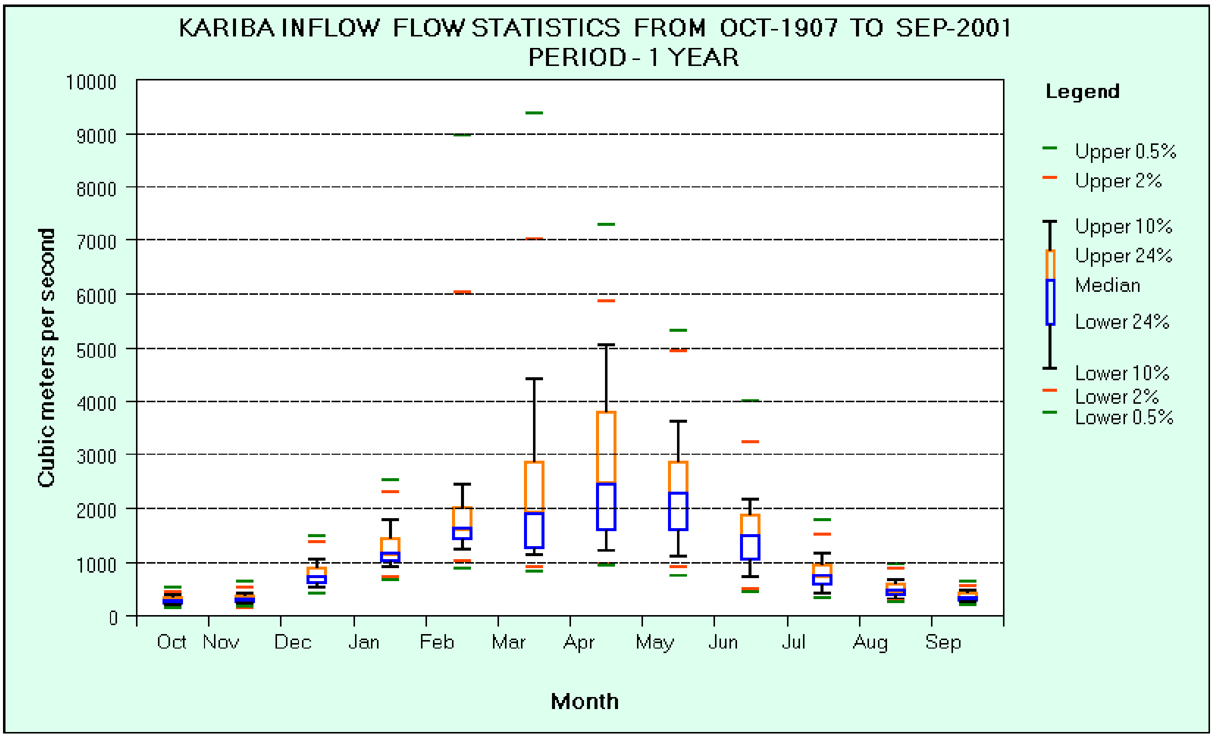


Figure 5.17: Lake Kariba - variation in inflows

The findings from this section, Section 5.7, contribute to the recommendations detailed in Recommendation Sheet 2.3.

5.8 Testing "new" modes of dam operations including prescribed floods

The proposed operating modes are tested for hydrologically significant periods in the history of dam operation on the Zambezi River system. The most informative high flood and dry periods in history (1907 to 2001) which takes into consideration the situation of the Zambezi Delta are selected for this exercise. Inflows were selected inflows based on the exceedence levels which best represent the required wet and dry periods. The following modes of operation were tested:

(a) Mode 1: Wet period: One year operating rule considering dam safety, hydropower and flood management objectives
(b) Mode 2: Wet period: One year operating rule considering dam safety, hydropower, flood and environmental management objectives
(c) Mode 3: Wet period: Multi-year operating rule considering dam safety, hydropower and flood management objectives
(d) Mode 4: Wet period: Multi-year operating rule considering dam safety, hydropower, flood and environmental management objectives
(e) Mode 5: Dry period: Multi-year operating rule considering 50% curtailment of hydropower production
(f) Mode 6: Dry period: Multi-year operating rule considering stepped curtailment (60% then 50%) of hydropower production

The five year "dry" and "wet" periods were also superimposed on the Kafue sub-system and the system behavior was captured in this report.

The analysis and results are presented in the following sections.

5.8.1 One year operating rule considering dam safety, hydropower, flood management and environmental release objectives

The history of floods on the Zambezi reviewed on this study shows that the flooding which occurred in 1968/69, 1974/75 and 1977/78 could be related to releases from Kariba dam. The hydrographs for these seasons are shown in Figure 5.18 against the long term statistics of inflows into the lake. The climate change scenarios generated in Chapter 3 of this report for the Lake Kariba and Cahora Bassa Dam for the period 2030-2050 suggest the application of a "wet" (+1 degree Celsius, +15% change in rainfall) for the wet periods as worst case for floods to accommodate peaks in annual inflow higher than the historical maximum in the period 1956-1997. The estimated mean inflow with climate change is higher than the inflow for the 10% wettest year. The 1968/69 inflow corresponds to 2% exceedence flow for the period 1901 to 2001 and is thus appropriate for consideration on this study. The 1968/69 season was also the wettest in the history of the operation of Kariba dam. It was selected to test of the impact of incorporating the dam safety, hydropower, flood management and environmental management objectives over a one year operating window.

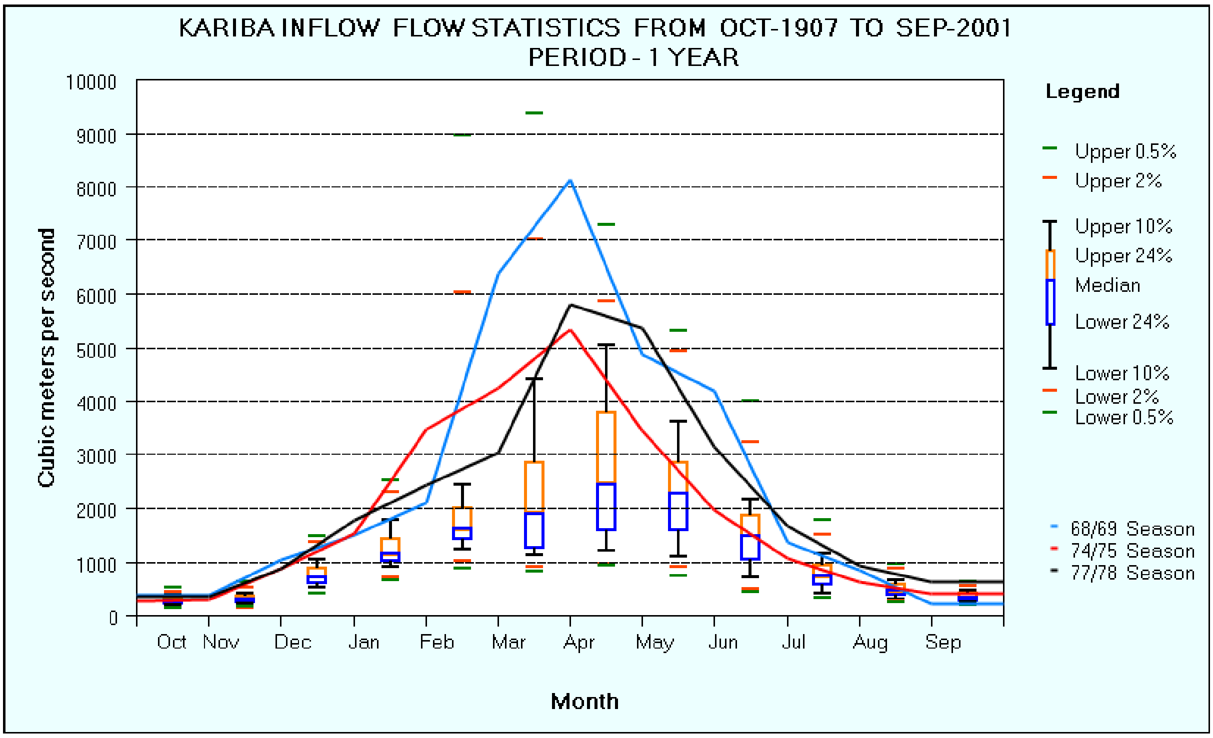


Figure 5.18: Lake Kariba - variation in inflows in selected wet seasons

For 1968/69 outflow from Kariba Dam increased from around 400 m^3/s at the start of the season to slightly over 1000 m^3/s at the beginning of January 1969 as shown in Figure 5.18. It then increased rapidly to about 6400 m^3/s at the start of March rising again to about 8000 m^3/s at the beginning of April after which the falling limb commenced. The graphs suggest that most of the inflow was retained in storage until the levels were very close to the dam safety rule. The increase in releases could not avoid violation of the rule. The experience shows the following:

(i) The dam safety rule was violated from around mid February to April.

(ii) The outflow hydrograph was suggests an emergency situation from mid February to beginning of April.
(iii) The head available for hydropower was kept quite high throughout the season.

Four objectives were tested as follows:

Objective 1	Dam Safety: Manage releases to avoid the reservoir reaching unsafe levels. Provide adequate capacity to safely storing and pass the design flood.
Objective 2	Hydropower: Provide adequate head and firm yield for electricity generation. Failure of Hydropower has severe socio-economic consequences beyond the Zambezi basin riparians.
Objective 3	Flood management: Attenuate floods to avoid loss of life and reduce socio-economic impacts.
Objective 4	Environmental management: Maintain flow characteristics. Provide quantity and quality of water required to maintain ecosystems and enable them to provide sustainable services and good quality water

To accommodate the dam safety, flood management and hydropower objectives the outflow rising limb was started at beginning of November crossing inflow rising limb in mid February.

The objective function for hydropower to maximize the available head for power production was implemented. The resultant hydrograph is shown in Figure 5.19.

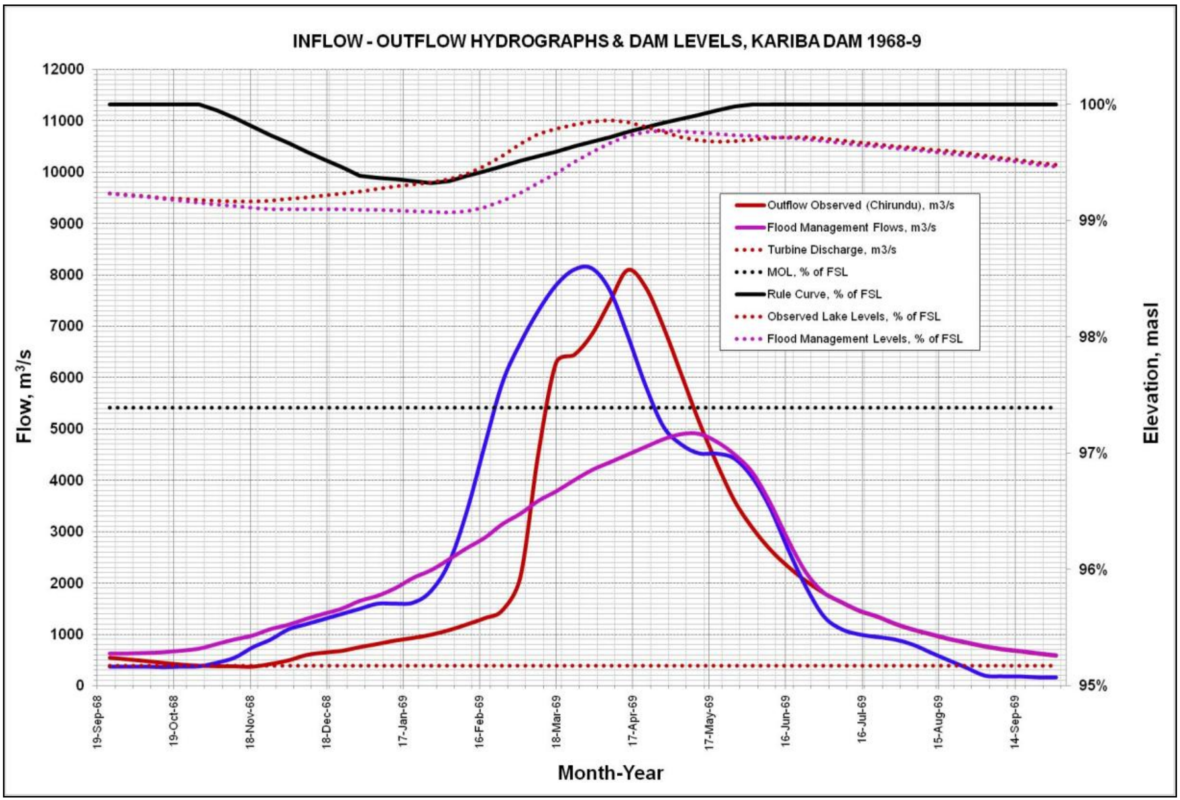


Figure 5.19: Mode 1 - Lake Kariba - Addressing flood management objectives with a 1year wet period and 2% exceedence inflow

The simulations with the 2% exceedence inflow achieved the following results with this new mode of operation:

(i) Violations of the dam safety rule are eliminated. This is a positive outcome for dam safety.

(ii) An additional four weeks is added to the lag on peak outflow. This provides additional early warning time for downstream dams and stakeholders
(iii) Although the peak is reduced, releases are over a longer period.
(iv) The outflow to meet the average hydro power is satisfied throughout
(v) The peak outflow is reduced by about 36% below the historical experience.
(vi) It is estimated that the power outputs was reduced by about 5% compared to the simulated historical operations mainly because of reduction in head.

To accommodate the environmental objective the outflow rising limb starts beginning of November and crosses with inflow rising limb also starts in mid February but peaks in mid March and tries to follow the same pattern as the inflow hydrograph. The resultant hydrograph is shown in Figure 5.20.

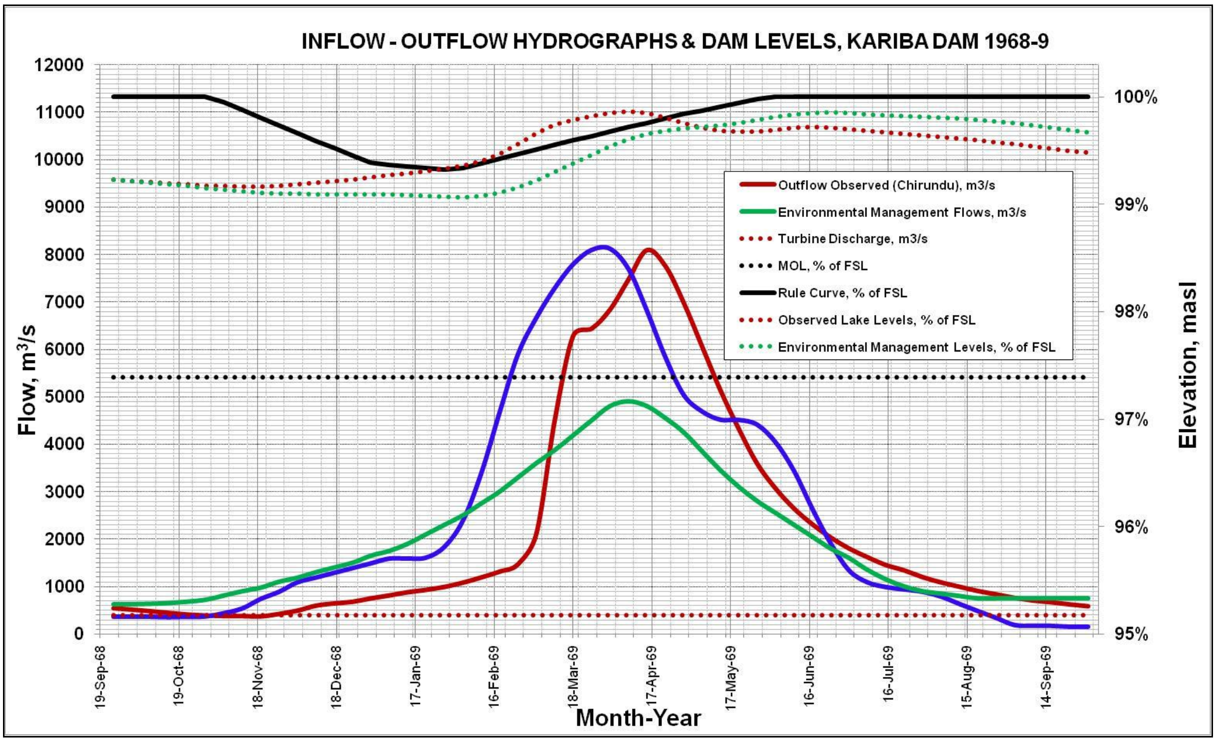


Figure 5.20: Mode 2 - Lake Kariba - Addressing environmental management objectives with a 1year wet period and 2% exceedence inflow

The simulations with the 2% exceedence inflow achieved the following results with this new mode of operation:

(i) Violations of the dam safety rule are eliminated. This is a positive outcome for dam safety.
(ii) About two weeks of lag on peak outflow is lost. An advanced communication system floods is required to warn downstream dams and stakeholders
(iii) Although the peak is reduced, releases are over a longer period.
(iv) The outflow to meet the average hydro power is satisfied throughout
(v) The peak outflow was reduced by about 36% of the historical experience.
(vi) It is estimated that the power outputs was reduced by about 2% compared to the simulated historical operations mainly because of reduction in head.

5.8.2 Wet period: multi-year operating rule and multiple objectives – Kariba

Climate change scenarios generated in Chapter 3 of this report for the Lake Kariba and Cahora Bassa Dam for the period 2030-2050 suggest a "wet" (+1 degree Celsius, +15% change in rainfall) for the wet periods as worst case for floods. Peaks in annual inflow have to be accommodated, whereby the 10% wettest year gives a far higher inflow than is the historical maximum in the period 1956-1997. The mean was higher than the 10% wettest year. The period 1961 to 1969 had very high inflows of 2% to 9% exceedence but in terms of reservoir operation the inflow variability in the period 1974 to 1979 as shown by the "wet" year in between "very wet" years presents more challenges for dam operations (range of inflows of 5% to 39% exceedence). This period was selected for the analysis conducted on this study. Figure 5.21 shows the inflow during this period superimposed on the long term statistics of inflow.

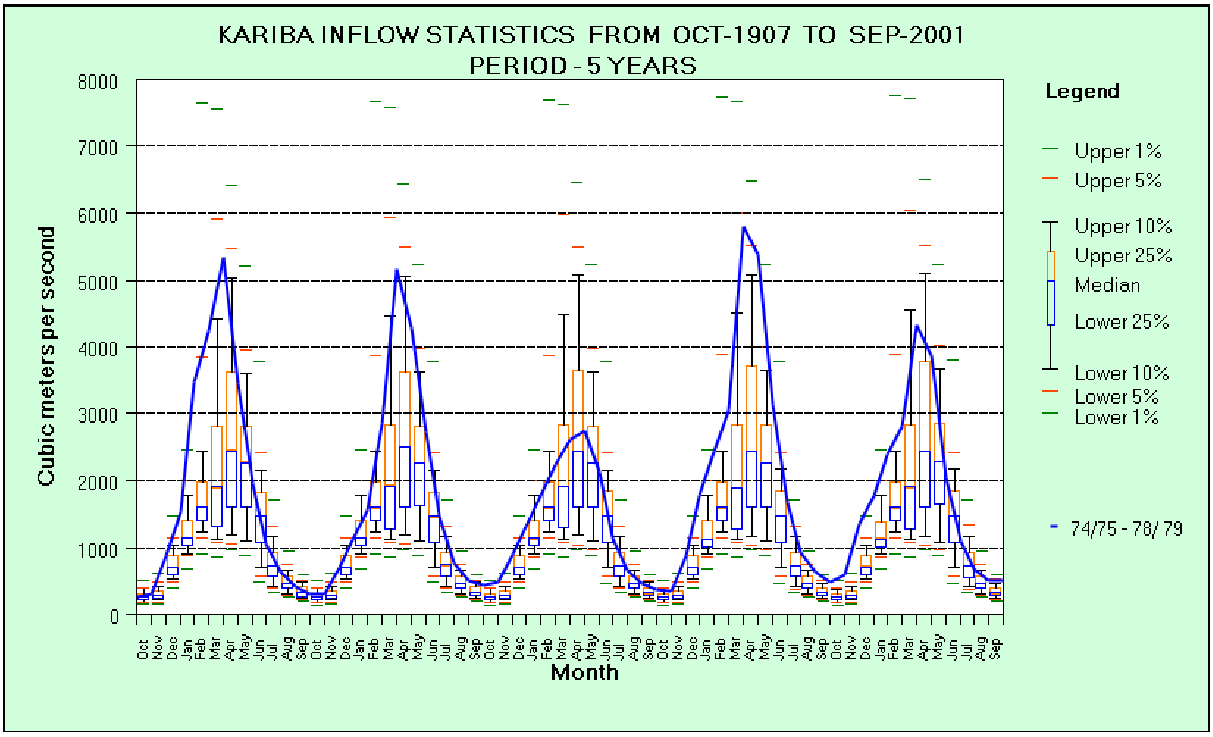


Figure 5.21: Lake Kariba - Selected 5-year "very wet" period with 13%, 16%, 39%, 5% and 18% exceedence inflows

(a) Consideration of dam safety, hydropower and flood management objectives

The following three objectives were tested here:

Objective 1	Dam Safety: Manage releases to avoid the reservoir reaching unsafe levels. Provide adequate capacity to safely storing and pass the design flood.
Objective 2	Hydropower: Provide adequate head and firm yield for electricity generation. Failure of Hydropower has severe socio-economic consequences beyond the Zambezi basin riparians.
Objective 3	Flood management: Attenuate floods to avoid loss of life and reduce socio-economic impacts.

The historical storage levels for Kariba derived from largely simulated inflow data for this period are shown in Figure 5.22: An attempt was made to obtain the levels to match the experience of flooding as much as possible. Flood management safety objectives were simulated by reducing the peak flood and delaying releases while keeping dam levels below the dam safety operating rules of the dam safety objectives. Hydropower objectives were satisfied by keeping the water levels as high as possible without violating the dam safety operating rule. This is the third mode of dam operation tested here. The resultant outflows and dam levels are shown in the same diagram. These simulations achieved the following results with this new mode of operation which considers a 5year wet period with 13%, 16%, 39%, 5% and 18% exceedence inflows:

(i) Violations of the dam safety rule are eliminated. This is a positive outcome for dam safety.
(ii) An additional two weeks is added to the lag on peak outflow. This will provide additional early warning time for downstream dams and stakeholders
(iii) Although the peak is reduced, releases are over a longer period.
(iv) The inflow and outflow hydrographs can cross in December and June of each year with further refinement.
(v) The outflow to meet the average hydro power is satisfied throughout
(vi) It is estimated that the power outputs reduced by about 5% compared to the simulated historical operations mainly because of reduction in head.

Additional turbines at Kariba could be used to minimize this loss of power. However, to maintain the shape of the outflow hydrograph these new turbines can only be operated when the discharge required is above the current turbine requirement. This means that they cannot be operated continuously but rather for peaking power supply or for feeding power into the SAPP. New hydro power plants such as Batoka will reduce pressure on Kariba to operate at maximum head thus reducing the risks on the safety of the dam.

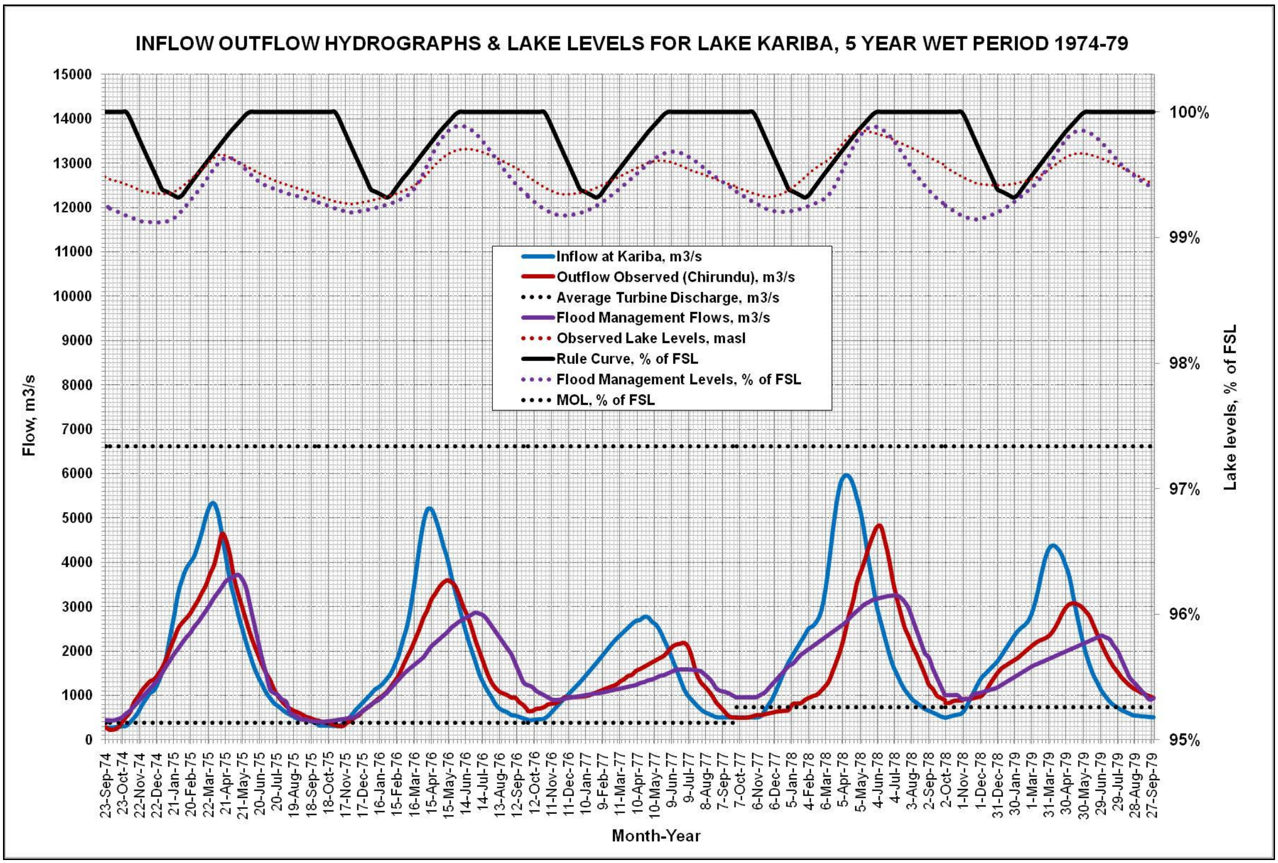


Figure 5.22: Mode 3 - Kariba Dam - Selected 5-year" very wet" period with 13%, 16%, 39%, 5% and 18% exceedence inflows, dam safety and flood management objectives

(b) Consideration of dam safety, hydropower, flood management and environmental management objectives

The following four objectives were tested here:

Objective 1	Dam Safety: Manage releases to avoid the reservoir reaching unsafe levels. Provide adequate capacity to safely storing and pass the design flood.
Objective 2	Hydropower: Provide adequate head and firm yield for electricity generation. Failure of Hydropower has severe socio-economic consequences beyond the Zambezi basin riparians.
Objective 3	Flood management: Attenuate floods to avoid loss of life and reduce socio-economic impacts.
Objective 4	Environmental management: Maintain flow characteristics. Provide quantity and quality of water required to maintain ecosystems and enable them to provide sustainable services and good quality water

The same historical simulations considered in (a) were used to evaluate the impact of introducing environmental management objectives while meeting the dam safety and hydropower objectives. The resultant outflows and dam levels are shown in Figure 5.23. These simulations show that the following is achieved with this new mode of operation which considers a 5year wet period with 13%, 16%, 39%, 5% and 18% exceedence inflows:

(i) Violations of the dam safety rule are eliminated.
(ii) The peaks occur a week to two weeks earlier than the simulated historical flow. An advanced communication system is required to warn downstream dams and stakeholders about impending floods.
(iii) The flood peaks are very close to or equal to historical simulations and releases are over a longer period
(iv) With further refinement the inflow and outflow hydrographs will cross only when inflow is not enough to satisfy there the hydro power requirement.
(v) With further refinement the inflow hydrograph can retain the properties of the inflow hydrograph which further addresses the requirement for environmental releases of prescribed floods.
(vi) The outflow to meet the average hydro power is satisfied throughout
(vii) It is estimated that the power outputs reduced by about 6% compared to the simulated historical operations mainly because of reduction in head.

Additional turbines at Kariba could be used to minimize this loss of power. However, to maintain the shape of the outflow hydrograph these new turbines can only be operated when the discharge required is above the current turbine requirement. This means that they cannot be operated continuously but rather for peaking power supply or for feeding power into the SAPP. New hydro power plants such as Batoka will reduce pressure on Kariba to operate at maximum head thus reducing the risks on the safety of the dam.

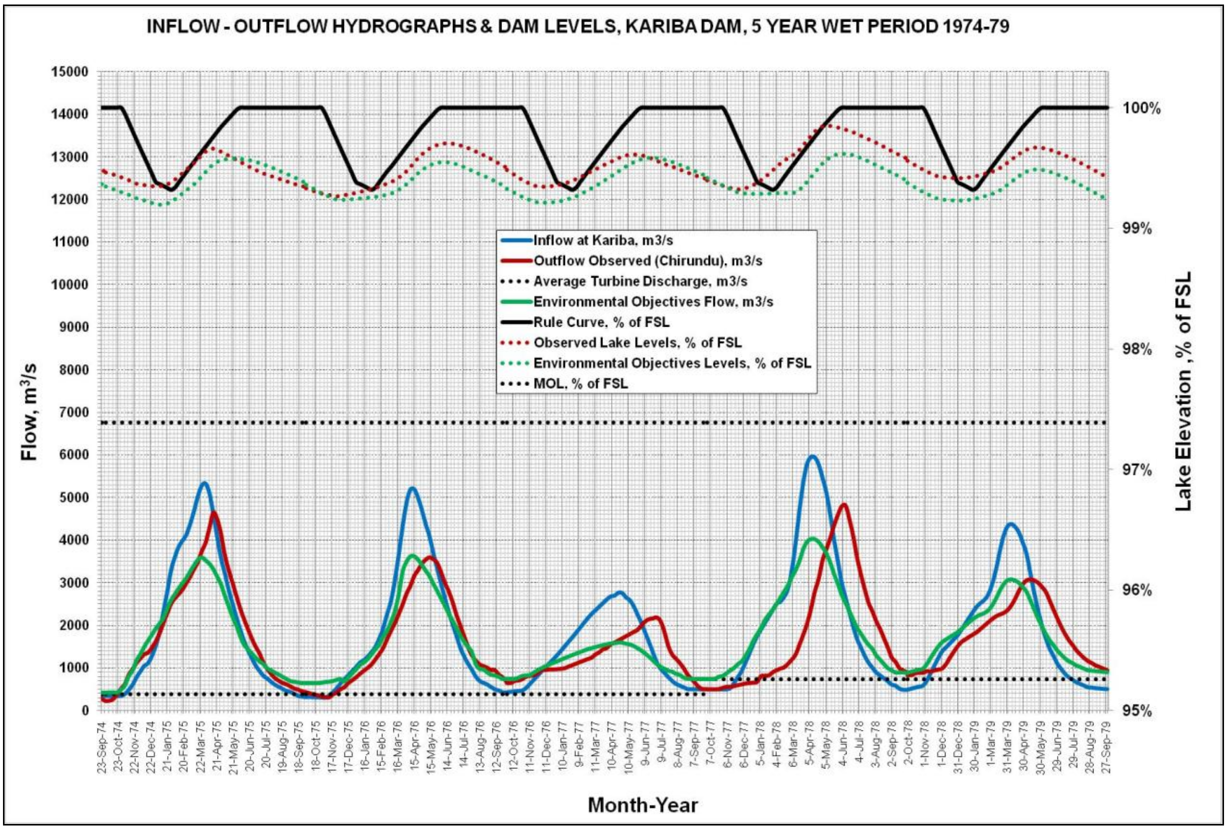


Figure 5.23: Mode 4 - Kariba Dam - Selected 5-year "very wet" period with 13%, 16%, 39%, 5% and 18% exceedence inflows, dam safety, flood and environmental management objectives

5.8.3 Dry period: multi-year operating rule and multiple objectives – Kariba

A prolonged low inflow period was experienced during the period 1981 to 1985 as shown in Table 5.13 but the period 1993 to 1996 had much lower inflows. This period was extended back to 1992/93 season and considered in this analysis. Climate change scenarios generated in Chapter 3 of this report for the Lake Kariba and Cahora Bassa Dam for the period 2030-2050 suggest a "dry" (+2 degrees Celsius, + 0% change in rainfall) scenario for dry periods for dam operations as the worst case for droughts. On this scenario the mean annual inflow available for storage increase, turbines or spilling is less than was available historically 10% driest years for the simulated period 1956-1997. Thus selection of period 1993 to 1996 which had much lower inflows of 92% to 99% exceedence is appropriate for this study. Figure 5.24 shows the inflow during this period superimposed on the long term statistics of inflow.

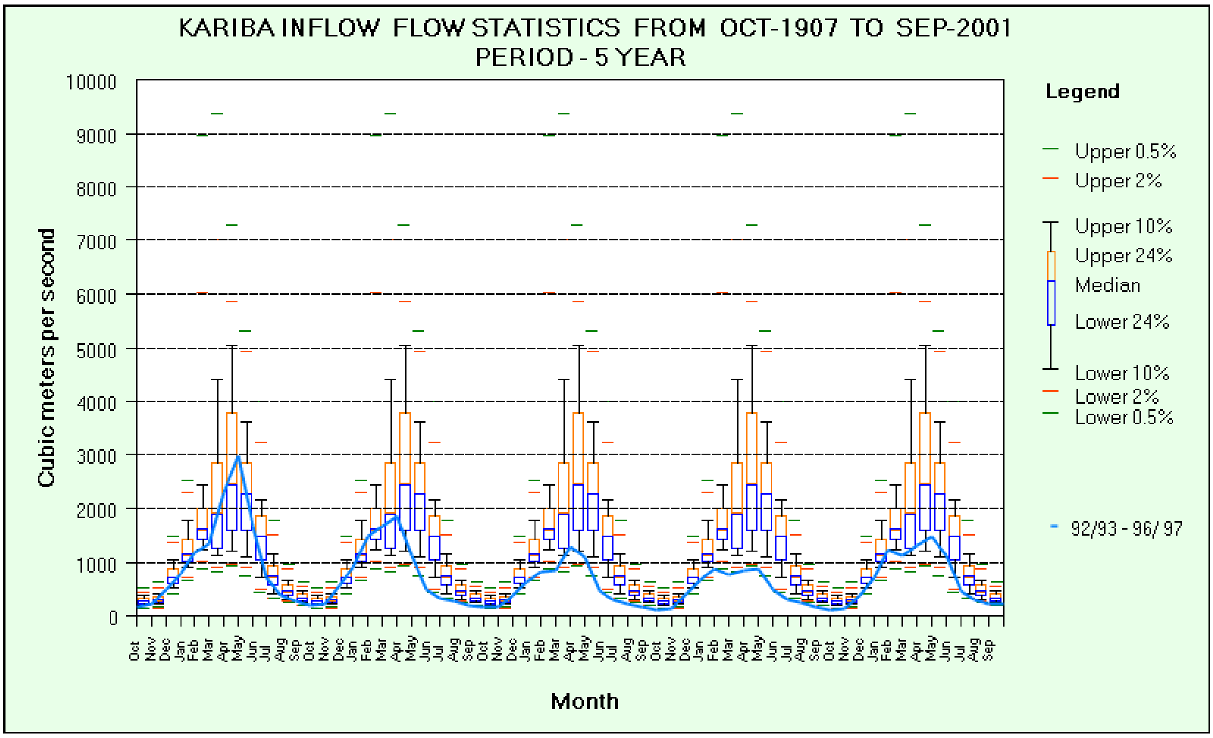


Figure 5.24: Kariba Dam -Selected 5-year "very dry" period with 66%, 92%, 98%,99% and 93% exceedence inflows

The following three objectives were considered:

Objective 1	Dam Safety: Manage releases to avoid the reservoir reaching unsafe levels. Provide adequate capacity to safely storing and pass the design flood.
Objective 2	Hydropower: Provide adequate head and firm yield for electricity generation. Failure of Hydropower has severe socio-economic consequences beyond the Zambezi basin riparians.
Objective 4	Environmental management: Maintain flow characteristics. Provide quantity and quality of water required to maintain ecosystems and enable them to provide sustainable services and good quality water

The low lake levels were not a threat to the dam safety operating rule and the levels were below the flood gates therefore these were not operational. The historical storage levels for Kariba derived from largely simulated inflow data for this period are shown in Figures 5.25 and 5.26.: An attempt was made to obtain the levels to match the experience on available head for power production as much as possible. Hydropower objectives were satisfied by keeping the water levels above the minimum level for hydropower production. This was a very dry season and power production almost stopped in 1997 when lake levels were too close to this level. Two tests were conducted one to meet 50% of the turbine flow requirement from the second season and the other 60% in the second season and 50% thereafter.

The resultant outflows and dam levels are shown Figures 5.25 and 5.26. Simulations achieved the following results with this new mode of operation:

(i) Dam levels are well above the minimum level for hydro power generation in both scenarios but supplying 50% of hydro power requirement from the second year achieves the highest lake levels

(ii) The low flow periods for the resultant outflow hydrographs have higher flows than the observed because of the need to satisfy there the hydro power requirement for each scenario.

(iii) The properties of the inflow hydrograph may be very difficult to retain with both scenarios

(iv) The outflow peaks lower than the historical simulations

(v) It is estimated that the power outputs for the 50% scenario was increased by about 42% compared to the simulated historical operations mainly because of the increased head and regulation of turbine releases.

(vi) It is estimated that the power outputs for the 60%-50% scenario was increased by about 36% compared to the simulated historical operations mainly because of the increased head and regulation turbine releases.

Curtailment of power production at Kariba avoids complete failure of hydro power operations. During these periods support from SAPP is essential.

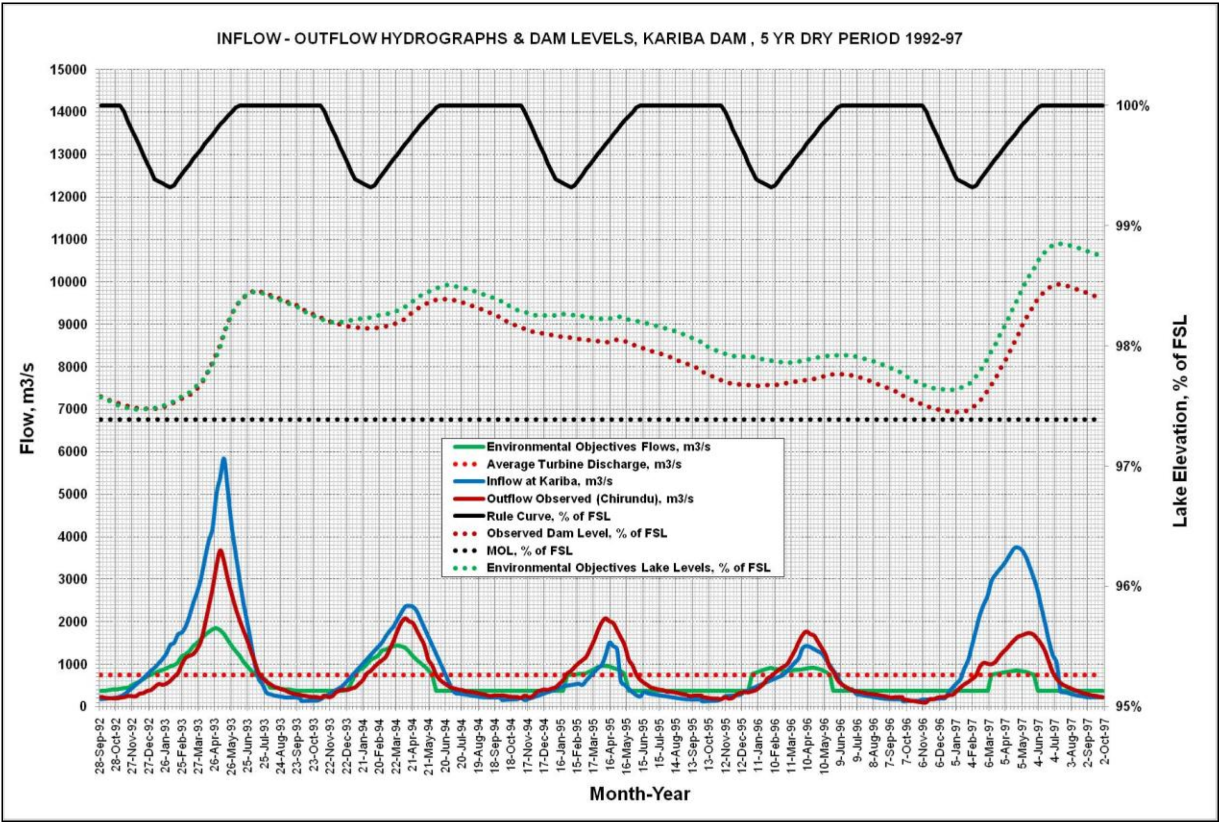


Figure 5.25: Mode 5 - Kariba Dam - Selected 5-year "very dry" period with 66%, 92%, 98%,99% and 93% exceedence inflows and hydropower objectives (50% supply from 2nd year)

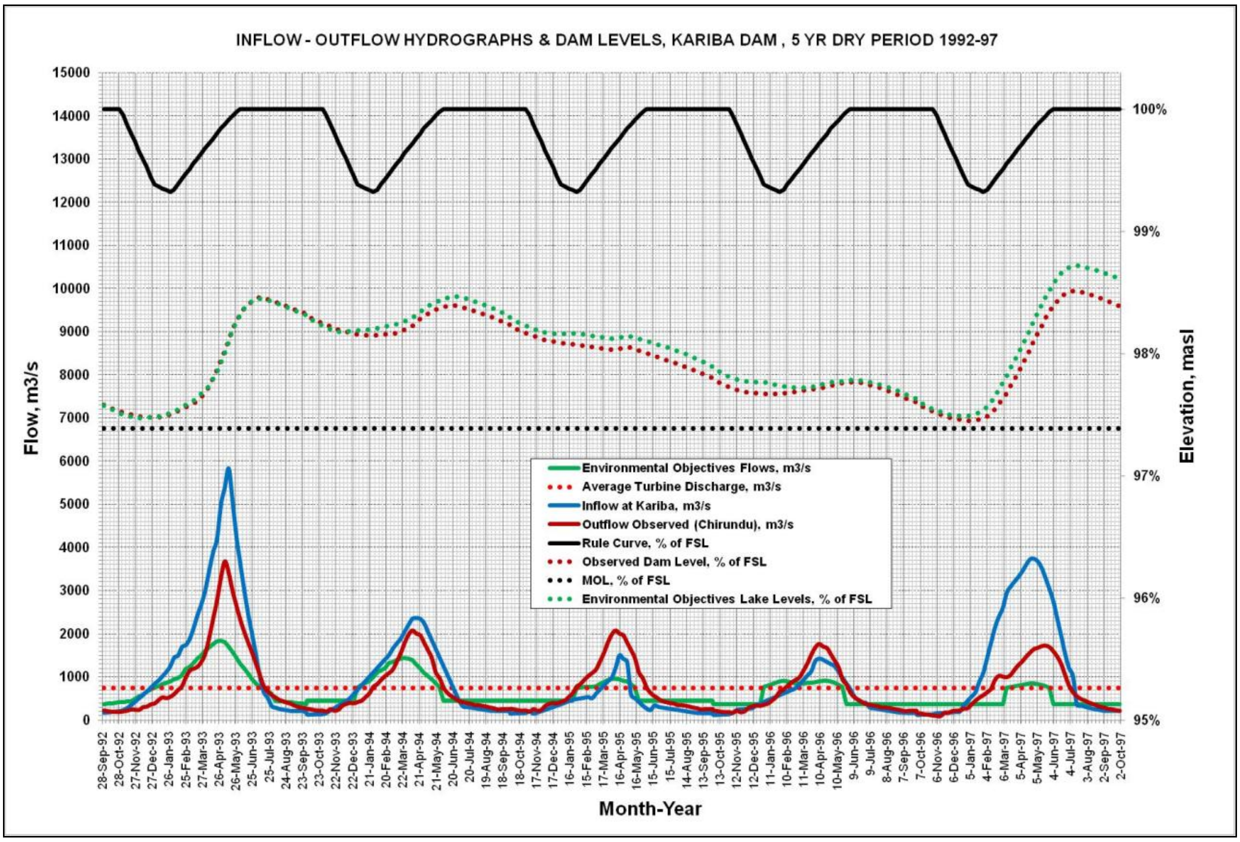


Figure 5.26: Mode 6 - Kariba Dam - Selected 5-year "very dry" period with 66%, 92%, 98%,99% and 93% exceedence inflows and hydropower objectives (60% supply from 2nd year and 50% from 3rd year)

5.8.4 Wet period: multi-year operating rule and multiple objectives – Kafue System

The Itezhi -tezhi and Kafue are operated conjunctively. Historical data shows that the most informative flood period was from 1977 to 1982. The following can be deduced from the historical operations of Itezhi-tezhi and Kafue Gorge during this wet period as shown in Figure 5.27 and 5.28.

(i) Itezhi -tezhi is operated above the rule curve but there is no distinct seasonal pattern for minimum levels for Kafue Gorge.

(ii) the operating levels for Kafue Gorge are generally above 595m

(iii) the operating levels for Kafue Gorge are generally within the lower and upper bounds of the operating rule(between 975.4m and 976.6m)

(iv) Kafue Gorge spillway discharges are between January and August each year with peaks in the range of 700 m^3/sec to 1300m^3/sec. The graph suggests a stepped hydrograph. High discharges were experienced in 1978 (1300 m^3/sec) and 1981 (1000 m^3/sec)

(v) Kafue Gorge turbine releases for power productions varied between 22 m^3/sec to 262 m^3/sec and were not impacted on by available storage

Figure 5.27 shows that the pattern of the outflow from Itezhi Tezhi generally meets the environmental objectives.

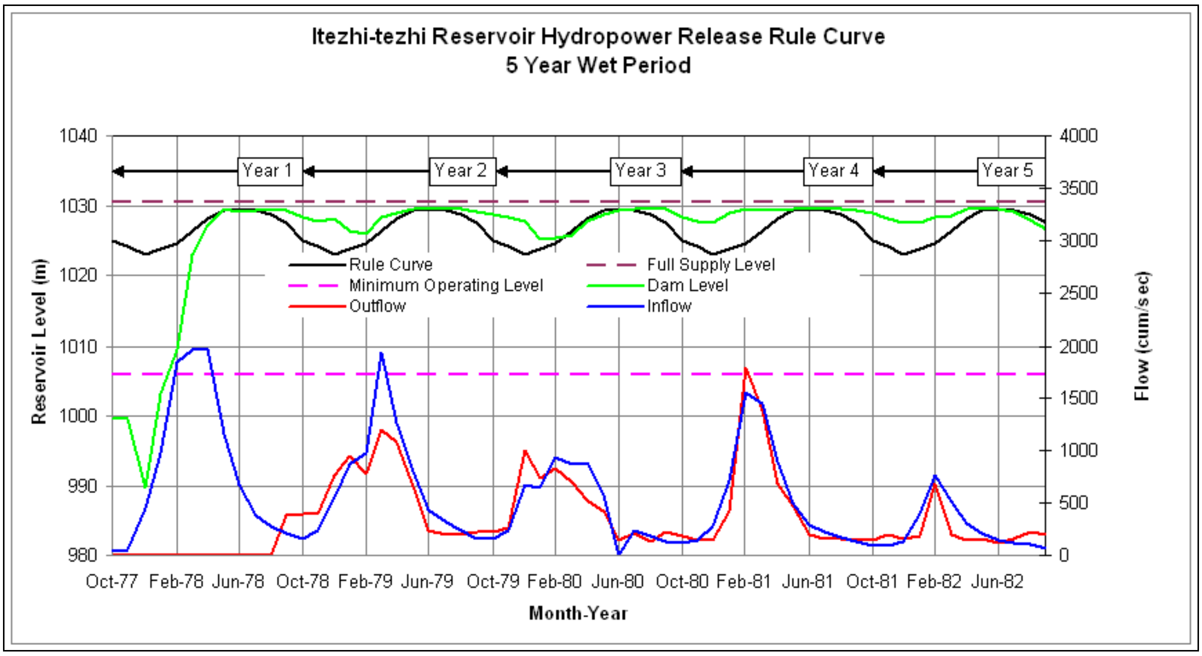


Figure 5.27: Itezhi-tezhi - 5-year wet season historical operations

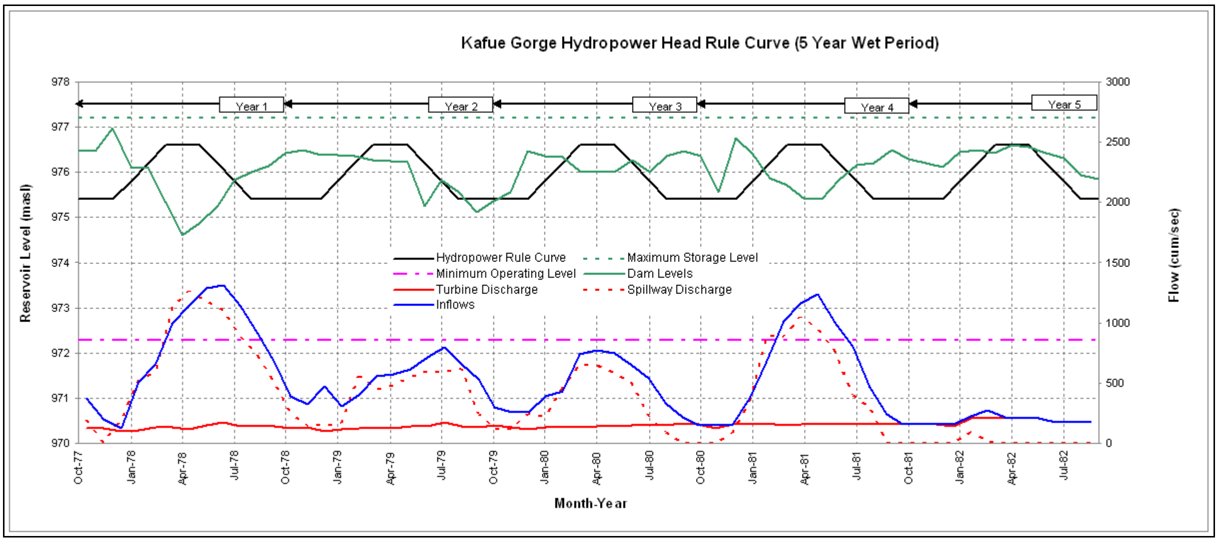


Figure 5.28: Kafue Forge - 5-year wet season historical operations

Figure 5.28 shows that the pattern of the outflow from Kafue Gorge can be adjusted to meet the environmental objectives without a significant loss of power as both the historical head and outflow can be maintained. However increase in releases would reduce the available head.

5.8.5 Dry period: multi-year operating rule and multiple objectives – Kafue System

Historical data shows that the most informative flood period was from 1977 to 1982. Figure 5.29 shows that Itezhi-tezhi retained a significant proportion of its inflow while Figure 5.30 shows that Kafue Gorge passed on most of the inflow. The discharge from Kafue Gorge in high 1989/90 could have been in anticipation of high inflows. The water levels in both dams dropped significantly below the operating rule for hydropower.

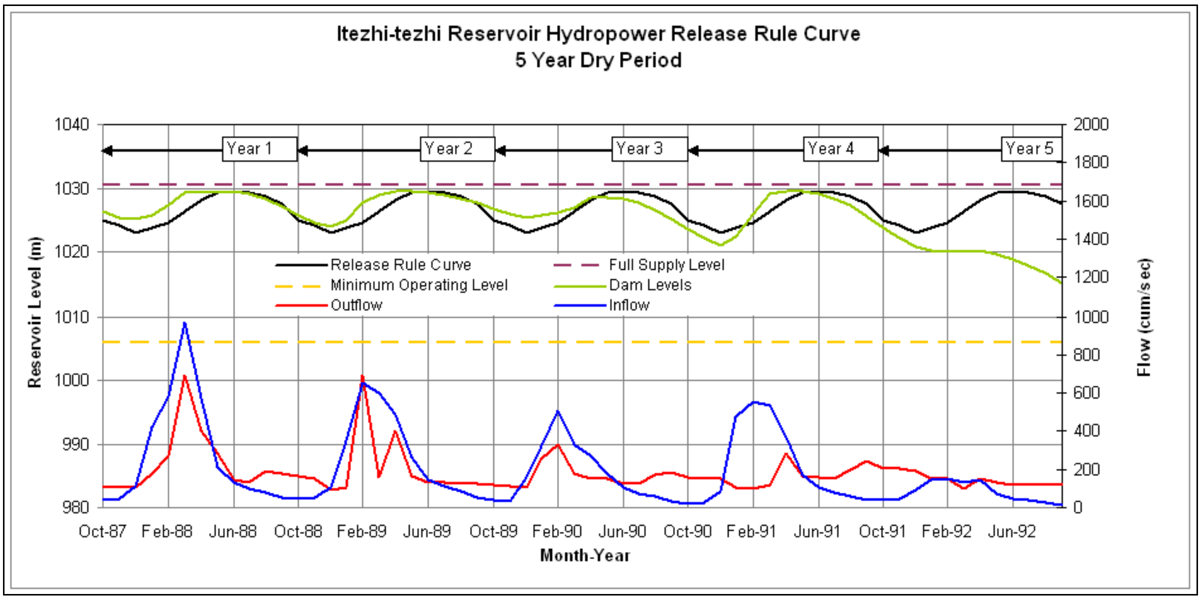


Figure 5.29: Itezhi-tezhi longest very dry period - historical operations

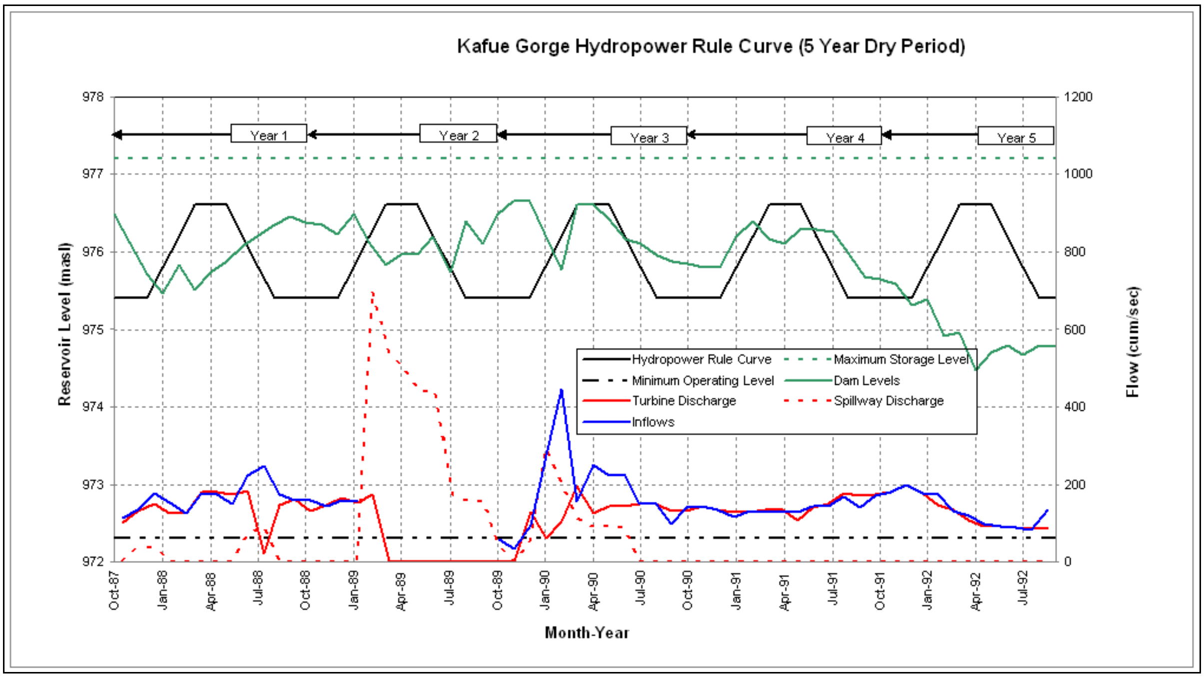


Figure 5.30: Kafue Gorge - longest very dry period - historical operations

5.8.6 Summary of test results

Table 5.16 summaries the results obtained with the six "new" modes of operation using Kariba dam as a test case and deductions made from the Kafue sub-system.

Table 5.16: Impact of new modes of dam operation

Mode of operation	Impacts during wet and dry and season				
	Safety of dam infrastructure	**Electricity production**	**Flood management:**	**Environmental flow requirements**	**Other water users**
One year operating rule considering dam safety, hydropower, and flood management objectives	Violations of the dam safety rule are eliminated.	The outflow to meet the average hydro power is satisfied throughout. It is estimated that the power outputs reduced by about 5% compared to the simulated historical operations mainly because of reduction in head. New dams additional turbines on existing dams may compensate for loss in power.	An additional four weeks is added to the lag on peak outflow. The peak outflow is reduced by about 36% below the historical experience.	Total flow requirements for modified state can be met but timing is out of sync with natural flows	Improvements in the shape of the rising and recession limbs are important for wildlife and recession agriculture.
One year operating rule considering dam safety, hydropower, flood management and environmental release objectives	Violations of the dam safety rule are eliminated.	The outflow to meet the average hydro power is satisfied throughout. Power output was reduced by about 2% compared to the simulated historical operations mainly because of reduction in head. New dams additional turbines on existing dams may compensate for loss in power.	About two weeks of lag on peak outflow is lost. The peak outflow by about 36% below the historical experience.	Total flow requirements for modified state can be met but timing is out of sync with natural flows	
Wet period, multi-year operating rule and consideration of dam safety, hydropower and flood management objectives - Kariba Dam	Violations of the dam safety rule are eliminated.	The outflow to meet the average hydro power is satisfied throughout. Power output was reduced by about 5% compared to the simulated historical operations mainly because of reduction in head. New dams additional turbines on existing dams may compensate for loss in power.	An additional two weeks is added to the lag on peak outflow. This will provide additional early warning time for downstream dams and stakeholders. Although the peak is reduced, releases are over a longer period. The inflow and outflow hydrographs can cross in December and June of each year with further refinement.	Total flow requirements for modified state can be met but timing is out of sync with natural flows	Use of long term statistics of inflow on a five year operating window improves management of outflow patterns. Improvements in the shape of the rising and recession limbs are important for wildlife and recession agriculture

Impacts during wet and dry and season					
Mode of operation	**Safety of dam infrastructure**	**Electricity production**	**Flood management:**	**Environmental flow requirements**	**Other water users**
Wet period, consideration of dam safety, hydropower and environmental management objectives – Kariba Dam	Violations of the dam safety rule are eliminated.	The outflow to meet the average hydro power is satisfied throughout. It is estimated that the power outputs reduced by about 6% compared to the simulated historical operations mainly because of reduction in head. With further refinement the inflow and outflow hydrographs will cross only when inflow is not enough to satisfy the hydro power requirement. New dams additional turbines on existing dams may compensate for loss in power.	The peaks occur a week to two weeks earlier than the simulated historical flow. An advanced communication system floods is required to warn downstream dams and stakeholders. The flood peaks are very close to or equal to historical simulations and releases are over a longer period	With further refinement the inflow hydrograph can retain the properties of the inflow hydrograph which further addresses the requirement for environmental releases of prescribed floods.	
Dry period: multi-year operating rule and dam safety, hydropower production and environmental objectives – Kariba	The low lake levels were not a threat to the dam safety operating rule and the levels were below the flood gates	Dam levels are well above the minimum level for hydro power generation in both scenarios but supplying 50% of hydro power requirement from the second year achieves the highest lake levels. It is estimated that the power outputs for the 50% scenario was increased by about 42% compared to the simulated historical. It is estimated that the power outputs for the 60%-50% scenario was increased by about 36% compared to the simulated historical operations. Reduction in releases for hydropower will prevent the dam from reaching the minimum operating level, protect the lake environment and allow storage in the reservoir to recover. Connection to the Southern Africa Power Pool (SAPP) is required to offset the reduction in power output	No flooding occurs	Outflows patterns are modified to match hydropower turbine requirements.	Low lake storage may affect the flora and fauna it supports.
Wet period, consideration of dam safety and multiple objectives – Kafue System	Itezhi-Tezhi operated above the rule curve but there is no distinct seasonal pattern for minimum levels for Kafue Gorge	Kafue Gorge spillway discharges are between January and August each year with peaks in the range of 700 m^3/sec to 1300 m^3/sec . The graph suggests a stepped hydrograph. Kafue Gorge turbine releases for power productions varied between 22m^3/sec to 262m^3/sec and were not impacted by available storage	High discharges were experienced in 1978 (1300m^3/sec) and 1981 (1000 m^3/sec)	The pattern of the outflow from Itezhi Tezhi generally meets the environmental objectives.	Not considered in this mode

	Impacts during wet and dry and season				
Mode of operation	**Safety of dam infrastructure**	**Electricity production**	**Flood management:**	**Environmental flow requirements**	**Other water users**
Dry period: multi-year operating rule and dam safety and multiple operating objectives – Kafue System	No violation of dam safety rule	The water levels in both dams dropped significantly below the operating rule for hydropower. Reduction in releases for hydropower will prevent the dam from reaching the minimum operating level, protect the lake environment and allow storage in the reservoir to recover. Connection to the Southern Africa Power Pool (SAPP) is required to offset the reduction in power output.	Itezhi Tezhi retained a significant proportion of its inflow while Kafue Gorge passed on most of the inflow. The high discharge from Kafue Gorge in 1989/90 could have been in anticipation of high inflows.		Low lake storage may affect the flora and fauna it supports.

5.9 Recommendations for a Cooperation Protocol between the Dam Operators

The main concerns that challenge any cooperation arrangement centre around management of risks, cost and benefit sharing. Changes in modes of operations as discussed above require sharing of costs, risks and benefits. Organizations always avoid to the prospect of taking on all the costs and all the risks. Some organizations may wish to have no risks at all and to incur no additional costs. Invariably, however, all organizations aim to maximize benefits. All these considerations notwithstanding, it is *sin qua non* that cooperation that is perpetually sustainable can only thrive where costs, risks and benefits are shared, reviewed and updated when conditions change.

5.9.1 Review of current cooperation arrangements between Dam Operators

At present, the major dam operators and power producers on the Zambezi river namely ZRA, HCB, ZESA and ZESCO have a platform for cooperation called the Joint Operation Technical Committee (JOTC). ZINWA and ARA Zambeze are also part of the committee. This corporation arrangement also includes an MOU to provide for executive decisions to consider recommendations from this technical committee. The JOTC is focused on the operations of the Kariba, Kafue and Cahora Bassa dams. The JOTC conducts meetings on cooperation.

The existing cooperation arrangement amongst operators in the Zambezi basin is based on a draft memorandum of understanding (MOU) as summarised in Table 5.17, where the MOU is evaluated according to the parameters representation, vision, objectives, action plan, obligations, enforcement, financing, communication strategy to ensure that the concepts of cost, benefit and risk sharing are adequately embedded.

The realization of the new modes for reservoir operation proposed on this study will require revised Cooperation Protocol for the Dam Operators and Power producers.

The increasing complexity of dam and hydro power operations procedures to meet various competing objectives requires strengthening of the draft MOU for the JOTC in the areas identified in Table 5.11. However it is also clear that to address the extended objectives there is need to involve a broader range of stakeholders on the Zambezi River System. It is therefore proposed that The Zambezi River System Operators Forum be formed to operate alongside and in cooperation with the JOTC.

The vision as presented in the draft MOU for the JOTC can be strengthened by providing for formal links to the Zambezi River System Operators Forum while the obligations require links with the SARCOF and the Regional Meetings of Hydrologists.
In the past hydrologists working on the Zambezi Basin met once a year following the SARCOF meeting. This meeting allowed these specialists to engage and interpret recommendations from SARCOF into practical forecasts. These meetings have since stopped, and should be resuscitated.

The JOTC is essentially a technical committee with representation drawn primarily from power producers and dam operators. The management of the Zambezi River Basin in a system-wide context will entail the accommodation of other uses of the river such as hydropower production, flood protection, agriculture and the environment. This study identified the need for a broader forum of stakeholders to address the extended objectives, and recommends the establishment of a System Operating Forum (SOF). This includes organizations responsible for Disaster Management, Water Management, Environmental Management, Local Government and Civic Society. This broader forum will enhance sharing of data between operators and other stakeholders. It will facilitate close liaison with different ongoing programs by various organizations as well as updating the ZAMWIS database. The second Advisory Group meeting deliberated on the continuation of the AG meetings to take the form of the SOF. Most of the members of the AG are in support of the SOF and can see its benefits, therefore the transformation of the AG into a fully operational the SOF can be achieved within a very short time, not exceeding two years. The SOF will provide a platform for interested and affected stakeholders to contribute to the effective management of the Zambezi River System and improve communication

Table 5.17: Review of existing draft agreement and recommendations for improvements

Parameter	How the parameter is addressed	Comment on cost sharing	Comment on risk sharing	Comment on benefit sharing
Vision	To ensure the greatest possible benefit from the efficient utilisation of the Zambezi River.	Cost sharing not explicitly mentioned.	Risks sharing not explicitly mentioned.	Benefits to recognize through provision of water to meet socio-economic and hydropower requirements.
Objectives	To set a framework for collaboration and information exchange between members to ensure informed management of the water resources.	Cost sharing not explicitly mentioned. Collaboration and information exchange can open up discussions on benefit sharing.	Risks to safety of dams, hydropower supply and flooding are recognized. Timely sharing of information can enable different stakeholders to manage their risks. The JOTC should consider how to dam operations can meet system-wide objectives	Clear objectives and procedures on benefit creation and sharing can open up stakeholders to collaborate and exchange information. System-wide objectives should be considered.
Representation	To qualify for membership of the JOTC, an institution should be a water manager or large dam operator in the Zambezi River Basin. Presently the following organisations constitute the JOTC: ZRA, ARA-Zambeze, ZESCO, HCB, and ZPC.	The parties represented in the JOTC are primarily the Power Producers and Dam Operators on the Zambezi main stem. The current focus is clearly on water management for hydropower production and dam safety.	It is not clear how operators of dams and collectors of hydrological and rainfall data on the tributaries such as Water Authorities/Managers and Meteorological Departments are engaged. Disaster Management Agencies are not represented which presents challenges in implementing risk management interventions. Other fora is required to address these issues.	Environmental Management Agencies are not represented. Environmental requirements may not be implemented or monitored. The vision cannot be realised with the current stakeholders alone.
Obligations	1. Timely information exchange in agreed format and frequency. 2. Regularly update each other on the reservoir operation schedules 3. Sharing of expertise in implementation of tools for reservoir operation and environmental protection 4. Regular sharing of expertise and experiences in dam safety monitoring and analysis 5. Agreement on special working provisions in case of floods, droughts and any other emergency situations	Data collection carries a cost. The obligations will ensure knowledge exchange and may eventually result in standardization of dam operations and response to emergency situations.	The time frames are not defined and type of information to be shared is not defined. There is no reference to a shared risk management framework. Responsibilities for actions need to be negotiated and agreed. Obligations on other stakeholder such as Water Authorities/Managers and Meteorological Departments on collection and sharing of climatic and flow data are not clear. The protocol should recognize other relevant fora and provide for formal linkages.	Obligations on knowledge sharing can result in benefits to all parties.

Parameter	How the parameter is addressed	Comment on cost sharing	Comment on risk sharing	Comment on benefit sharing
Enforcement	The Member Institutions will work together with reasonableness and honesty of purpose to establish and maintain a relationship of mutual benefit based on goodwill, cooperation and partnerships	Members are able to engage and enforce collection of funds for shared items/activities.	The MOU is entirely dependent on the goodwill of Members. Moreover the Members are free to withdraw upon giving a notice. As such, a Member is likely to implement only the resolutions which are beneficial to them. The vision may be difficult to achieve.	Enforcement of benefit sharing can make stakeholders more accountable to each other and to the achievement of system-wide objectives.
Financing	Member Institutions shall meet their own expenses.	This is rather a limited view possibly focused to participation in JOTC only. Upstream and downstream movements of costs need to be monitored and they may burden them with certain financial responsibilities.	A desirable decision beneficial in a system context may disadvantage others. A framework to assess the financial implications is essential	A mechanism for monitoring movement of costs is essential.

5.10 Conclusions

The following conclusions were drawn from this chapter:

(a) Floods and droughts are part of the history of the Zambezi with and without dams. Large floods and severe droughts are a fact of life in the Zambezi system. However, dams impound floods and modify downstream flows and the lake environment. However releases can be managed to minimize upstream and downstream impacts.

(b) The major dams on the Zambezi except for Kariba will fill up every year on average. These other dams cannot capture and store large floods and on average they will spill every year. The operation of Kariba dam is important for management of floods in the Zambezi river system

(c) Unregulated tributaries on the Zambezi River System contribute significantly to flooding and they influence timing and magnitude of flood releases. "New" dams on the Zambezi main stem and tributaries are unlikely to be larger than Kariba but can reduce pressure on existing large dams and indirectly contribute to flood management.

(d) The major dams of the basin have, to date, been operated more of less independently, without regard to requirements of other stakeholders in the basin. Similarly, all dams have been managed without any provision for environmental flows and other socio-economic considerations for downstream or other riparian users. Dam operations have focused primarily on dam safety and maximization of hydropower production on a one year operating window. New modes of operation which consider multiple-objectives and a multi-year operating window should be considered for the Zambezi River system. . This recommendation is captured in Intervention Sheet 2.4 in Chapter 10.

(e) The high coefficient of variation on MAR experienced in the Zambezi River system shows why the management of floods is important for these dams to pass on large floods safely and to retain water to bridge periods of low inflow

(f) Different flow categories can be linked to different ecosystems requirements but timing, frequency and duration are important. These flow conditions can be used to define flow requirements for the environment. The establishment of environmental flow requirements for the Zambezi River basin requires more detailed studies. This is recommendation is captured in Intervention Sheet 2.6 in Chapter 10.

(g) Operating objectives for the Zambezi River system should consider dam safety; hydropower flood management, environmental management dry season floodplain agriculture, plantation irrigation, navigation and other water users. The actual setting up of multiple objective operating rules should be informed by a set of guidelines and detailed studies. This is recommendation is captured in Intervention Sheet 2.5 in Chapter 10.

(h) Inflow variability and climate change scenarios can be incorporated in dam operations by use of statistical approaches which consider historical patterns.

- Using Kariba dam as a test case with a one year operating window, the 2% exceedence inflow can be safely discharged to provide for the environment, reducing the flood peak but with a loss of 2% reduction in power output compared to historical practice. This outflow hydrograph is improved by eliminating lag to match the requirement for environmental releases. Accurate prediction of the inflow is a prerequisite for this mode of operation.
- Using Kariba dam as a test case with a five year operating window, the 13% 16%, 39%, 5% and 18% exceedence inflows for year 1 to year 5 respectively it was demonstrated that floods can be safely discharged while providing for the environment, reducing the flood peak but with a loss of 6% reduction in power output compared to historical practice. This outflow hydrograph is improved by

eliminating lag to matches the requirement for environmental releases. Accurate prediction of the inflow is a prerequisite for this mode of operation. Climate change scenarios the period 2030-2050 suggest worst case for floods with annual inflow falling within that experienced in the 10% wettest year for the period 1956-1997. High variability is also suggested for the transitional season. These two aspects are well within the range of inflows (5% to 39% exceedence) considered in the tests.

- Using Kariba dam as a test case with a five year operating window, the 66%, 92%, 98%, 99% and 93% exceedence inflows for year 1 to year 5 respectively it was demonstrated that the 50% curtailment level on releases for hydropower can increase power output by 42% while storage levels are maintained well above the minimum operating level for the dam. Climate change scenarios for the period 2030-2050 suggest the worst case for droughts. with mean annual inflow available for storage increase, turbines or spilling less than was available historically 10% driest years for the simulated period 1956-1997. These two aspects are well within the range of inflows for four of the five years (92% to 99% exceedence) considered in the tests.

These are preliminary findings, more detailed studies on reservoir and system operation modeling are essential. This recommendation is described in Intervention Sheet 2.5.

(i) During "wet" and very wet" periods dam operations can observe the dam safety rule, and meet other objectives and reduction in power output can be met through the provision of additional turbines on existing dams.

(j) During droughts or when storage and inflow are low, releases should be curtailed to avoid violation of minimum operating level for hydropower, protect that the lake environment and allow storage in the reservoir to recover. During these periods connection to the SAPP is essential for augmenting power supply.

(k) Dams alter downstream flow regimes and however while they cannot restore the original conditions the operation of existing and new dams can result in significant improvements in downstream conditions.

(l) The existing draft MOU for the JOTC should be strengthened to facilitate the better management of risks, sharing of costs and benefit through improved dam operation.

(m) The vision of the MOU is very wide and the broader system objectives of the Zambezi River system cannot be realized with the limited range of stakeholders in the JOTC membership. It is therefore proposed that the Zambezi System Operating Forum be created to include a wider range of stakeholders. Further details on this recommendations are in contribute to the recommendations detailed in Recommendation Sheet 2.1 in Chapter 10 of this document.

(n) Training of hydrologists, JOTC and SOF members on the new modes of operating dams described in this chapter will to improve their understanding and to capacitate them for effective participation in their meetings. This training should consider the requirements of different stakeholders as detailed in Intervention Sheet 2.2.

6 Regulation of Shire River and Lake Malawi

6.1 Introduction

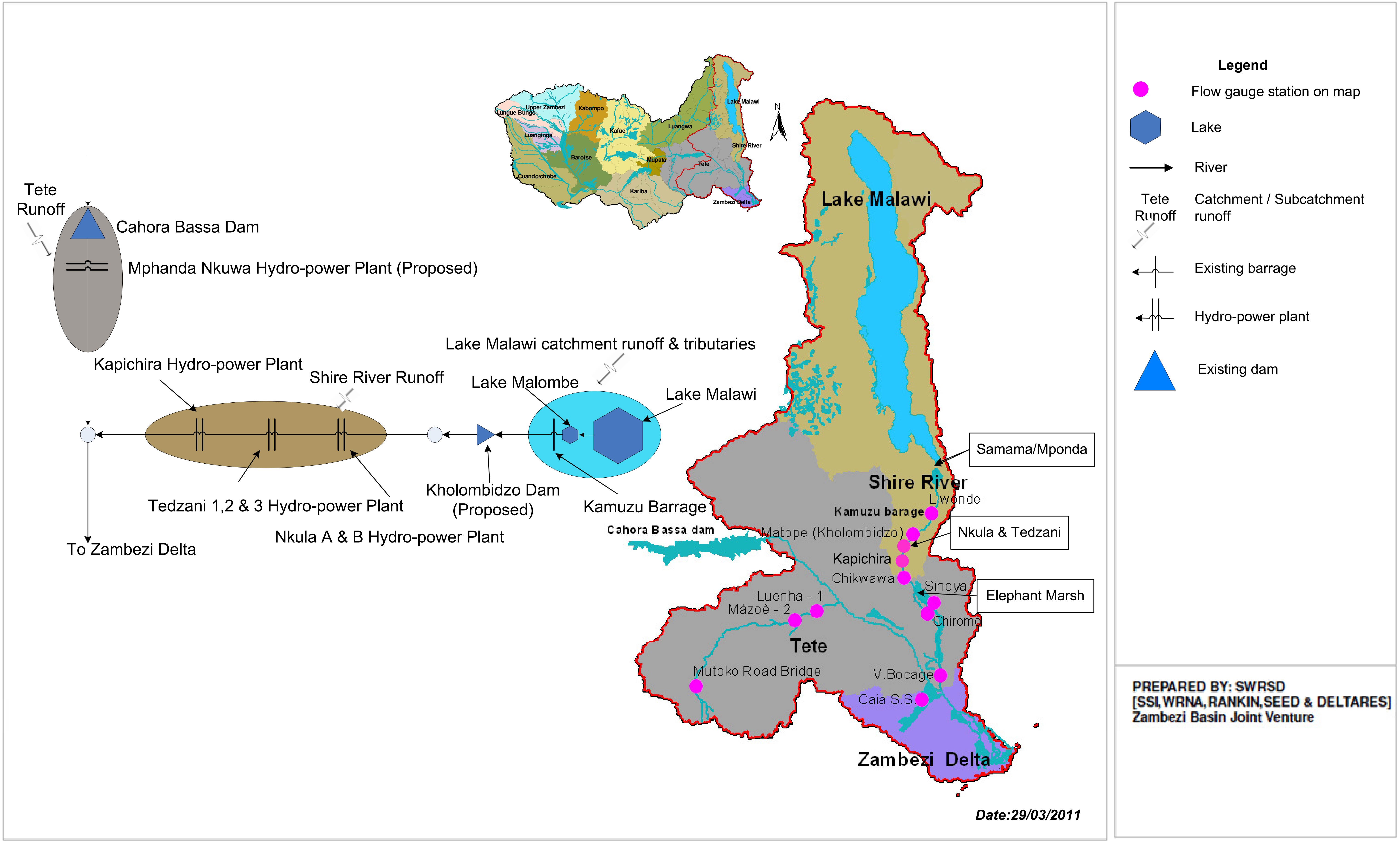
Lake Malawi is of fundamental importance to the three countries of Malawi, Tanzania and Mozambique. Some basic data on the Lake is presented at the beginning of Chapter 2 of this document. For Malawi the Shire River and Lake Malawi together represent the country's single most important natural water resource system. Lake Malawi supports fishing and water transport, agriculture and tourism industries. Hydropower plants located in the Lower Shire produce about 95% of Malawi's electricity requirements.

The Lake Malawi/Shire River system is part of the Lower Zambezi Sub-basin and the elements of this sub-basin that are relevant to flood control and hydropower production are shown in Figure 6.1.

For the purpose of this study, the Lake Malawi/Shire River sub-system is divided into an upper part and lower part. Lake Malawi and its tributaries down to the Kamuzu Barrage at Liwonde are considered as the upper part of the subsystem. The major tributaries include the Ruhuhu from Tanzania, Songwe River from Malawi/Tanzania, North Rukuru, South Rukuru, Bua and Linthipe Rivers from Malawi. These tributaries contribute over 40% of input into the water balance of the lake (the other input being direct rainfall on the lake). The level of water in the Lake peaks in April/May instead of peaking in March when Lake rainfall is at its peak. This is because peak flows in the tributaries to the northern part reach their peak in April. Shela *et al* 1995 indicated changes in run-off (increased wet season flows and decreased dry season flows) due to deforestation and catchment degradation. A rise in the water level in the Lake can cause local flooding around the shoreline. This occurred in the early 1980s when the level reached a peak of 477.2 m.a.s.l.

There are no significant tributaries feeding into Lake Malombe, its flow is effectively the Shire River flows or Lake Malawi outlet flow. The water levels of the Lake Malawi and Lake Malombe are virtually the same.

The lower part of the sub-system comprises the Shire main stem and its tributaries. The hydro power stations downstream in the lower sub-system also rely on outflows from Lake Malawi. The relationship between the two sub-systems and the Zambezi main stem is shown in Figure 6.1.



TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

FIG 6-1 MAIN FEATURES OF THE LAKE MALAWI / SHIRE RIVER SUB-SYSTEM RELEVANT TO FLOOD CONTROL & HYDROPOWER PRODUCTION.

SOUTHERN AFRICAN DEVELOPMENT COMMUNITY
SADC
TOWARDS A COMMON FUTURE
giz
On behalf of:
Federal Republic of Germany
The Federal Government
UKaid
from the Department for International Development
Australian Government
Aid Program

6.1.1 Socio-economic and environmental impacts of Lake Malawi water levels

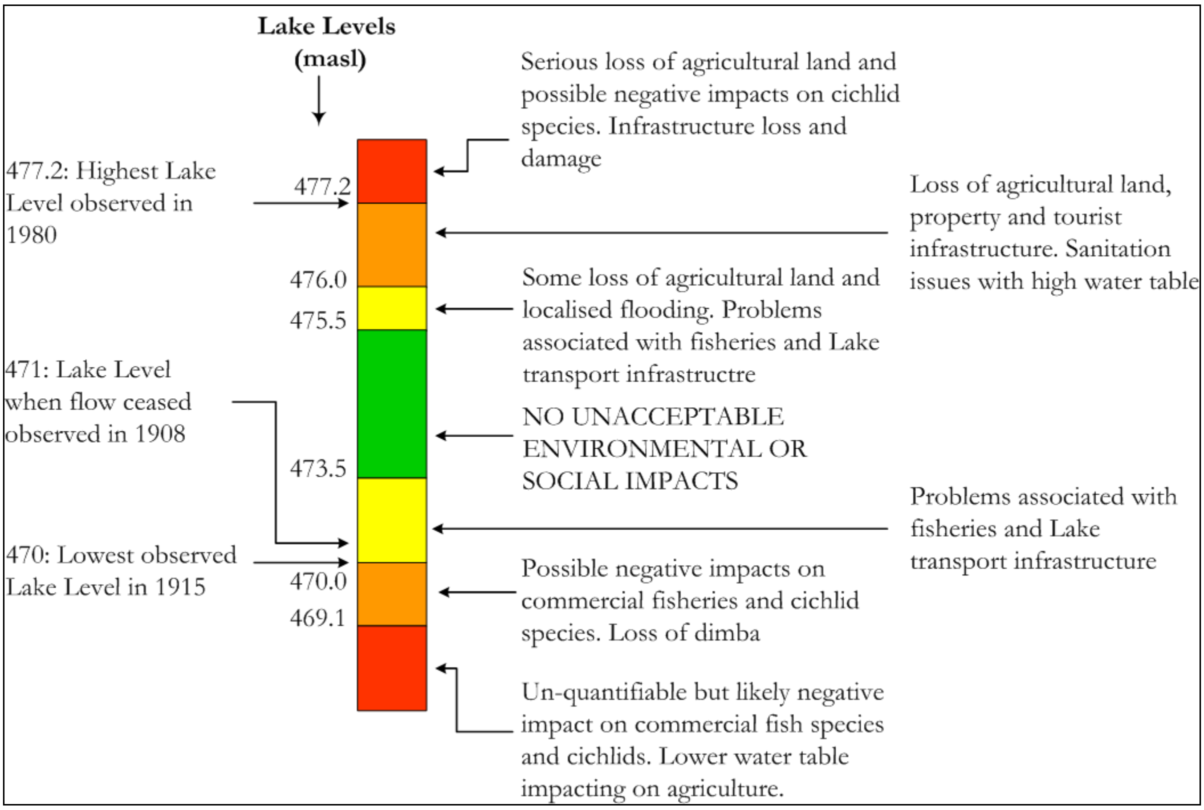


Figure 6.2: Impacts of different levels of water in Lake Malawi (Government of Malawi, 2003c)

Flooding and low water levels impact negatively on the economic activities supported by the sub-system. Economic, social and environmental activities/functions on Lake Malawi are affected by low lake levels while the viability of the hydropower production requires maintenance of constant and sufficiently high river flows as shown in Figure 6.2. Navigation and fisheries industries have a similar criterion with regards to lake levels for their viability. In the Upper Shire to Liwonde, inundation caused by increase in Lake levels can cover a large area due to the flat terrain. Levels at 476m result in serious flooding and above 476m the impacts will rise exponentially. From Liwonde to Matope low flows are generally experienced but serious flood problems occur in the Lower Shire. These are influenced much more by localized inflow from tributaries than Shire flows in terms of flood peaks.

The existing arrangements for regulating the sub-system have not adequately protected the important economic activities and settlements that are affected by the lake and river levels. This is of concern to the various stakeholders dependent on the system.

This task considers the regulation of outflows from the Lake Malawi from a flood control point of view and impact on power production.

6.1.2 Description of Operating Objectives for the sub-systems

The main operational objective of the upper sub-system is to stabilize the lake levels and manage outflows into the Shire River. Environmental flows for the lower sub-system do not feature explicitly in the current operating objectives.

6.2 Situation Assessment

6.2.1 Description of current operation of the sub-system

The outflow from Lake Malawi into the Shire River at lake levels between 473.22 m.a.s.l. and 475.32 is regulated by the Kamuzu Barrage which is located at Liwonde immediately downstream of Liwonde National Park.

Kamuzu Barrage - August 17, 2010

Figure 6.3: Location of Kamuzu Barrage

It is the only point where flow is currently being regulated in the sub-system. Above 475.32m the barrage has no flow control function. Therefore during floods outflows from Lake Malawi cannot be reduced or suspended. In that event, the hydropower plants will receive the full flood flows from Lake Malawi. This is a very important point for the management of the lake and any discussions relating to flood management in the sub-system. The relationship between water levels in Lake Malawi and discharges into the Shire River at Liwonde under natural conditions is shown in Figure 6.3.

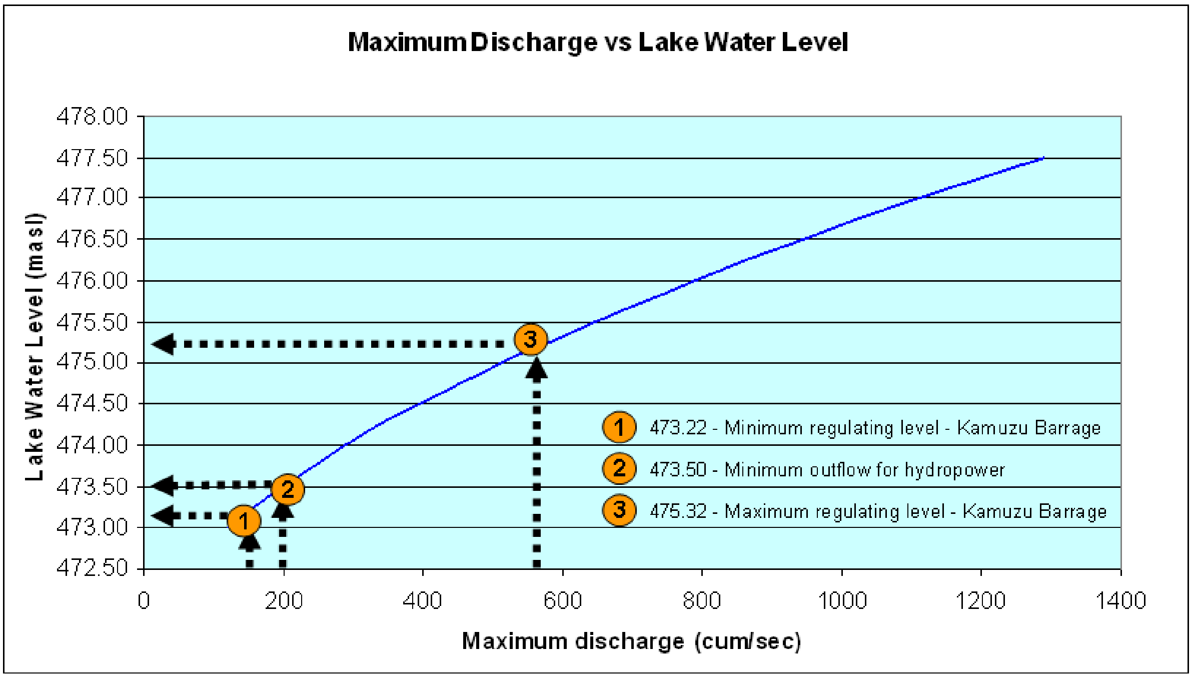


Figure 6.4: Relationship between Lake Malawi and outflows into the Shire River under natural conditions (Norcosult, 2003)

The Government of Malawi (2003c) estimates that the probability of Lake water levels rising above 476 m.a.s.l. 3% , with the Kamuzu Barrage operating at a maximum level of 475.32m.a.s.l. This is considered to be within the natural long-term variation in water level due to long term variation in rainfall.

6.2.2 Description of the main features of the existing infrastructure related for flood control

The Kamuzu Barrage was commissioned in 1966 (Malawi Government, 2003) and it has 14 sluice gates which can be operated to maintain a constant release to meet downstream hydropower flow requirements while regulating the level of water in Lake Malawi. Above the level of 475.32 m.a.s.l. the barrage is fully open and it has no flow control function. By design, the outflow can exceed 600m^3/sec as shown in Figure 6.4 although this can cause flooding downstream. Major floods occurred in the early 1980s when the level reached a peak of 477.2 m.a.s.l., Overtopping of the barrage can occur.

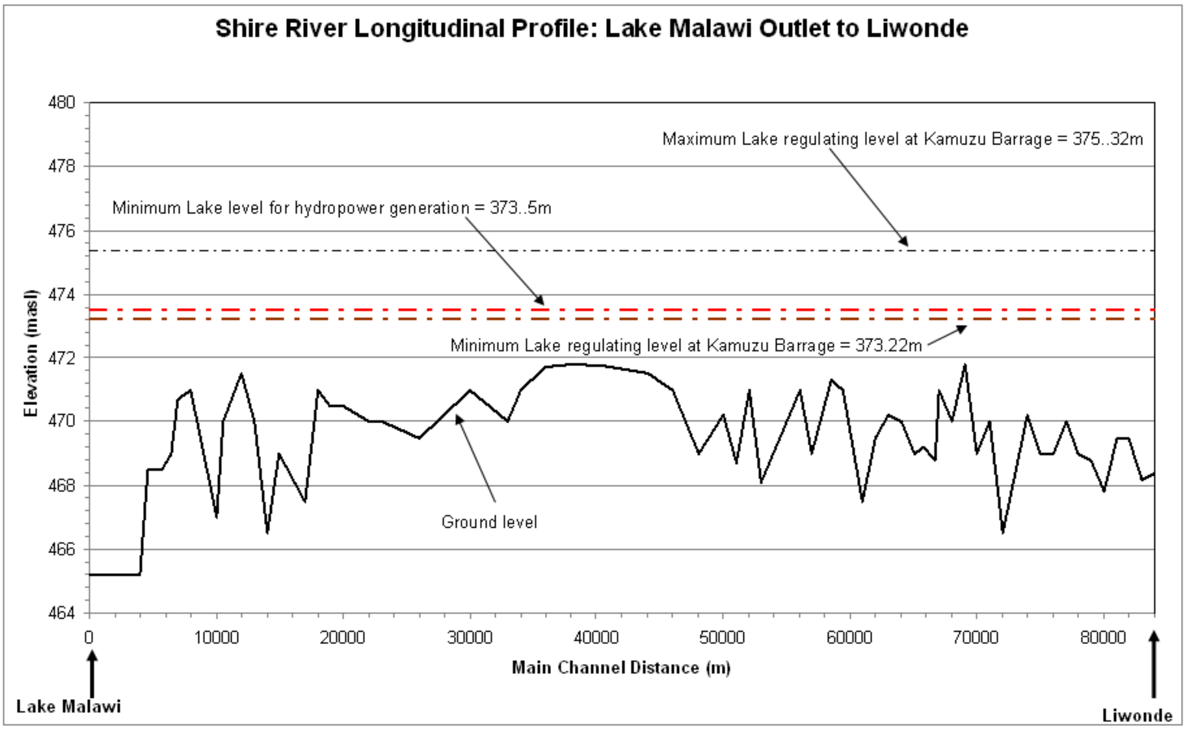


Figure 6.5: Longitudinal profile of the Shire River from Lake Malawi outlet to Liwonde

6.2.3 Description of existing Operating Rules

The rule curve for the Kamuzu Barrage has evolved over time from 1965 as described in the following sections:

1. Rule Curve for 1965 - 1992 Operations

The first operating rule curve for the Kamuzu Barrage was developed in 1965 but limited data was available at the time, which meant that little hydrologic analysis could be done. This rule was used until 1992. Under this rule curve, the lake levels were allowed to increase up to 475.32 meters above sea level (m.a.s.l.). At this level the gates are fully opened and water was allowed to flow freely to avoid undermining the safety of the barrage which can be overtopped if the gates are closed or partially open. The equation of the operating curve was as follows:

Lake Malawi Water Level	Flow released into the Shire River at Liwonde	Comment
Greater than 475.32 m.a.s.l.	Natural Flow	Gates are full opened
473.82 <Lake water level < 475.32 m.a.s.l.	237(Lake water level -471.37) – 411 m^3/s	Gate partially closed to reduce outflow
473.22 < Lake water level < 473.82 m.a.s.l.	170 m^3/s	Gate partially closed
Equal to or less than 473.22 m.a.s.l.	Natural Flow	Flow not affected at gates

The unregulated outflow rating curve from Lake Malawi is commonly referred to as "Nature curve" in existing literature.

2. Rule Curve for 1992 - Present Operations

Since 1992, an "administrative" operating rule was developed. This started as a temporary operating curve but it has become almost permanent. With this rule ESCOM requests releases based on the water they need to operate their hydropower plants. The policy is that the Water Resources Board meets to debate pro and cons of the request, which is then approved with or without modification. Releases are thus made according to the agreed figure, with fluctuations being made in response to increases in head immediately upstream of the barrage. The Board regularly circulates monthly Lake Malawi water levels. Any change in the flow has to be negotiated and approved by the Board. Between 1992 and 2003 the agreement was for a release of 180m^3/s and this was increased to 380m^3/s from 2003.

In the actual operation, the lake levels are not actively monitored, the levels used are taken from a point downstream of the Barrage. The objective is to ensure that the releases are not less than the requirement for power generation. The lag between the release and the barrage and Nkula power station is about 24 hours which means releases are based on forecast requirements. The discharges at the barrage are controlled and kept between 318 and 329 m^3/s which is higher than the design firm flow to satisfy hydropower production downstream of Shire River. The power plants are in series and Nkula is most upstream and it has the highest flow requirement. According to ESCOM the flow for peak power demand is about 284m^3/s but 380m^3/s is released. This means that a significant portion of the flow actually by-passes the intake for Nkula power station, indicating a need to closely monitor releases against actual use.

The storage from the small reservoirs at the power plants is equivalent to 1 to 2 hours operation which means that they are run-of-river schemes. The maximum flows into the turbines at Nkula, Tedzani and Kapichira are 284, 275 and 135m^3/sec respectively while the design flows are 264, 254.6 and 135m^3/sec respectively. This means that the flow requirements of the power plants will vary depending on how the operations are managed, particularly at Nkula power station.

6.3 Impact of existing operating rules on flooding of the Lake Malawi area and the Shire River

The operation of the Kamuzu Barrage to maintain sufficient storage to supply hydro power operations on the Shire River and release a predetermined flow below 300m^3/sec means that some measure of flood control is being afforded which benefits downstream users. However from Figure 6.3 it is evident that since 1970 lake levels have exceeded 476.0 m.a.s.l. during 8 out of 36 years.

The outflow from Lake Malawi gradually reduces to zero at 471.5 m.a.s.l., the natural ground level at its outlet. This occurred between 1908 and 1935. The level needed to maintain firm hydropower generation in the lower part of the sub-system is 473.5 m.a.s.l. In the mid 1990s the lake level fell to as low as 473 m.a.s.l. which resulted in a significant reduction in outflow to the Shire River. The lake level then rose to about 476 m.a.s.l. during the 2003 wet season. High floods on the Shire also affect hydro power operations. The historical levels are shown in Figure 6.5.

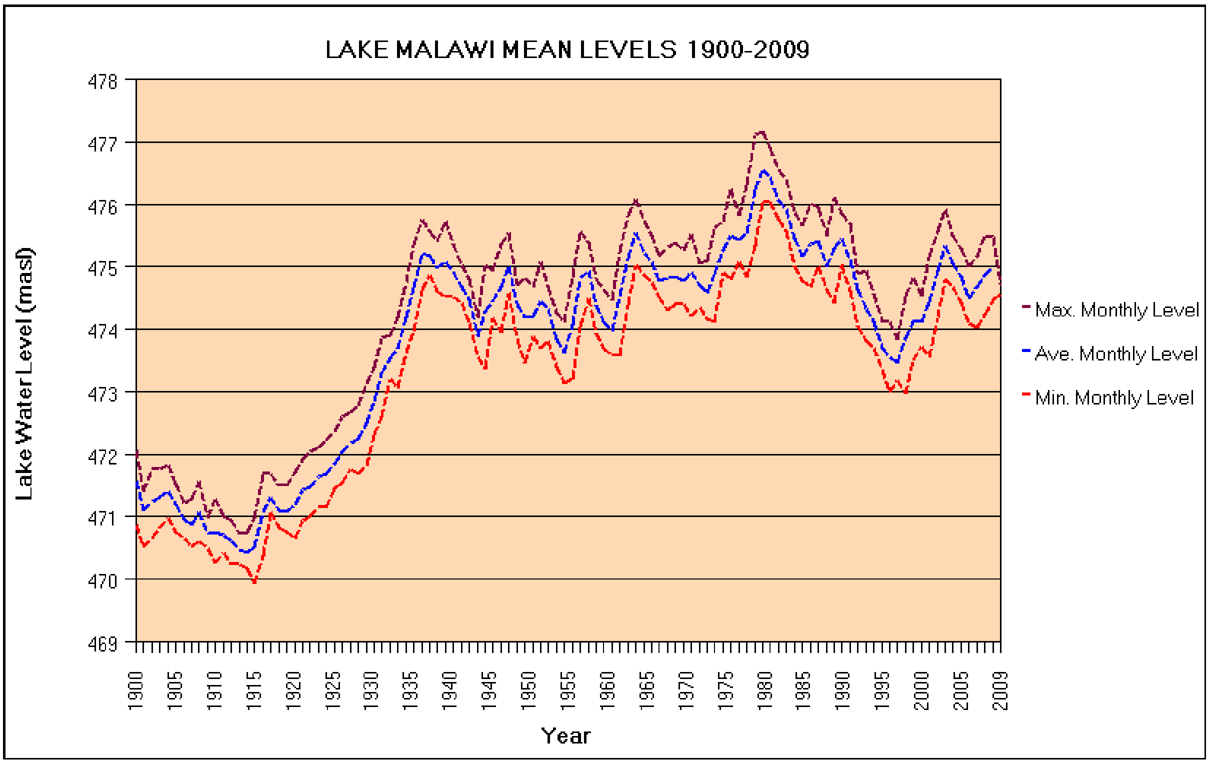


Figure 6.6: Historical water levels in Lake Malawi 1900 to 2009

Figure 6.6 shows the variation of lake levels during the period 1900 to 1964 when the Kamuzu Barrage was not in place. The levels vary widely within the range of about 470.2 m.a.s.l. to 475.8 m.a.s.l. The median varies between 473.2 m.a.s.l. and 473.8 m.a.s.l. The lower limit for hydro power generation of 473.5 is close to the median in certain years. The upper level for negative environmental impacts to start on the Lake area of 475.5 m.a.s.l. was a rare event (this was exceeded only 5% of the time in the months of April and May).

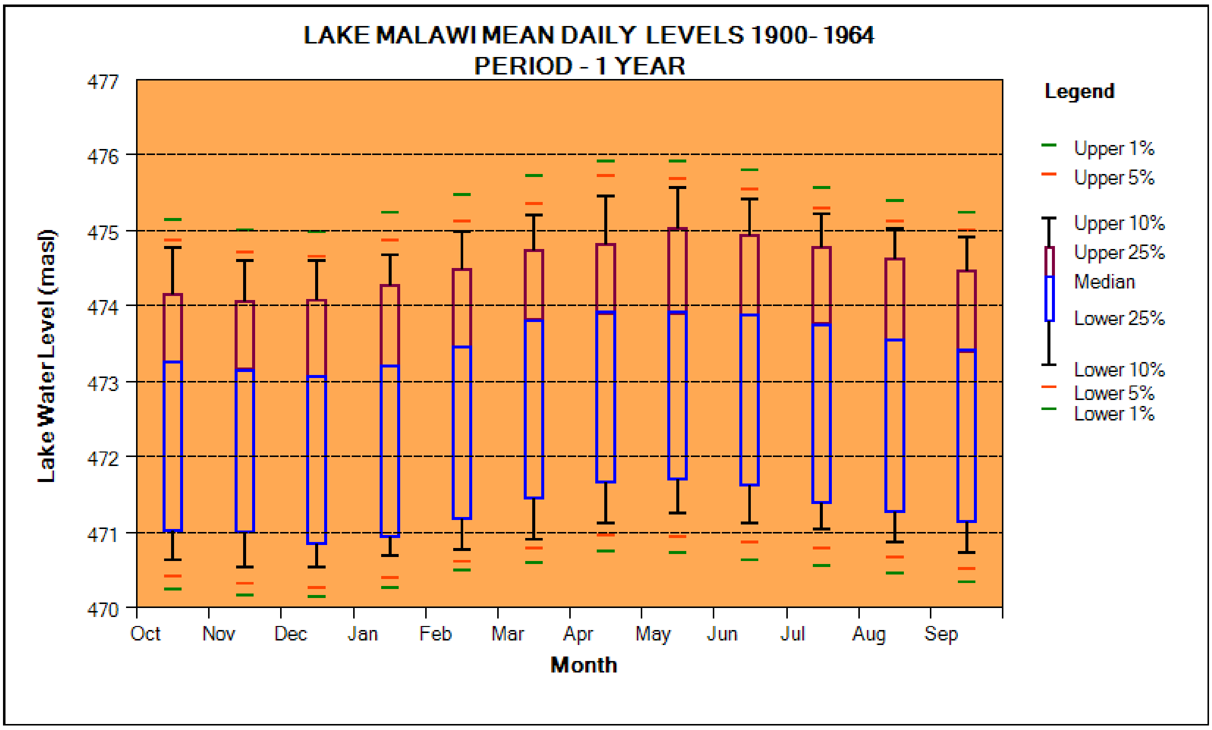


Figure 6.7: Variation in Lake Malawi water levels 1900 to 1964 (without Kamuzu Barrage)

Figure 6.7 shows that from 1966 to 2009 the lake levels were being managed within the range of 473.0 m.a.s.l. to 477.15 m.a.s.l. The levels below the lower limit for hydro power generation of 473.5 became rare events (lower 1%). Although the desirable lower limit of 473.0 m.a.s.l. for negative environmental impacts on the Lake area was not exceeded this was not the case with the upper level of 475.5 m.a.s.l. In April this level was exceeded 50% of the time. Thus the Kamuzu Barrage affected the Lake water level patterns increasing the lake levels and reducing variability.

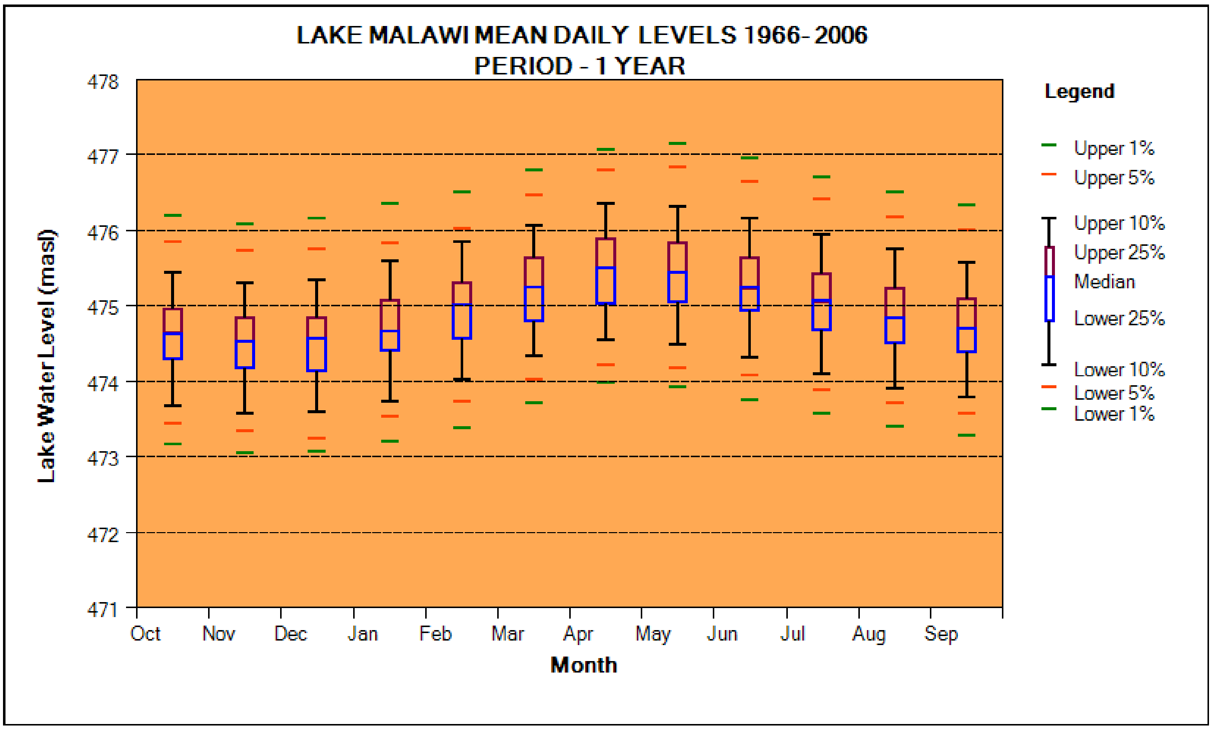


Figure 6.8: Variation in Lake Malawi water levels 1966 to 2006 (with Kamuzu Barrage)

The ten wettest years and two driest years are shown in Figure 6.9 and six of them were consecutive. Starting levels (October) for each of these years were above 474.5 m.a.s.l. which is lower than the median level with current operating procedures.

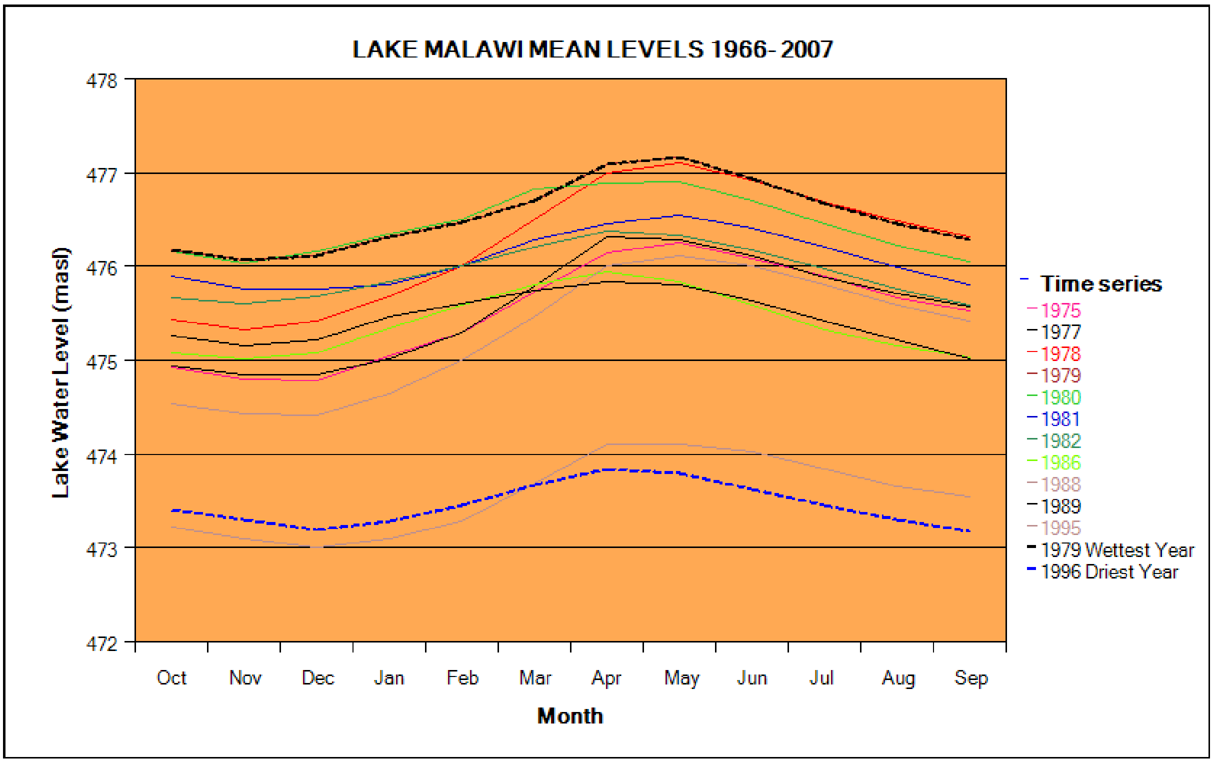


Figure 6.9: Lake Malawi water levels for ten wet years in the period 1966 to 2007

Consecutive years of high lake levels can create emergency conditions both in the lake area and downstream of it particularly if high inflows are also received. Figure 6.8 shows a higher variation in outflow at Kamuzu Barrage during the same wet years. March to July are distinct high outflow months with peaks in April and May.

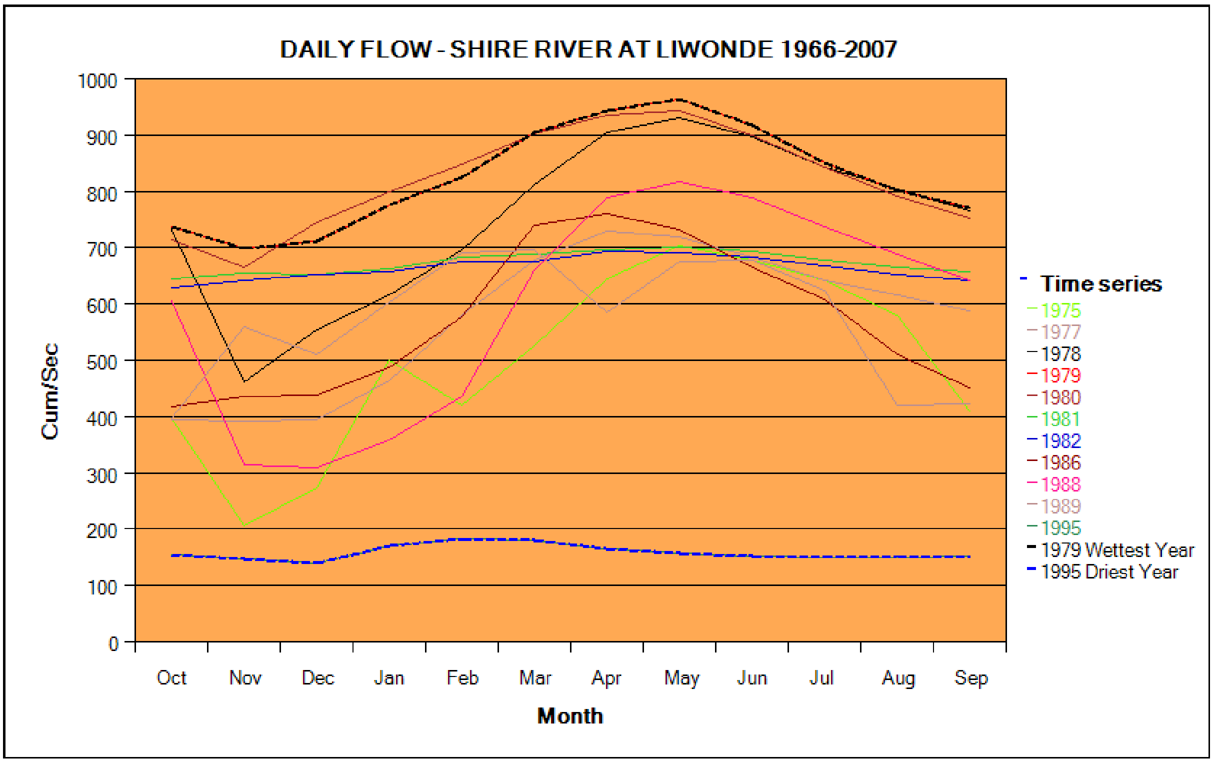


Figure 6.10: Outflows at Kamuzu Barrage for the ten wettest years in the period 1966 to 2007

The October 2002 to September 2003 hydrograph shows that this was a wet year and outflows from Lake Malawi were above 500m^3/s in March and rising. This observation suggests some serious challenges with the existing operating rule.

6.3.1 Impact of floods on operation of installed hydropower plants

The main hydro power plants on the Shire River are as follows:

Power Plant	Generation Capacity (MW)			Design Flow cum/sec	Normal Mode of Operation
	Minimum	Optimum	Maximum		
Nkula A	15	22.5	24	69	Run continuously for base load
Nkula B	60	90	100	195	Run continuously for base load
Tedzani I &II	36	38	40	120	Run continuously for base load
Tedzani III	48	51	52.7	134.6	Shut down during off peak periods
Kapichira	36	53	64.8	135	Run continuously for base load

Nkula (A and B) requires 264 m^3/sec but can take up to 284 m^3/sec. However since 1966 the operations of the Kamuzu Barrage the Lake Level has been above 475.32 m.a.s.l., 50% of the time between March and June. At this level the outflow from Lake Malawi can exceed 600m^3/sec which is far in excess of the power plants. In addition the existing reservoirs they draw of from are filled in a very short time (a minutes or maximum 3hrs) depending on their starting storage and the amount of water diverted to the turbines.

The spillway at the Nkula power plant has structures which raise the water level for hydro power but collapse to protect the dam and intake works when high floods are experienced. In 2001 floods damaged the intake structure at Tedzani and weeds blocked the trash screens causing cavitation of the penstock. Since then differential pressure sensors have been installed to determine in advance when interventions are required at the intake. Kapichira has a training wall which guides flow away from the intake works.

The Lake Malawi/Shire River system has large quantities of water weeds and trash. With the high flows these weeds and trash are carried down to the power plants where they can block off the intake works and causing damage to civil and mechanical works. In March 2003 all 5 turbines on Nkula B power plant were affected. Weed and trash management is therefore important for continued operation of the power plants especially during periods of high floods.

Figure 6.11: Trash management Nkula hydropower plant

An extrapolation can be made that a rise in Lake water levels above 476 m.a.s.l. occurring 3% of time will result in similar reduction or suspension of hydropower operations. However this study has shown that hydropower operations will be disrupted further by the higher and more frequent flows from unregulated rivers.

6.4 Impact of unregulated rivers on flooding on the Lower Shire

From Figures 6.12 and 6.13 it is evident that during the period 1966 to 1989 the hydrograph at Matope had the same shape as that for Liwonde hence down to this point on the Shire River the tributaries have no major impact or influence on flood flows.

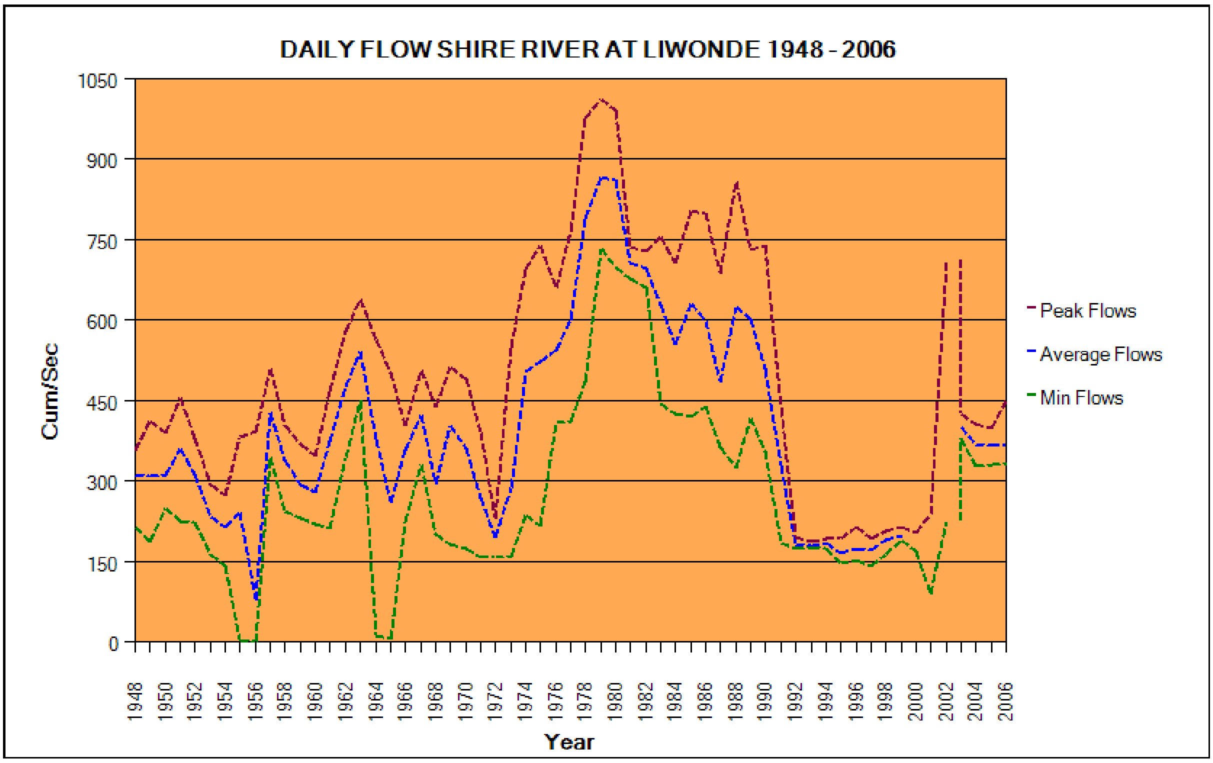


Figure 6.12: Shire River flow at Liwonde.

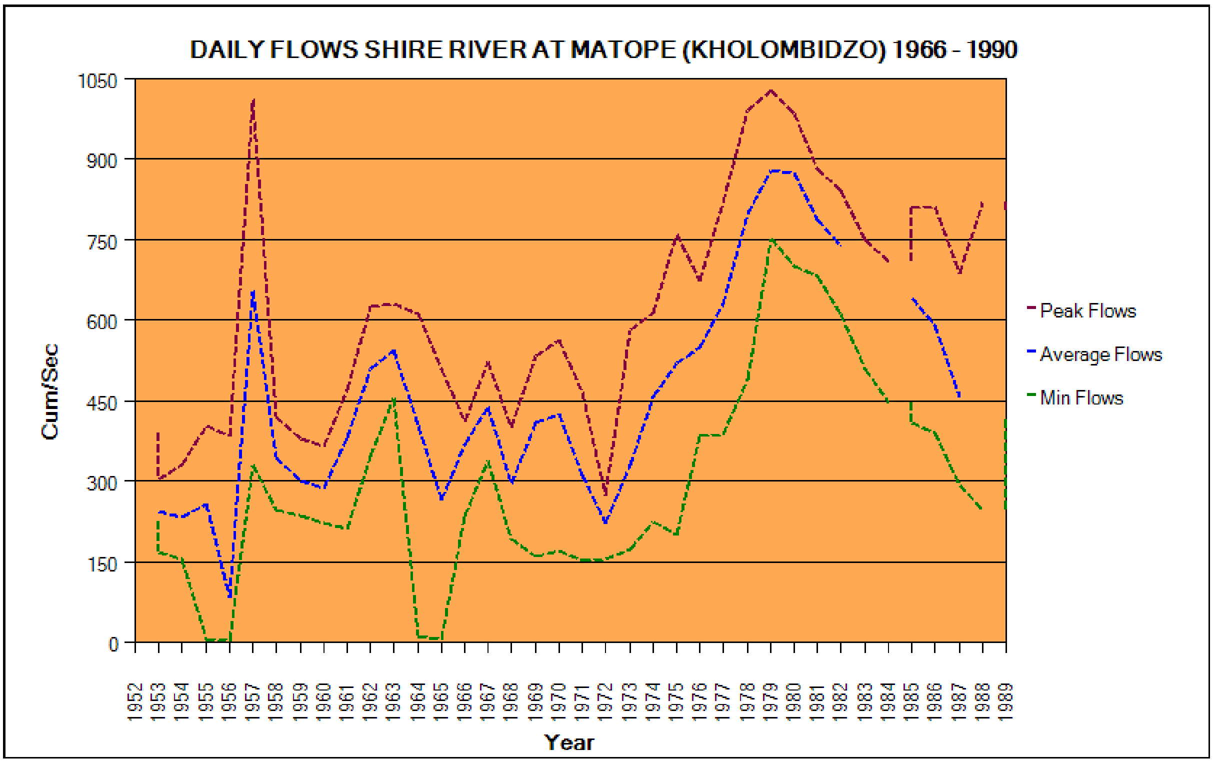


Figure 6.13: Shire River flow at Matope.

The hydrograph at Chiromo in Figure 6.14 shows a different picture especially for the period 1977 to 1984 which suggests that high flows were received from tributaries between Matope and Chiromo.

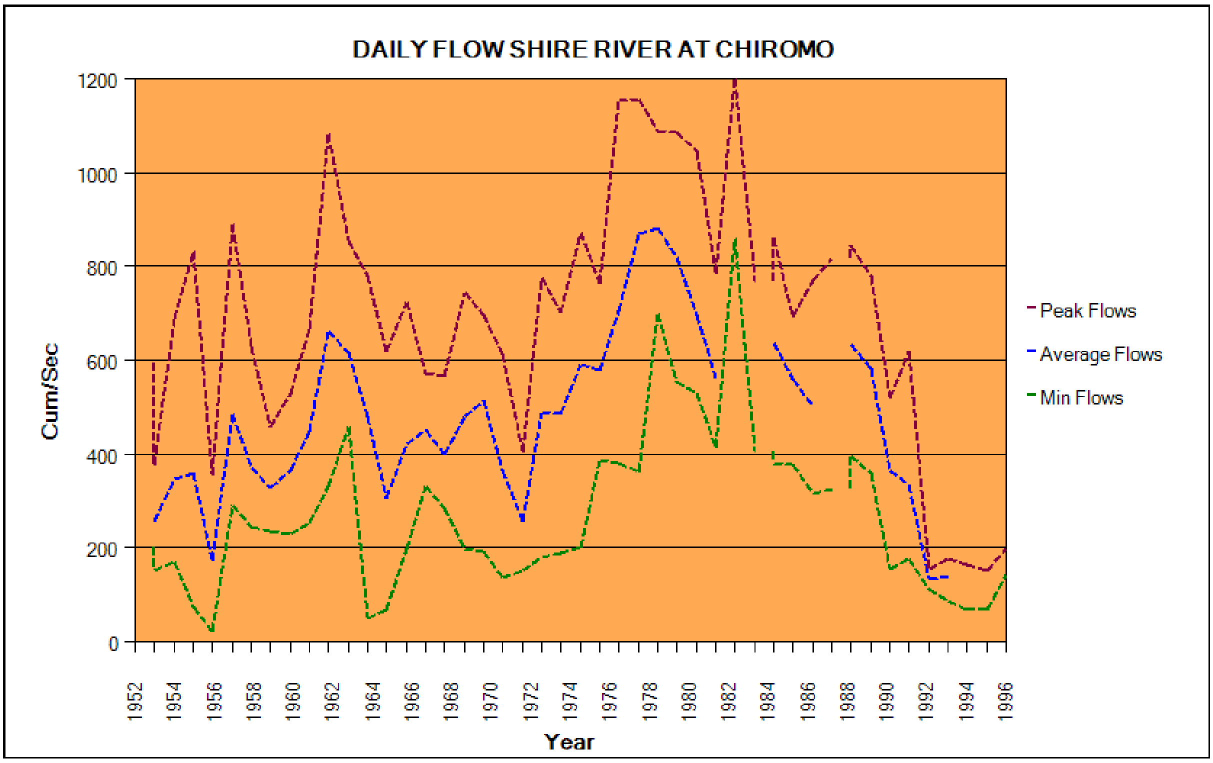


Figure 6.14: Shire River flow at Chiromo

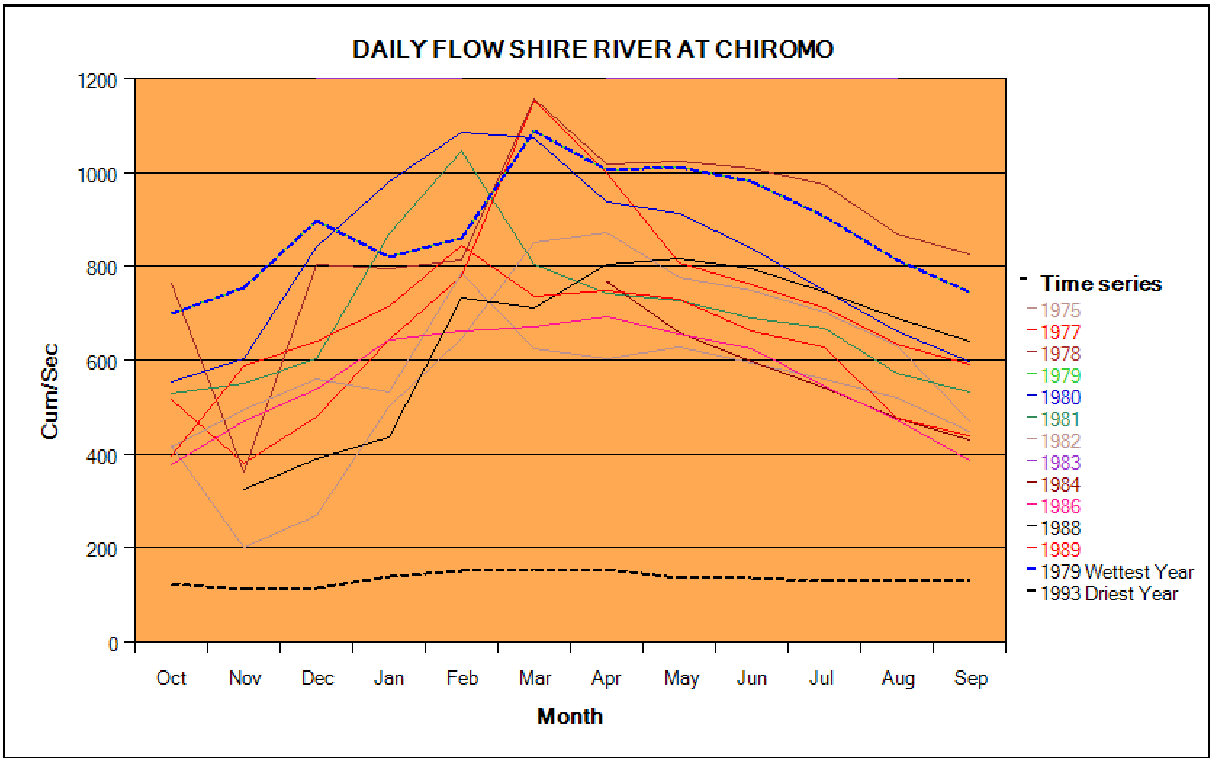


Figure 6.15: Flow at Chiromo wettest years ten wet years in the period 1966 to 1996

Figure 6.15 shows that February to April are distinct high flow months with peaks in February and March and sometimes April.

The most serious and most frequent flooding takes place in the Lower Shire towards its confluence with the Zambezi River. The flooding in this region is mainly caused by the tributaries to the Shire River especially the events in the Ruo River, the Elephant Marsh areas and backwater from the Zambezi. These floods cannot be managed through the regulation functions at Kamuzu Barrage. A combination of high outflow from Lake Malawi and the high flows from tributaries on the Shire can result in very high floods as illustrated using the flood peaks at Kolombidzo are estimated by Government of Malawi (2003b) presented below.

Item	1:100 year flood (cum/sec)	Maximum Probable Flood cum/sec
Outflow from Lake Malawi	1000	1150
In flow from sub-system	1000	4150
Total	2000	5300

Flooding in the lower Shire caused by unregulated tributaries could be mitigated/reduced by infrastructure development and implementation of an early warning and communication system. If the operation of the Kamuzu Barrage (within its effective range to reduce outflow from the lake) also considers the flood hydrographs and concentration times of downstream tributaries it is possible from the above table that the extent of downstream flooding could be reduced. The wetlands on the Shire River are listed in section 4.2.

6.5 New interventions under consideration and impacts on flood releases and environmental flows

Three interventions have been investigated to improve the operation of the Lake Malawi – Shire subsystem as follows:

(a) Installation of pumps at Samama/Mponda
(b) Rehabilitation of Kamuzu Barrage and
(c) Construction of a dam at Kholombidzo

The implication of each of these options on management of flood releases, Lake levels and environmental flows is evaluated in the following sections.

6.5.1 Installation of pumps at Samama/Mponda

The outlet from Lake Malawi is at Samama. Low Lake levels were experienced in the 1990s which affected power production. A proposal was put forward to pump water from the Lake at Samama and later Mponda in order to sustain the flow required for power generation on the Shire River. This option entails the construction of a pumping barrage at Mponda.

According to the government of Malawi (2003) the Pumping Barrage concept is a standby approach to sustain hydro power production using the existing power stations and also providing a guarantee on the minimum flows in Shire. It removes the risk of power shortfalls and lack of water downstream. The intention is to use the pumps in emergency situations only as it is understood that extended draw-down to 470 m.a.s.l. and below has unacceptable environmental consequences which should be avoided. The pumps are justified on a very cautious approach which considers that Lake level recession and thus the flow reduction is a very slow and fairly deterministic process, so there will be ample time to evaluate the need to operate the pumps each time a drought is experienced.

The proposed 20 pumps would be used to lift water from the lake to enable it to then flow downstream under gravity. The total pumping head is about 6m and with a design capacity of 10cum/sec per pump. Backflow into the lake would be eliminated by means of gates which can allow the water downstream to rise to about 478.5m.a.s.l. However during pumping the Lake level will recede and under extreme dry conditions the pumping action may draw the Lake Malawi water surface down to unacceptably low levels from ecological as well as socioeconomic points of view.

This critical 'trigger level' of 473.50 for the start of pumping from the Lake was suggested for hydro power but if the balance of electricity is imported to meet needs of downstream water users the trigger level could be set at either 473.0 or 472.5 m.a.s.l.

With a minimum suction level of 465.75 and a maximum delivery level of 471.75 m.a.s.l. the pumps cannot be used during periods of high lake levels.

This pumping option could reduce Lake levels below what is possible naturally which would negatively affect ecosystems and other activities on the Lake.

6.5.2 Rehabilitation of Kamuzu Barrage

The Kamuzu Barrage is currently manually operated, unsafe, in need of repairs and maintenance. One of the gates is permanently stuck in a closed position. During the 1980s (generally wet) the Lake level frequently exceeded 475.32 m.a.s.l. and all the gates were kept full open during the wet season in line with the existing operating rule. If similar weather conditions are experienced the current condition of the barrage will leave no room to control flooding of upstream areas. The barrage is also by uncontrolled downstream erosion and proliferation of weeds. This option entails the refurbishment of the existing barrage to its original condition. The Kamuzu Barrage will operate at 475.75 m.a.s.l. after raising and rehabilitation.

The alternative option is to separate the regulating structure from vehicular and pedestrian overpass by introducing a new structure immediately adjacent on the upstream side of the present barrage to serve as a new gate facility. This is intended to protect the gates and their hoisting functions. The old gates will then be dismantled, upgraded and reinstalled about 20m upstream of their present location. The existing barrage structure will be maintained as an overpass for vehicles and people only. The regulation height at Liwonde will be increased to 20cm above the present flash boards of the Kamuzu Barrage. However, investigations of upstream site alternatives to Kamuzu Barrage came up negative due to the unfavourable foundation conditions and the high costs of relocating the structure.

The Government of Malawi (2003c) estimates that Lake water level will rise above 476 m.a.s.l. 3.3% of the time with the Kamuzu Barrage operating at a maximum level of 475.5 m.a.s.l. Thus in relation to Figure 6.6 the Upgraded Liwonde Barrage will not have any major impact on the long-term natural variation in lake levels.

6.5.3 A new dam at Kholombidzo

This involves the construction of a regulating dam at Kholombidzo falls, 50km downstream of the Kamuzu Barrage on the Shire River. Two alternatives are available under this option namely a high dam providing a head for hydropower of about 75m and a low dam providing a head for hydropower of about 71m.

Kholombidzo dam will be upstream of the existing power plants in the cascade development of the hydropower plants in Shire River. The capacity of the proposed power plant would be such that the outflow will match the maximum flow required at Nkula and Tedzani in order not to minimize spillage as the reservoirs on the existing power plants cannot store additional discharge from Kholombidzo. When upgraded to 132MW Kapichira will require 270m^3/sec which is lass than the requirements for any of these other power stations.

During floods the High Kholombidzo reservoir will extend all the way to Lake Malawi, creating a vast reservoir area. The effect of a rise in reservoir surface at Kholombidzo on Lake Malawi will depend on the lake level prior to the flood. The worst case is a PMF flood in Lake Malawi simultaneously with a PMF downstream of Lake Malawi. In this situation the lake level is about 477.0, the level at Liwonde 475.4 and the discharge 1150m^3/sec. There will still be considerable reservoir volume available for storage if the water level at Kholombidzo is allowed to rise. A water level rise would also result in reduced outflow from Lake Malawi. Since the PMF flood downstream of Lake Malawi has a short duration, the resulting rise in Lake Malawi would be minimal. Thus when the inflow to Kholombidzo is lower than the maximum turbine capacity, the power plants along the Shire may be operated at full capacity during the peak hours of the day and at a lower capacity the rest of the day.

Kholombidzo High Dam can be used to control flooding downstream when the level of water in Lake Malawi goes above 475.32 m.a.s.l. and to better manage fluctuations in flow required for hydropower and downstream activities.

6.6 Recommendations from an ecosystems management perspective

The following should guide the operation of the subsystem:

(a) Flows of the Shire river and the Lake should maintain the integrity of the national parks and river system

(b) The reduction of Lake Malawi levels below what is possible naturally should be avoided

(c) Enhance the flooding of Elephant Marshes

(d) Maintain sediment transport through to the Zambezi Delta

(e) Reconsider the entire system and infrastructure to include environmental flows to the extent possible (considering hydropower and flood control water requirements)

(f) Manage water hyacinth and alien vegetation to reduce their nuisance value

6.7 Recommended concepts for management of flood releases

The following improvements in the operation of the subsystem have been identified:

(a) The Kamuzu Barrage regulates the level of water in Lake Malawi/Shire River to keep enough water in storage for regulated releases for hydropower. The Barrage in its current state (on gate stuck closed) is in fact an obstruction to floods and poses safety risks to operators through manual operation of gates. Local flooding can also occur because of the floods should the Lake receive large inflows. Rehabilitation is required to improve the current state of the Barrage and allow for its safe operation.

(b) The existing rule should be implemented. Monitoring should capture actual releases, lake levels (not only levels downstream of the barrage) and flows at Nkula

(c) Avoid low lake water levels, low flow and levels in the Lake and lower Shire River for navigation and fisheries industries. The river flow augmentation pumping scheme proposed at Samama or Mponda will aggravate this situation and its construction should be avoided.

(d) The height of proposed Kholombidzo dam should not cause more flooding than the operations of the existing Kamuzu Barrage.

(e) Provide advance information on the following:
- The timing floods above the range of control of the Barrage.
- Estimates of flows and concentration times of unregulated downstream tributaries to manage flooding in the Shire
- Movement of the backwaters from Zambezi into the lower Shire

(f) Develop and implement operating rules for the Kamuzu Barrage to maintain flows and dampen fluctuations in the Shire River to improve hydropower capacity and reliability while respecting other system objectives. This may require increases in power drawings from the SAPP when lake levels are low and sale of peaking power to the same pool when lake levels are high.

(g) Consider the entire system and its infrastructure in formulating environmental flows to enhance the environmentally sensitive ecosystems to the extent possible while considering hydropower and flood control requirements. This would require new operating rules for the Kamuzu Barrage to accommodate these other objectives. These multiple objectives should be considered in the design and operation of new hydropower infrastructure.

These recommendations are captured in Intervention Sheets 2.4, 2.5 and 2.6 in Chapter 10.

7 New Multipurpose Dams and Regulation of the Zambezi and its Tributaries

7.1 Introduction

In Chapter 5 a shift in the operation of existing dams from a focus on dam safety and hydro power production to new modes of operation which consider multiple objectives was proposed but these will be constrained by the configuration and capacities of existing infrastructure at these dams. Chapter 5 also makes the point that all future dam operations will need to be take a basin-wide perspective a departure from the current local focus on a particular dam. The following conclusions reached in Chapter 5 are thus very important:

(a) Unregulated tributaries on the Zambezi River System contribute significantly to flooding and they influence timing and magnitude of flood releases. “New” dams on the Zambezi main stem and tributaries can reduce pressure on existing large dams and indirectly contribute to flood management

(b) The proposed new modes of operation result in some reduction in power output but have benefits for dam safety, the environment and other uses. More specifically, during “wet” and very wet” periods dam operations can observe the dam safety rule, and meet other objectives and the small reduction in power output arising from following the new rules can be made up from either the construction of new dams on the Zambezi or from the installation of additional turbines on existing dams.

(c) Dams alter downstream flow regimes. However, while they cannot restore the original conditions, the operation of existing dams under new operating rules can result in significant improvements in downstream conditions.

The current chapter examines the contribution of tributaries of the Zambezi River to floods. Possible worst case scenarios for flooding are identified. The potential contribution of proposed multi-purpose dams to improved dam management and addressing basin wide objectives is also evaluated.

7.2 Situation assessment

For the assessment of flood flows, the Zambezi River Basin was divided into three zones namely the Upper Zambezi (from source to Victoria Falls) Middle Zambezi, from Victoria falls to Cahora Bassa Dam; and Lower Zambezi, downstream of Cahora Bassa Dam to the river mouth at the Indian Ocean. The ZAMWIS database was applied to review available historical flow data to establish continuity (longest period of continuous record, duration of observations and whether the station is active or not). The gauge stations applied on this section represent the ones with the most reliable and fairly long historical data. Some data was extended using in-house developed routing equations. The corporation of ZINWA, ZESO, ESCOM and ARA Zambezi in this regard is fully acknowledged.

7.2.1 Assessment of contribution of unregulated rivers to historical floods

The top ten peak monthly floods were identified for each tributary. Victoria Falls has the longest record of historical flows in the Zambezi system. The hydrographs for the years that coincide with high flows at Victoria Falls were constructed for the other stations. The results obtained are presented in this section.

Upper Zambezi

The contribution of tributaries in Upper Zambezi to floods on the Zambezi main stem is illustrated in Figure 7.1. The results show that 1968 and 1977 the tributaries peaked during the same month and the result was exceptionally high floods. The 1977 peak floods are shown in Table 7.1.

Table 7.1: Upper Zambezi - Flood peaks from 1977 flood event

Locality	Peak Flood (m^3/sec)
Chavuma	971
Zambezi Pump House	1063
Kabompo Watopa	1344
Lukulu	1827
Senanga	2582
Katima Mulilo	6828
Victoria Falls	5433

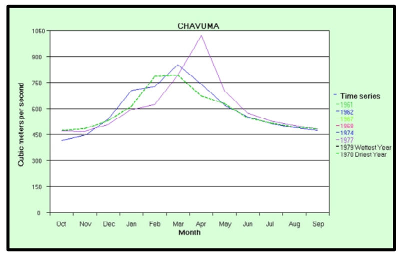
Historical flows also show the Zambezi can peak up to 1050 m^3/sec at Chavuma near the border with Angola. The Kabompo River can discharge up to 1800 m^3/sec into the Zambezi River main stem upstream of the confluence of the Zambezi River with the Lungwebungu River. In 1977 flow at Lukulu near the inlet to the Barotse floodplain reached about 2600 m^3/sec. Flows at the downstream end of the Barotse are recorded at Senanga and can reach up to 2800m^3/sec and Katima Mulilo can reach 7000 m^3/sec. The hydrographs show that the tributaries peak in March or April. The Upper Zambezi, Kabompo and Barotse sub-catchments are the main drivers of floods and flow variability in this sub-system. The historical data show that the Barotse Plain has a storage function but the flood peaks increases from Lukulu to Senanga because of the contribution other tributaries feeding into the wetland and this is collaborated in section 4.3.1 of this report. However the stretch of the catchment from Katima Mulilo to Victoria Falls is more important for reducing the peak floods for example, in 1977 peak flow at Katima Mulilo was significantly higher (>25%) than the peak flow at Victoria Falls downstream.

The history of floods shows that the worst case scenario is when the tributaries are all experiencing high flows.

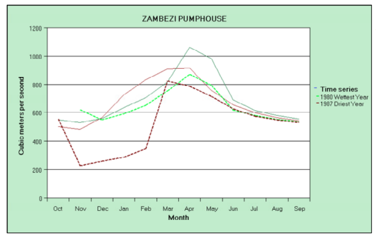
Upper Zambezi Subsystem

Chavuma

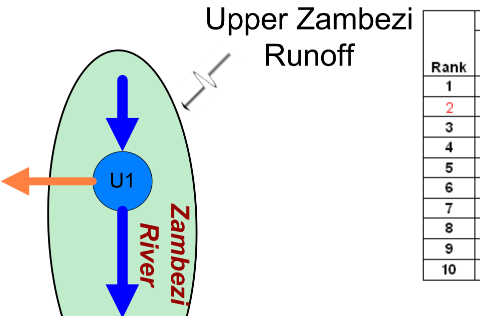
Rank	Chavuma		
	Year	Month	Value (cum/sec)
1	1977	Apr	970.77
2	1975	Mar	851.24
3	1988	Apr	844.23
4	1974	Mar	809.33
5	1976	Apr	771.43
6	1980	Apr	767.7
7	1985	Apr	756.85
8	1970	Mar	752.65
9	1973	Apr	701.5
10	1983	Mar	698.07

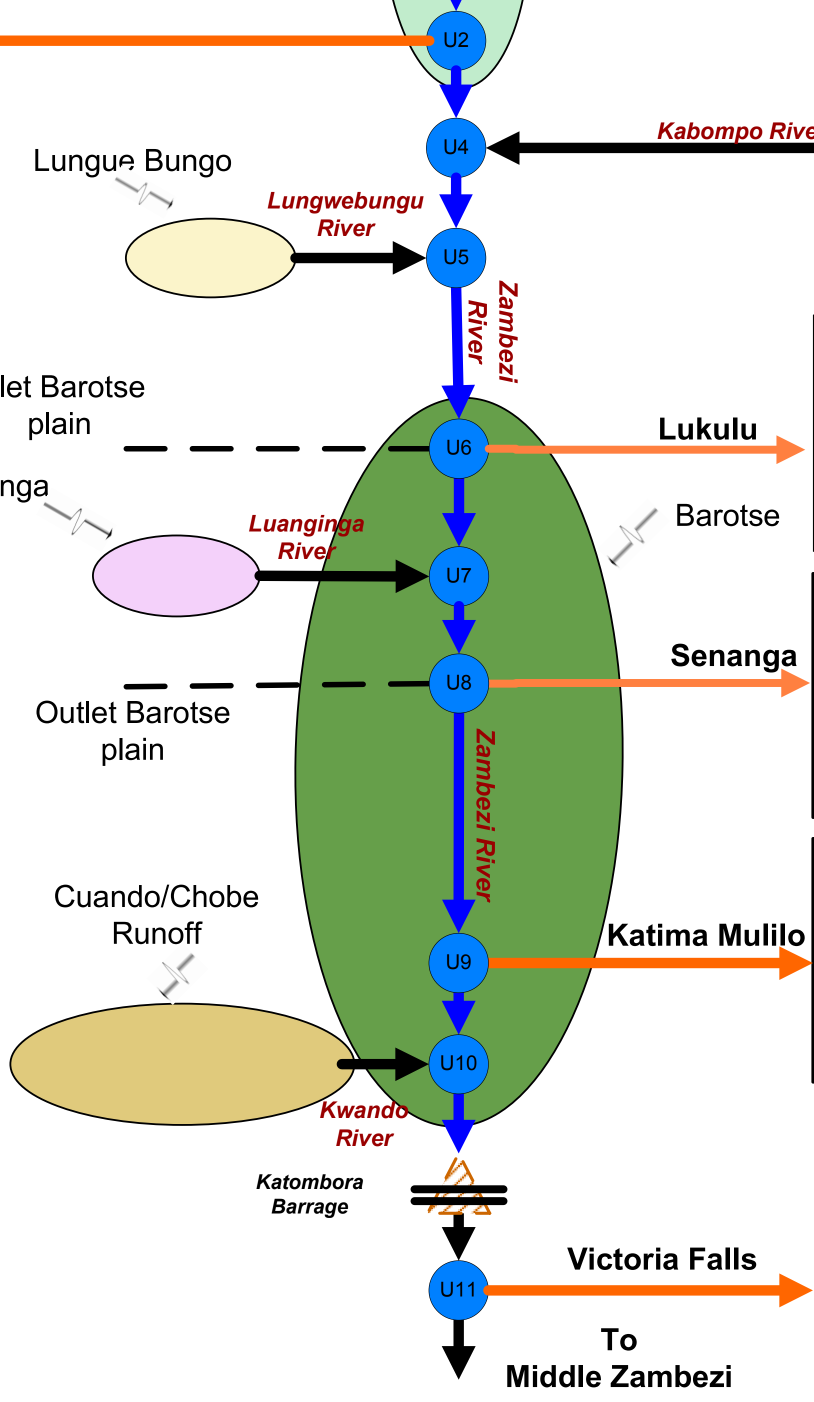


Rank	Zambezi P House		
	Year	Month	Value (cum/sec)
1	1977	Apr	1062.90
2	1975	Apr	1030.06
3	1988	Apr	957.12
4	1974	Apr	915.10
5	1976	Apr	891.34
6	1985	Apr	878.36
7	1990	Mar	841.13
8	1983	Mar	834.43
9	1986	Mar	828.35
10	1987	Mar	826.34

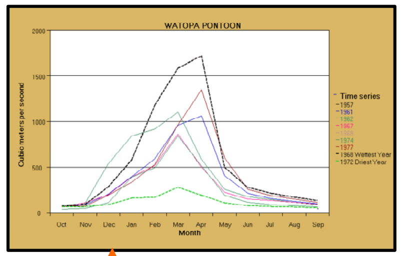


Pump House

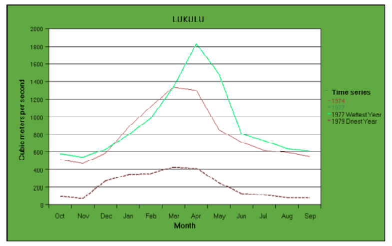




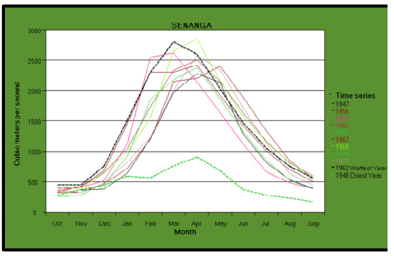
Rank	Watopa		
	Year	Month	Value(cum/sec)
1	1968	Apr	1716.93
2	1977	Apr	1344.12
3	1978	Apr	1174.08
4	1969	Feb	1164.1
5	1962	Mar	1103.05
6	1961	Apr	1062.04
7	1975	Apr	980.07
8	1960	Mar	970.93
9	1965	Mar	915.79
10	1970	Feb	897.36



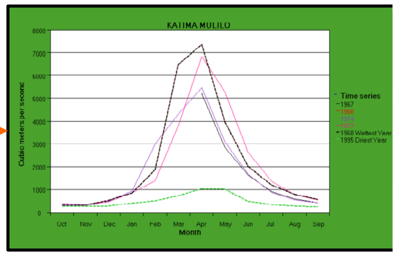
Kabompo Watopa



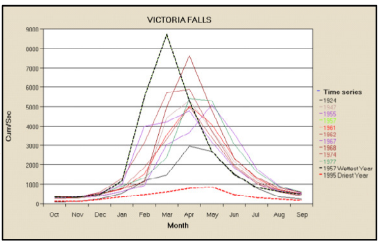
Rank	Lukulu		
	Year	Month	Value (cum/sec)
1	1977	Apr	1826.53
2	1975	Apr	1622.51
3	1978	Mar	1567.95
4	1980	Apr	1401.51
5	1974	Mar	1336.70
6	1976	Apr	1259.69
7	1986	Mar	1215.87
8	1985	Apr	1188.18
9	1990	Mar	1151.69
10	1987	Apr	1133.66



Rank	Senanga		
	Year	Month	Value (cum/sec)
1	1968	Apr	2844.64
2	1962	Mar	2797.49
3	1957	Mar	2615.8
4	1977	Apr	2582.12
5	2000	Apr	2563.34
6	1956	Mar	2562.84
7	1988	Apr	2544.85
8	1961	Apr	2501.32
9	1951	Mar	2498.91
10	1969	Mar	2497.3



Rank	Katima Mulilo		
	Year	Month	Value (cum/sec)
1	1968	Apr	7352.84
2	1977	Apr	6825.99
3	1975	Apr	5615.39
4	1978	Apr	5542.89
5	1969	Mar	5458.83
6	1974	Apr	5456.89
7	1988	May	4017.39
8	1992	Apr	3917.74
9	1980	Apr	3820.96
10	1979	Apr	3666.43



Victoria Falls			
Rank	Year	Month	Value (cum/sec)
1	1957	Mar	8719.96
2	1968	Apr	7610.39
3	1962	Apr	5894.17
4	1977	Apr	5432.39
5	1967	Apr	4775.58
6	1955	May	5088.19
7	1961	Apr	5015.39
8	1947	Apr	5303.51
9	1974	Apr	4990.61
10	1951	Mar	5177.54

Date:29/03/2011

Legend

●	Flow gauge station on map
U7	Flow gauge station on schematic
→	Main stem
→	Tributary
Barotse	Catchment / Subcatchment runoff
Lupata	Identified proposed dam
	Proposed barrage
▲	Existing dam
▲	Existing barrage
Senanga	Station hydrograph & flood ranks

PREPARED BY: SWRSD
[SSI, WRNA, RANKIN, SEED & DELTARES]
Zambezi Basin Joint Venture

TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

FIG 7-1 UPPER ZAMBEZI SUB-SYSTEM – CONTRIBUTION TRIBUTARIES TO FLOODS & IDENTIFIED PLANNED DAMS.

giz
On behalf of:
Federal Republic of Germany
The Federal Government
UKaid
from the Department for International Development
Australian Government
Aid Program

Middle Zambezi

The experience of operating the Kariba Dam shows that the worst flood situation has occurred when the Upper Zambezi was experiencing high floods and the tributaries of the Zambezi River below Victoria Falls were also discharging high flows. The Gwayi and Sanyati rivers can contribute 300 m^3/sec and 800 m^3/sec respectively and if it happens at a time when the Upper Zambezi is discharging close to 9000 m^3/sec, this would present operational challenges for Kariba.

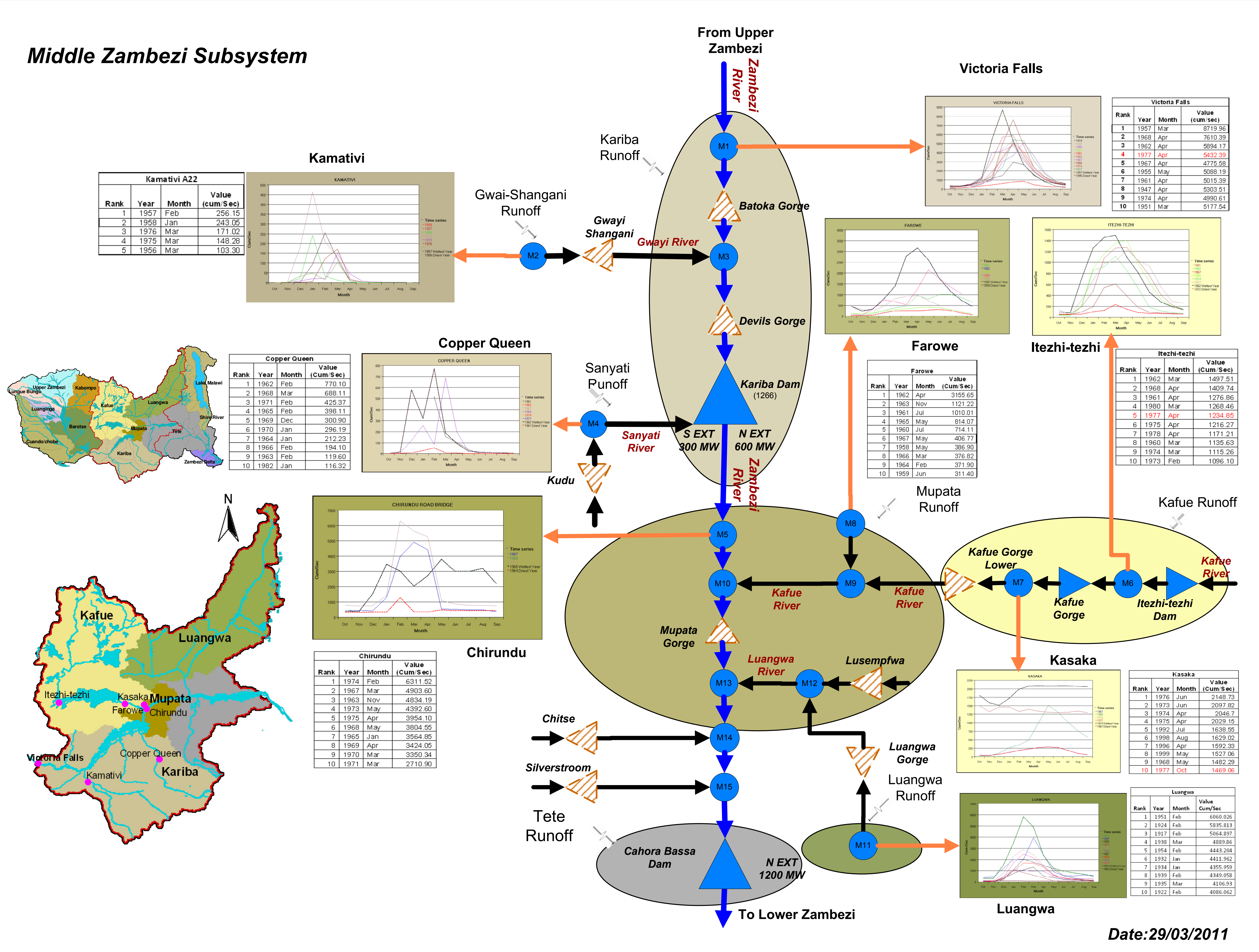
According to ZINWA (2010) flooding has occurred in the Mzarabani and Angwa areas as a result of backflows from Cahora Bassa and Zambezi respectively. In addition inflows from the tributaries are held back because of the high levels of water in the dam. The Angwa River has been affected severely in the recent past. ARA Zambeze (2010) distinguishes three categories as follows:

- releases from Cahora Bassa,
- flow from tributaries and
- flow from tributaries and releases from Cahora Bassa combined.

According to them a flood that only comes from Cahora Bassa will probably never happen. In the Middle Zambezi, the Luangwa meets the Zambezi upstream of Cahora Bassa and it can discharge very high flows. The Msengezi and Manyame rivers discharge into the Cahora Bassa Dam. The Machanga river discharges on the left bank of the Zambezi at a point downstream of the mouth of the Luangwa. Peak floods from Cahora Bassa are in the order of 6000 to 7000 m^3/s.

The contribution of tributaries in Middle Zambezi to floods on the Zambezi main stem based on available daily flow data is illustrated in Figure 7.2. The top ten peak flood flows from each tributary are also shown. Hydrographs were constructed for the years that coincide with high flows at Victoria Falls. The 1977 flood does not feature on the high floods recorded at Chirundu downstream of Kariba dam but appears at Kasaka which is downstream of Kafue Gorge dam. This is a clear illustration of the attenuation capabilities of Kariba dam and the limitations of the Kafue Gorge dam.

Middle Zambezi Subsystem



Kamativi A22			
Rank	Year	Month	Value (cum/Sec)
1	1957	Feb	256.15
2	1958	Jan	243.05
3	1976	Mar	171.02
4	1975	Mar	148.28
5	1956	Mar	103.30

Copper Queen			
Rank	Year	Month	Value (Cum/Sec)
1	1962	Feb	770.10
2	1968	Mar	688.11
3	1971	Feb	425.37
4	1965	Feb	398.11
5	1969	Dec	300.90
6	1970	Jan	296.19
7	1964	Jan	212.23
8	1966	Feb	194.10
9	1963	Feb	119.60
10	1982	Jan	116.32

Chirundu			
Rank	Year	Month	Value (Cum/Sec)
1	1974	Feb	6311.52
2	1967	Mar	4903.60
3	1963	Nov	4834.19
4	1973	May	4392.60
5	1975	Apr	3954.10
6	1968	May	3804.55
7	1965	Jan	3564.85
8	1969	Apr	3424.05
9	1970	Mar	3350.34
10	1971	Mar	2710.90

Victoria Falls			
Rank	Year	Month	Value (cum/sec)
1	1957	Mar	8719.96
2	1968	Apr	7610.39
3	1962	Apr	5894.17
4	1977	Apr	5432.39
5	1967	Apr	4775.58
6	1955	May	5088.19
7	1961	Apr	5015.39
8	1947	Apr	5303.51
9	1974	Apr	4990.61
10	1951	Mar	5177.54

Farowe			
Rank	Year	Month	Value (Cum/Sec)
1	1962	Apr	3155.65
2	1963	Nov	1121.22
3	1961	Jul	1010.01
4	1965	May	814.07
5	1960	Jul	714.11
6	1967	May	406.77
7	1958	May	386.90
8	1966	Mar	376.82
9	1964	Feb	371.90
10	1959	Jun	311.40

Itezhi-tezhi			
Rank	Year	Month	Value (Cum/Sec)
1	1962	Mar	1497.51
2	1968	Apr	1409.74
3	1961	Apr	1276.86
4	1980	Mar	1268.46
5	1977	Apr	1234.85
6	1975	Apr	1216.27
7	1978	Apr	1171.21
8	1960	Mar	1135.63
9	1974	Mar	1115.26
10	1973	Feb	1096.10

Kasaka			
Rank	Year	Month	Value (Cum/Sec)
1	1976	Jun	2148.73
2	1973	Jun	2097.82
3	1974	Apr	2046.7
4	1975	Apr	2029.15
5	1992	Jul	1638.55
6	1998	Aug	1629.02
7	1996	Apr	1592.33
8	1999	May	1527.06
9	1968	May	1482.29
10	1977	Oct	1469.06

Luangwa			
Rank	Year	Month	Value Cum/Sec
1	1951	Feb	6060.026
2	1924	Feb	5835.813
3	1917	Feb	5064.897
4	1938	Mar	4889.86
5	1954	Feb	4443.204
6	1932	Jan	4411.962
7	1934	Jan	4355.959
8	1939	Feb	4349.058
9	1935	Mar	4106.93
10	1922	Feb	4086.062

Date:29/03/2011

Legend

● Flow gauge station on map

U7 Flow gauge station on schematic

Main stem

Tributary

Barotse — Catchment / Subcatchment runoff

Lupata — Identified proposed dam

Proposed barrage

Existing dam

Existing barrage

Senanga — Station hydrograph & flood ranks

PREPARED BY: SWRSD
[SSI, WRNA, RANKIN, SEED & DELTARES]
Zambezi Basin Joint Venture

TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

FIG 7-2 MIDDLE ZAMBEZI SUB-SYSTEM – CONTRIBUTION TRIBUTARIES TO FLOODS & IDENTIFIED PLANNED DAMS

giz
On behalf of: Federal Republic of Germany The Federal Government
UKaid from the Department for International Development
Australian Government Aid Program

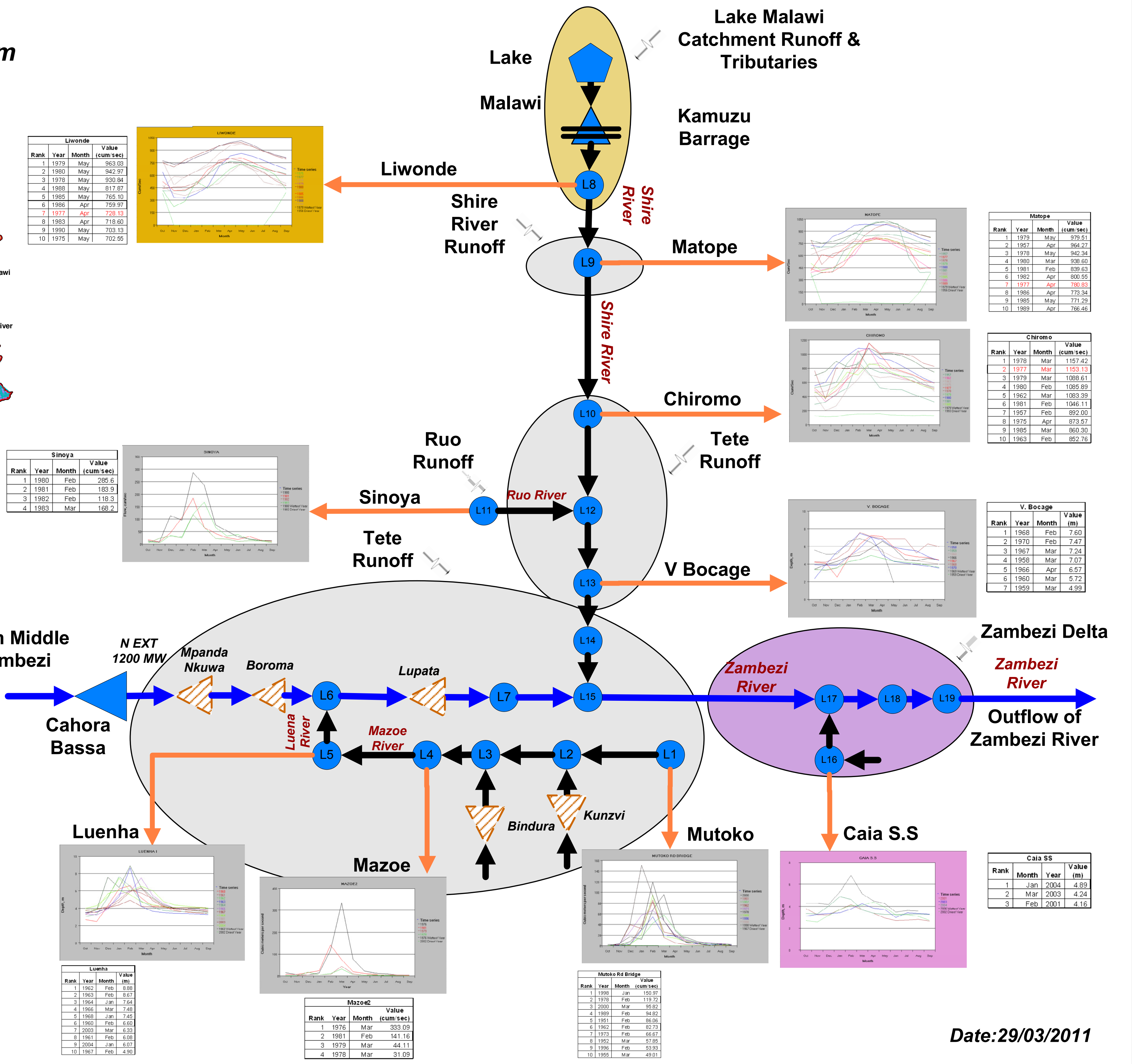
Lower Zambezi

According to ARA Zambeze (2010) the Luia (two tributaries called Luia), Revuboe, Luenya, Muira and Pompoe tributaries of the Zambezi can discharge very high flood flows. The Revuboe can add around 2000-3000 m^3/s, the Mazowe/Luenha about 3000 – 4000 m^3/s, Shire 2000-4000 m^3/s. When the Zambezi river is in flood, water flows into the Cuacua, goes into Luala then Licuane which then affects Quelimane. This system is called Rios Bons Sinais.

The contribution of tributaries in Lower Zambezi to floods on the Zambezi main stem based on available daily flow data is illustrated in Figure 7.3.

.

Lower Zambezi Subsystem



Liwonde			
Rank	Year	Month	Value (cum/sec)
1	1979	May	963.03
2	1980	May	942.97
3	1978	May	930.84
4	1988	May	817.87
5	1985	May	765.10
6	1986	Apr	759.97
7	1977	Apr	728.13
8	1983	Apr	718.60
9	1990	May	703.13
10	1975	May	702.55

Matope			
Rank	Year	Month	Value (cum/sec)
1	1979	May	979.51
2	1957	Apr	964.27
3	1978	May	942.34
4	1980	Mar	938.60
5	1981	Feb	839.63
6	1982	Apr	800.55
7	1977	Apr	780.83
8	1986	Apr	773.34
9	1985	May	771.29
10	1989	Apr	766.46

Chiromo			
Rank	Year	Month	Value (cum/sec)
1	1978	Mar	1157.42
2	1977	Mar	1153.13
3	1979	Mar	1088.61
4	1980	Feb	1085.89
5	1962	Mar	1083.39
6	1981	Feb	1046.11
7	1957	Feb	892.00
8	1975	Apr	873.57
9	1985	Mar	860.30
10	1963	Feb	852.76

Sinoya			
Rank	Year	Month	Value (cum/sec)
1	1980	Feb	285.6
2	1981	Feb	183.9
3	1982	Feb	118.3
4	1983	Mar	168.2

V. Bocage			
Rank	Year	Month	Value (m)
1	1968	Feb	7.60
2	1970	Feb	7.47
3	1967	Mar	7.24
4	1958	Mar	7.07
5	1966	Apr	6.57
6	1960	Mar	5.72
7	1959	Mar	4.99

Luenha			
Rank	Year	Month	Value (m)
1	1962	Feb	8.88
2	1963	Feb	8.67
3	1964	Jan	7.64
4	1966	Mar	7.48
5	1968	Jan	7.45
6	1960	Feb	6.60
7	2003	Mar	6.33
8	1961	Feb	6.08
9	2004	Jan	6.07
10	1967	Feb	4.90

Mazoe2			
Rank	Year	Month	Value (cum/sec)
1	1976	Mar	333.09
2	1981	Feb	141.16
3	1979	Mar	44.11
4	1978	Mar	31.09

Mutoko Rd Bridge			
Rank	Year	Month	Value (cum/sec)
1	1998	Jan	150.97
2	1978	Feb	119.72
3	2000	Mar	95.82
4	1989	Feb	94.82
5	1951	Feb	86.06
6	1962	Feb	82.73
7	1973	Feb	66.67
8	1952	Mar	57.85
9	1996	Feb	53.93
10	1955	Mar	49.01

Caia SS			
Rank	Month	Year	Value (m)
1	Jan	2004	4.89
2	Mar	2003	4.24
3	Feb	2001	4.16

Date:29/03/2011

Legend

●	Flow gauge station on map
U7	Flow gauge station on schematic
→	Main stem
→	Tributary
Barotse	Catchment / Subcatchment runoff
Lupata	Identified proposed dam
	Proposed barrage
▲	Existing dam
	Existing barrage
Senanga	Station hydrograph & flood ranks

PREPARED BY: SWRSD
[SSI, WRNA, RANKIN, SEED & DELTARES]
Zambezi Basin Joint Venture

TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

FIG 7-3 LOWER ZAMBEZI SUB-SYSTEM – CONTRIBUTION TRIBUTARIES TO FLOODS & IDENTIFIED PLANNED DAMS

SOUTHERN AFRICAN DEVELOPMENT COMMUNITY
SADC
TOWARDS A COMMON FUTURE
giz
On behalf of:
Federal Republic of Germany
The Federal Government
UKaid
from the Department for International Development
Australian Government
Aid Program

7.2.2 Review of literature on proposed new planned dams

Table 7.2 shows the list of proposed dams, new power plants and extensions to existing power plants obtained from literature and reviewed.

Upper Zambezi

The site for the proposed Katombora weir is 42km upstream of Victoria Falls on the Zambezi main stem and it will have insignificant storage. The proposal is for a barrage to regulate flows for hydropower production. It presents a possibility to divert part of the Zambezi flows to Botswana and Zimbabwe. The Victoria Falls is a heritage site and the diversion of upstream flows may not meet required conditions to maintain the site. The weir will not have enough storage to perform any significant flood management function.

Middle Zambezi

A total of 17 schemes were identified in the Middle Zambezi. They comprise 5 new dams for hydro power generation, extensions to 4 existing power generation schemes, 5 new dams for irrigation water supply and 3 new dam for irrigation water supply and hydro power.

Extensions to existing power stations can increase power output by about 300MW at the Victoria Falls runoff river scheme, 600MW at Kariba, 80MW at Itezhi-Tezhi and 1200MW at Cahora Bassa.

Potential new power generation schemes can bring in about 300MW at Victoria Falls, 1200MW at Devils Gorge, 1600MW at Batoka Gorge, 450MW at Kafue Gorge and 640MW at Mupata Gorge.

All these potential new schemes are not associated with huge storage works compared to current dams. They are basically run-of-river schemes that will operate on a "use it or lose it" basis in terms of flow. Thus while there will be less pressure on Kariba and Cahora Bassa to operate at maximum capacity all the rime, storing enough water for power security will remain one of the objectives of two dams.

Table 7.2: Middle Zambezi - Proposed dams, power plants and power plant extensions

Scheme Number	Scheme	Location	Purpose of scheme	Additional Gross Storage ($x10^6$ m^3)
1. Schemes for hydro power generation				
1-1	Victoria Falls North Bank	Zambezi main stem (Zimbabwe)	Hydro power generation, 300MW	Nil
1-2	Devils Gorge	Zambezi main stem, at the headwater of Lake Kariba	Hydro power generation, 1200MW potential.	Not determined
1-3	Batoka Gorge	Between Victoria Falls and Kariba, 54km downstream of Victoria Falls	Hydro power generation, 1600MW potential	1.68
1-4	Kafue Gorge Lower Hydropower Project (KGLHP)	Kafue Gorge, 65km upstream of confluence of Kafue River and Zambezi River, and 2km downstream of existing Upper Kafue Gorge Hydro Project	Hydro power generation, 450MW potential	3.8; 10.1 and 54.5 depending on which site is finally chosen
1-5	Mupata Gorge	Between Kariba and Cahora Bassa	Hydro power generation, 640 MW potential	Not determined

Scheme Number	Scheme	Location	Purpose of scheme	Additional Gross Storage (x10^6 m^3)
2.Extensions to existing power plants/schemes				
2-1	Victoria Falls South Bank	Zambezi main stem,	Hydro power generation, 390MW potential	16
2-2	Kariba Extension	Kariba	Hydro power generation, 600MW potential.	Nil
2-3	Cahora Bassa Extension	Cahora Bassa	Hydro power generation, 1200MW potential	Nil
2-4	Itezhi-Tezhi Hydroelectric Project	At Itezhi-Tezhi Dam on the Kafue river, 295km upstream of confluence with Zambezi River, and 230km upstream of existing Upper Kafue Gorge Hydro Project	Hydro power generation, 80MW potential	Nil
3.Dams for irrigation water supply and hydro power				
3-1	Gwayi Shangani	On Gwayi river	Irrigation, urban water supply and hydro power generation	635
3-2	Lusemfwa Lower	On Lusemfwa a tributary of the Luangwa river. Near confluence with Lusemfwa river	Hydro power (35MW) and irrigation water supply	500
3-3	Luangwa	On Luangwa river near confluence with Lusemfwa river	Hydro power (40MW) and irrigation water supply	2500
4.Dams for irrigation an water supply				
4-1	Gwayi Umguza	On Gwayi river	Irrigation water supply	195
4-2	Bubi Lupane	On Bubi	Irrigation water supply	40
4-3	Kudu	On Munyati	Irrigation water supply	1,550
4-4	Chitse	On Ruya river	Irrigation water supply	290
4-5	Silverstroom	On Msengezi river	Irrigation water supply	140

Lower Zambezi

A total of 6 schemes were identified in the Lower Zambezi as shown in Table 7.3. They comprise 4 new dams for hydro power generation and 2 dams for irrigation water supply.

The new power generation schemes can bring in 1,800MW at Mphanda Nkuwa, 180MW at Kholombidzo, 444MW at Boroma and 654MW at Lupata. Smaller power schemes are also feasible.

Table 7.3: Lower Zambezi - Proposed dams and power plants

Scheme Number	Scheme	Location	Proposed Mode of Operation	Additional Gross Storage ((x10^6 m^3))
1	Mphanda Nkuwa	61km downstream of Cahora Bassa on Zambezi main stem	Hydro power generation, 1,800MW potential	2 500

Scheme Number	Scheme	Location	Proposed Mode of Operation	Additional Gross Storage (($x10^6$ m^3))
2	Kholombidzo	Shire River downstream of Liwonde	High Kholombidzo (75m gross head) has an estimated capacity of 180MW and Lower Kholombidzo (71m gross head) has an estimated capacity of 170MW with a firm flow of 250 m^3/s.	
3	Baroma	Downstream of Mphanda Nkuwa on the Zambezi main stem, Mozambique	Hydro power generation, 444MW	
4	Lupata	Downstream of Baroma site on the Zambezi main stem, Mozambique	Hydro power generation, 654MW	
5	Bindura	On Mazowe	Irrigation water supply	87
6	Kunzvi	On Mazowe	Urban water supply	146

The following potential storage was identified on this study as follows:

- Luia River (5600Mm^3, 2700Mm^3 and 300Mm^3),
- Revubué river (8000Mm^3),
- Luenha river (4000Mm^3, 2000Mm^3 and 11000Mm^3) and
- Muira river (2000Mm^3)

The figures in brackets are the potential gross storage capacities for each site. More detail on the identified sites is provided in Annex 4 report.

7.3 Evaluation potential for managing floods in unregulated rivers

The history of floods in the Zambezi river system reviewed in Chapters 5 and 6 shows that flooding is experienced in the upper, middle and lower Zambezi sub-systems but the frequency and severity depend on local conditions. The major tributaries contributing to floods are identified in section 7.2. In the Upper Zambezi the Kabompo river and the tributaries between Senanga and Katima Mulilo contribute significant flows. In the Middle Zambezi tributaries between Kariba and Vitoria Falls (including Gwayi and Sanyati rivers), and downstream of Kariba the Kafue, Luangwa and Msengezi and Manyame, Machanga experience very high flows. The lower Zambezi has the Shire, Luia (two tributaries called Luia), Revuboe, Mazoe / Luenya, Muira and Pompoe tributaries which can discharge very high flood flows.

The proposed schemes on the Zambezi river main-stem do not have significant storage compared to the incremental runoff received into their impoundments and will be run-of-river schemes. Thus they will be expected to pass on flood waters with little or no regulation. However thy will influence the low flow regime.

The proposed new dams in categories 3 and 4 of Table 7.2 as well as those on the tributaries of in the lower Zambezi sub-basin can contribute to the objective of supply of water for irrigation in the Zambezi river basin. The dams can also help manage flush floods but do not have enough space to accommodate the larger floods like those associated with cyclones. If these dams breach they can results in serious flood impacts, this can be avoided at design stage and through operational management interventions. However these dams will become important points for flood monitoring.

7.4 Evaluation of impact of proposed new dams on operation of system

Section 7.3 shows that in the middle Zambezi, the proposed power extensions can bring in about 1800MW and new .power generation schemes can bring in about 4190MW while in the lower Zambezi proposed new power generation schemes can bring in about 3800MW. This translates to a total hydropower generation development potential of nearly 10 000 MW, showing that the hydro power potential of the Zambezi river basin has barely been tapped.

The storage of the proposed schemes will be insignificant if it is compared to the incremental runoff received into their impoundments. As run-of-river schemes they will operate on a use it of lose it basis in terms of flow. The schemes should be operated to maximize available flow and head. The SAPP is experiencing a net deficit on its electricity demand/supply balance. In this situation the existing hydro power plants want have security of water for their. If more power becomes available it can be argued that the conditions will improve considerably for operations of Kariba and Cahora Bassa to consider other objectives. If the status quo persists marginal shifts can be realised from the two main objectives of storing enough water for power security and dam safety.

If we take Batoka Gorge for example the “wet” and “very wet” conditions the 1600MW output will offset the 6% reduction in power output with a five year operating window, the 13%, 16%, 39%, 5% and 18% exceedence inflows. This means that Kariba will be able to make environmental management releases. However the biggest impact will be reduced risk to dam safety as the dam can then be operated at lower level. Should the actual inflow received be lower that the expected inflow, Kariba can also curtail releases and the storage at Batoka can be used to compensate on power production but to a limited extend.

The case of Mphanda Nkuwa is different as it relies on release from Cahora Bassa. At present all discharges from Cahora Bassa are “lost” as far as power production is concerned. With Mphanda Nkuwa this water is captured and used to generate additional power. This means that Cahora Bassa will be able to make environmental management releases. However this will require timing of releases and accurate estimation of discharges so that water is not lost as spills at Mphanda Nkuwa.

When the storage levels are rising rapidly, the current mode of operation requires that flood gates be opened to release water. Power plant extensions will allow the dams to redirect some of this water to the new turbines and generate more power. However if operated to generate power for peak times without considering storage condition and inflows, the turbine extensions can result in unsustainable drawdown of the reservoirs.

Most of the proposed new dams on the tributaries will contribute to the objective of supply of water for irrigation and other uses. They can also contribute to environmental releases and sediment management within their sub-catchments Existing design guidelines should be reviewed to ensure that new dams can cater for multiple objectives. In addition, the new guidelines will be needed for their operation to ensure multipurpose use.

The impacts of the proposed new dams and power plant extensions on the operation of the Zambezi system are summarized in Table 7.4.

Table 7.4: Impact of proposed dams, power plants and power plant extensions on operation of the Zambezi system

Scheme Number	Scheme	Mode of operation	Possible impact on operation of system
Upper Zambezi to Kariba dam			
1	Victoria Falls North Bank	Run-of-river scheme. The power plant requires a firm flow	Power station to operate without adverse effects on the flow over the Falls. Diversion of flows at Victoria falls may not meet required conditions to maintain the site. The power plant may not have any significant flood or environmental management function
2	Victoria Falls South Bank	Run-of-river scheme. The power plant requires a firm flow	Power station to operate without adverse effects on the flow over the Falls. Diversion of flows at Victoria falls may not meet required conditions to maintain the site. The power plant may not have any significant flood or environmental management function.
3	Batoka Gorge	Maximise creation of head for electricity generation. A lower level outlet will be incorporated on the dam to enable environmental releases	If operated in conjunction with Kariba and Cahora Bassa may allow downstream to upstream sequencing of dam operations without loss of power generation capacity. This contributes directly to flood and environmental management.
4	Devils Gorge	Develops the head between Batoka and existing Kariba Dam.	The likely contribution to flood and environmental management is minimal and the same as for Batoka Gorge.
5	Gwayi Shangani, Gwayi Umguza, Bubi Lupane,	Maximize use of available yield. The Gwayi Shangani dam will have flood control gates and a bottom outlet.	May contribute to sediment management, environmental flows and flow monitoring
6	Kudu	Maximize use of available yield	May contribute to sediment management, environmental flows and flow monitoring
7	Kariba Extension	Uses existing storage capacity	Improves conditions for synchronization with Cahora Bassa and other new dams.
Kafue Sub-system			
1	Itezhi-Tezhi Hydroelectric Project	Will utilise existing regulatory storage at Itezhi-Tezhi reservoir for hydropower production.	May reduce pressure on Kafue Gorge if operated conjunctively Firm energy at both Itezhi-Tezhi and Kafue Gorge increases as the regulatory storage increases.
2	Kafue Gorge Lower Hydropower Project (KGLHP)	Utilise the remaining 200m of head on the Kafue River for hydropower production. Most flows will come from the existing Kafue Gorge Upper Hydro Project having passed through the turbines and exit via the tailrace tunnel discharge facility, 7.8km downstream from the dam. A minimum flow of 7.2m^3/s will be maintained in the river reach between the dam and the tailrace discharge..	May reduce pressure on Kafue Gorge if operated conjunctively

Scheme Number	Scheme	Mode of operation	Possible impact on operation of system
Below Kariba but excluding Kafue sub system			
1	Mupata Gorge	Hydro power generation, 640 MW potential	The likely contribution to flood and environmental management is minimal and similar to Batoka Gorge.
2	Chitse, Silverstroom	Maximize use of available yield	May contribute to sediment management, environmental flows and flow monitoring
3	Lusemfwa Lower	Hydro power (35MW) and irrigation water supply	May contribute to sediment management, environmental flows and flow monitoring
4	Cahora Bassa Extension	Utilises existing pondage. Extension on the North Bank with an additional tunnel spillway.	The likely contribution to flood and environmental management is the same as for Batoka Gorge. Improves generation capacity at Cahora Bassa.
Below Cahora Bassa			
1	Mphanda Nkuwa	Run-of-river scheme benefiting from releases from the Cahora Bassa dam.	Used to re-regulate flows from Cahora Bassa and hydropower production
13	Baroma	Run-of-river scheme	May contribute to sediment management
14	Lupata	Run-of-river scheme	May contribute to sediment management
15	Bindura	Maximize use of available yield	May contribute to sediment management
16	Kunzvi	Maximize use of available yield	May contribute to sediment management
Lake Malawi/Shire Sub-system			
12	Kholombidzo	The hydro power plant will utilize releases from Lake Malawi and inflows from minor tributaries. High Kholombidzo (75m gross head) has an estimated capacity of 180MW and Lw Kholombidzo (71m gross head) has an estimated capacity of 170MW with a firm flow of 250 m^3/s.	Improves generation capacity on the Shire river system and reduces pressure on Lake Malawi. This may contribute to environmental management.

7.5 Recommended concepts for management of flood releases and environmental flows

The following concepts which can result in improvements of management of flood releases and environmental flows have been discussed in this chapter:

- Proposed new dams can be used to provide information for improved flood management.
- Water can be secured for hydro power while meeting dam safety requirements:
  - Proposed power station extensions can allow operators to better manage incoming high flows by releasing flows through turbines thus avoiding loss of water for power generation.
  - Proposed new dams for hydro power generation can allow operators better manage incoming high flows.
- Synchronization of releases from upstream dams with the current state of downstream dams and expected inflows to attain desired dams and releases can result in optimum hydropower output and allow dam operators to release water for other requirements.
- Proposed new dams for hydro power generation can allow operators to better manage incoming high flows without compromising dam safety through their uses as more dependable flow monitoring points.

- Multi-purpose dams can contribute to improved dam management and addressing basin wide objectives such as supply of water for irrigation.
- Existing dam design guidelines should be reviewed to ensure that new dams can cater for new objectives such as provision of flow for the environment. This recommendation is captured in Intervention Sheet 2.5 in Chapter 10.
- New guidelines are required for the design and operation of multipurpose dams for example to provide for sediment management, environmental releases and dam safety. This is recommendation is also captured in Intervention Sheet 2.5.
- Some of the available historical data in the ZAMWIS has not been converted to flow and is presented as stage readings. There are rating curves for the respective gauge stations and there is need to develop them. The usefulness of ZAMWIS as a source of flow data can only be realized if this data is improved and the database is continuously updated and maintained. This is recommendation is captured in Intervention Sheet 2.7.
- Improved basin wide flow data from rainfall-runoff analysis and flow routing methods is a prerequisite for synchronization of releases from upstream dams. This is recommendation is captured in Intervention Sheet 2.8.

8 Synchronization of Dams for Flood Release

8.1 Introduction

The need to widen the range of possible flow regimes in the Zambezi River system downstream of major dams in order to provide for more uses/users has been established in this report. The goals of system optimization, water security and benefit sharing have been discussed in detail. Synchronisation and conjunctive operation are two terms which are very closely associated with modern scientific trends in dam management to achieve these goals.

8.1.1 Definition of synchronisation and conjunctive operation of dams

Synchronisation relates to timing of actions (near real time) in order to achieve or avoid an outcome which is certain to occur at a known position in space and time. For example, two hydro power dams in series can be synchronised such that spillway discharge is minimized and as water as possible goes through the turbines. To achieve this, the storage in the downstream dam is drawn down first. When it reaches a certain level the upper dam starts generating power or increases its releases for power generation in order to benefit the downstream dam. Similarly if the downstream dam receives runoff from incremental catchments and its level rises, at a certain level releases from the upstream dam are stopped or reduced to retain water in storage in the upper dam for later use. The releases also account for abstractions and losses between the two dams. Thus timing of releases and discharge rates are very important. An example of this is the Gariep dam (upstream) and VanderKloof dam (downstream) in South Africa (see location of these dams in Figure 8.1).

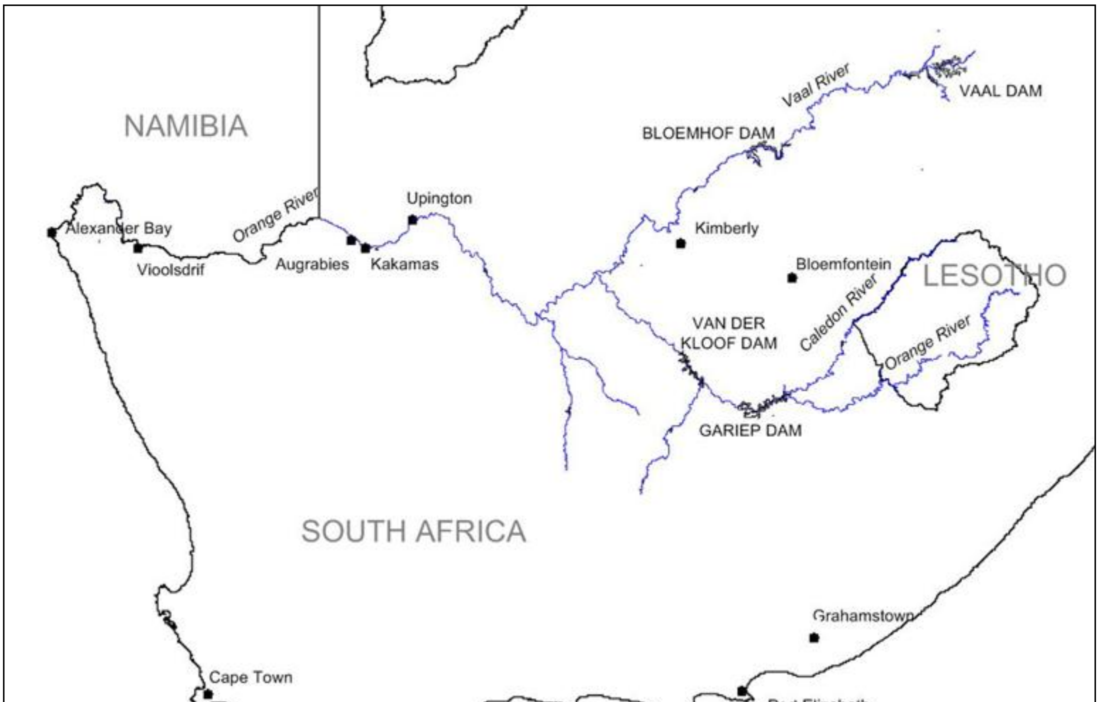


Figure 8.1: Location of the Integrated Gariep and Vanderkloof dams

The Gariep (5 670x10^6 m^3) and Vanderkloof (3 236 x10^6 m^3) Dams are the largest and second largest water reservoirs respectively in South Africa. Vanderkloof is situated 130 km downstream of Gariep in the Orange River catchment which is also affected by wet and dry climatic cycles. These two dams water for irrigation and agricultural production, municipal and industrial water supply, hydroelectric power generation, flood management, recreation and tourism. The operating rule for flood management limits reservoir levels to less than 80% of storage capacity during the critical period which occurs at the beginning of the flood season. The hydropower capacity of Gariep is 360MW and that of Vanderkloof is 240MW respectively and this is mainly for peaking power. Releases for hydropower are managed near real time to keep as much water as possible in storage in order to secure water for the other uses while observing the flood management rule. From this example it is also clear that near-real time synchronisation can be extended to environmental releases and flood management.

Conjunctive operation relates to getting different parts of a system to support each other or to support other systems in order to meet requirements such as quantity and/or quality and cost of water. Reservoir levels can be used as triggers for the support to kick in. The changes in state which influences the triggers do not happen suddenly, and are not near real time, but are measurable and predictable. This is a typical case for the Integrated Vaal River System which gets water from the Lesotho Highlands, the Vaal System and the Inkomati Systems as illustrated in Figure 8.2.

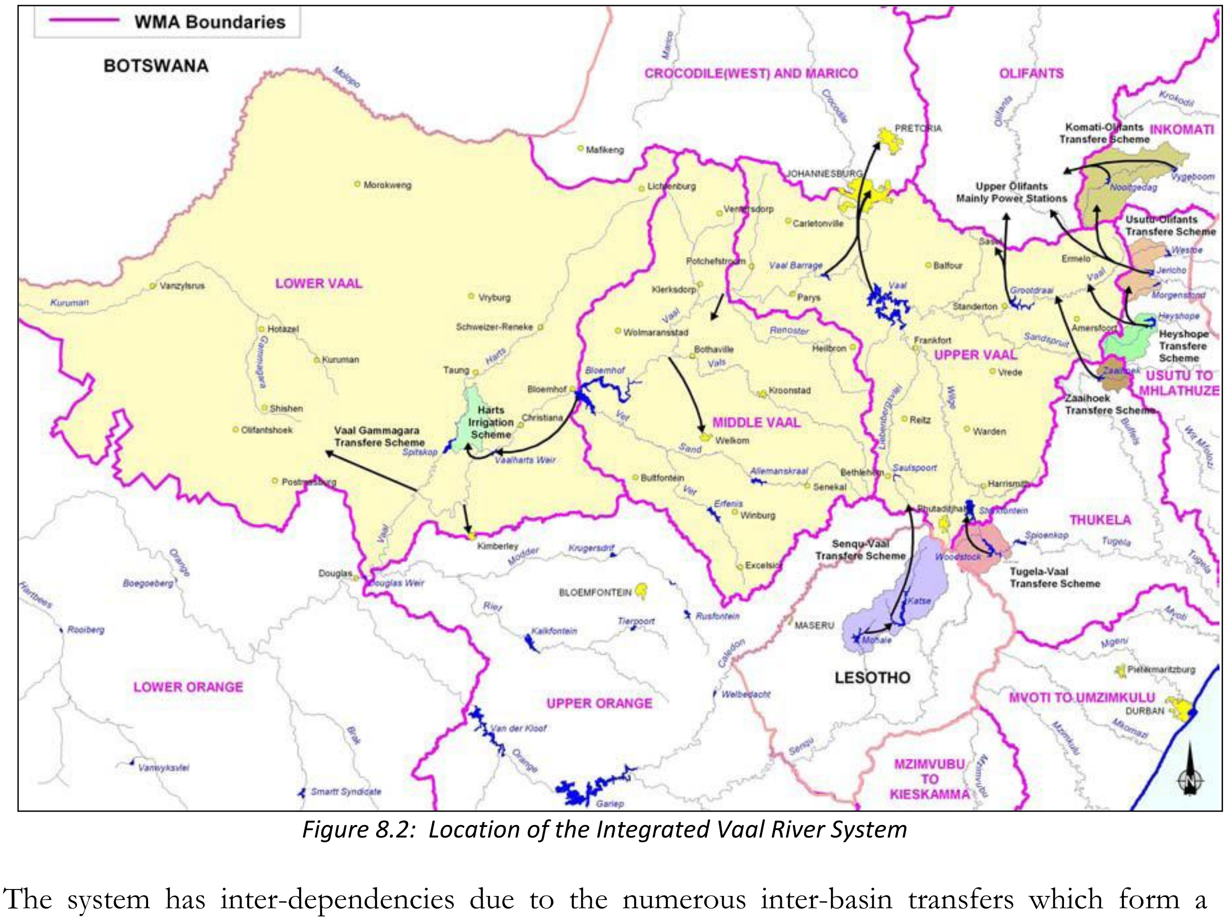


Figure 8.2: Location of the Integrated Vaal River System

The system has inter-dependencies due to the numerous inter-basin transfers which form a complex network of inter-linked reservoirs located in catchments with different hydrological characteristics. As general operation principle, the Integrated Vaal River System must be operated as an integrated system irrespective of who owns or operates each individual component of the system. The primary objective of the operation of the Integrated Vaal River System is to maintain the assurance of supply to all water users receiving water from the system.

This is achieved by transferring water between sub-systems with the aim of balancing the drawdown of the reservoirs during drought periods and preventing spillage and wastage from the system during wet periods. The main indicator variable, used for operation planning decisions, is the future projection of the probability of the reservoirs in the system reaching certain levels. Consideration is also given to cost savings through reducing the pumping of water through the inter-basin transfers for limited periods without jeopardizing the long term assurance of supply.

Since 1989, annual operating analyses has been undertaken to provide answers with respect to the following questions:

- Should restrictions be implemented over the following twelve months? This is only required during drought periods when the storage levels in the reservoirs of the system are low.
- Could reduced inter-basin support be tolerated for a twelve-month period? During periods when the system reservoirs are exceptionally full the question arises if cost savings could be achieved through reduced pumping for a year without jeopardising the long-term reliability of supply.
- What blending or dilution operating rule should be applied? Different salinity related operating rules have been identified and applied in the past to support the water requirements of Rand Water and the users downstream of Vaal Barrage. These analyses aim to lower the TDS (Total Dissolved Solids) concentration of water supplied to the users but with limited impact on the projected supply capability.
- What is the implication of the starting storage volumes on the implementation date of subsequent augmentation options?

8.2 Situation assessment

8.2.1 Flood management and dam synchronisation

The historical experience shows that peak flows from Upper Zambezi have resulted in Kariba to discharge up to 7300 m^3/s into the Middle Zambezi and this coincided with heavy runoff from the Luangwa catchment of about the same magnitude. Inflows into Cahora Bassa steadily increased to a peak of 17,900m^3/s. In this situation the backwaters affected the Kafue, Angwa and Manyame tributaries. The existing infrastructure failed to cope with such large floods. These existing dams can only be used to manage small- and medium-sized floods.

The existing operating procedures for the Lake Malawi/shire sub-system consider provision of adequate water for hydropower generation. Although the safe operation of the Kamuzu Barrage is mentioned current practice suggests that the Barrage can actually pose safety as well as flood risks. However the following synchronization issues have been identified on study:

(a) The operation of the Kamuzu Barrage maintains high lake water levels. If high inflows coincide with high lake levels emergency releases will cause downstream flooding. High water levels also increase risk of flooding the Lake Malawi area.

(b) High flows from Lake Malawi coinciding with high flows from unregulated tributaries of the Shire River will disrupt hydro power operations and cause flooding in the lower Zambezi.

(c) The Barrage works on lake levels and it eliminates low flows.

New rules should consider that the Kamuzu Barrage has been in operation since 1996 and the Lake Malawi may have adapted to the new condition of high water levels. This study has also shown that the environment, other uses including agriculture and flow control for flood management need to be accommodated in new operating rules for the Lake Malawi/Shire river system.

8.2.2 Main objectives of Dam synchronisation on the Zambezi River system

From Chapters 5, 6 and 7 of this report it is clear that the synchronization should address the following among others:

(a) to reduce risks on safety of dams;
(b) to improve hydro power output from the system ;
(c) to ensure that peak flows from different sub-systems or tributaries do not arrive at specific sites at the same time in order to reduce flood risk;
(d) to ensure that releases do not interfere with floodplain activities such as riverine and floodplain agriculture;
(e) to provide adequate flow and water quantities for all reliant users such as irrigation and navigation;
(f) to manage the flow regime to achieve environmental objectives, for example ensure that the different categories of flows are met and
(g) to release large but safe floods

This focus of this study is on synchronization of dam operations. The relevant concepts are of dam synchronisation in the Zambezi river basin are discussed in this chapter.

8.3 Framework for synchronizing dam operations

The unexpected arrival of flows of any magnitude higher than normal may cause alarm and/or damage. The same high flow, if expected, may have a different impact. The main issues here are accurate determination of anticipated releases and communication in such a way that the correct message is received and confirmed at the point where impacts will be felt. The following scenarios could be considered in the management of flood releases:

1. Same flood hydrograph but delayed to provide a "window of time" to effect communication to stakeholders. In this scenario the same hydrograph reaches the affected point but much later.
2. Slightly higher than normal releases are made to create storage for incoming flood. Total amount of water released may be more or less the same as in (1). This results in a shallower hydrograph with outflow peak less than inflow peak. The arrival of the peak discharge at a point may be the same as in (1).
3. Slightly lower than normal releases are made but over a long time (longer time than in (1) or (2)) to contribute to storage in the reservoir while releasing some water. This results in a shallower hydrograph and a lower outflow peak than in (1) and (2).
4. A variable hydrograph to generate releases of sufficient magnitude and duration to address ecosystems maintenance requirements.

These four scenarios are discussed relative to the specific situation in the Zambezi Basin in order to identify the opportunities and constraints for future multipurpose use of dams.

8.3.1 Scenario 1: Management of releases to delay arrival of peak of flood flow

As the same hydrograph reaches the affected point but much later, the inflow hydrograph is detained in storage up to a predetermined time. The amount is then released at the same rate as it came in.

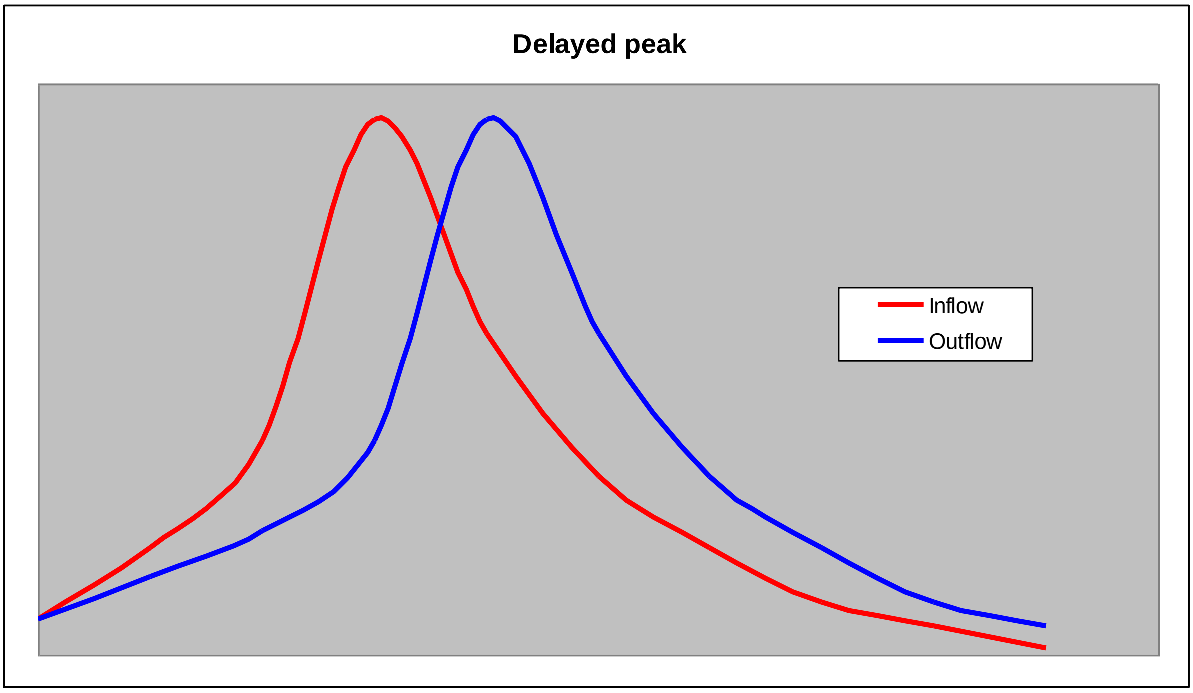


Figure 8.3: Concept of delayed peak

From this study the following options can be presented:

(a) managing releases from Kariba to allow the peak flow from Kafue Gorge to pass the Kafue/Zambezi confluence.

(b) managing releases from Kariba to allow peak flow from Angwa, Luangwa, Machanga, Manyame and Msengezi to reach Cahora Bassa

Kariba would need to create storage for the incoming flood by discharging earlier. The required storage will depend on the expected flood and current storage conditions. Since there is a six week delay in the arrival of flood waters from the upper Zambezi portion of the river into Kariba, this gives ample opportunity for the management of storage in Kariba and Cahora Bassa.

8.3.2 Scenario 2: Management of releases to reduce peak of flood flow

In this scenario the outflow hydrograph is initially slightly higher than the inflow hydrograph but it then reaches a reaches a peak lower than the inflow hydrograph. The peak at the downstream point occurs at the same time as that of the inflow peak. The total amount of water discharged is of the same order of magnitude as the inflow. The characteristics of the inflow flow duration curve are retained.

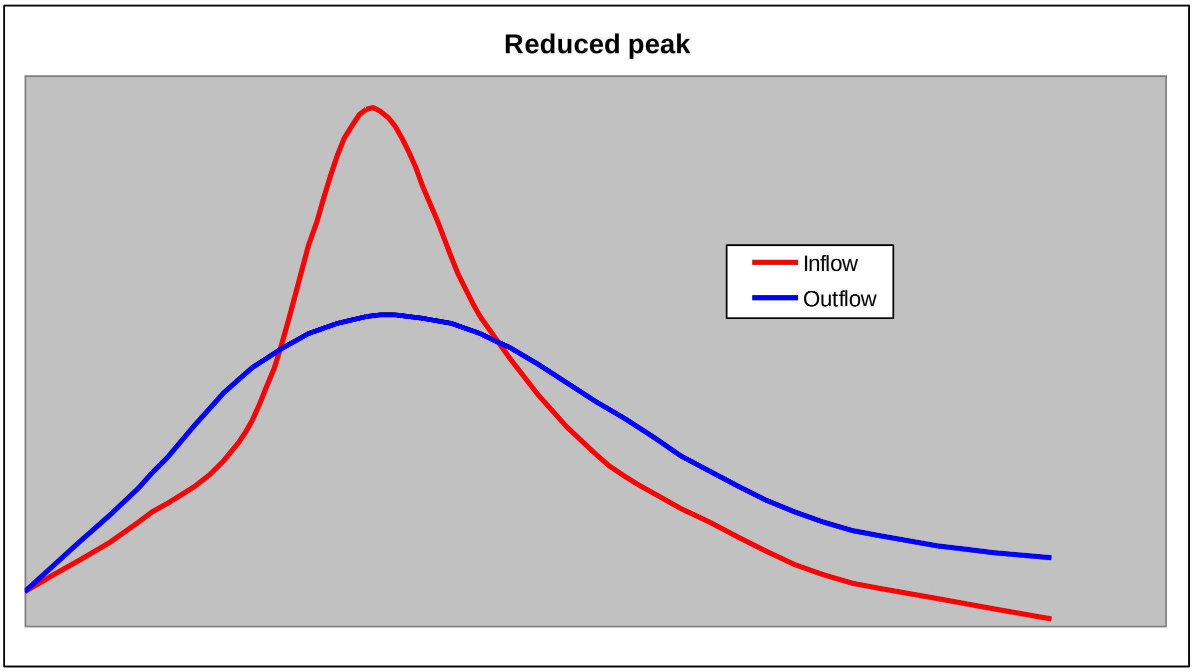


Figure 8.4: Concept of reduced peak

From this study the following options can be presented:
(a) this can be achieved by managing releases from Kariba when dam levels are within a specific range. Historical flows indicate that this has happened in the past.
(b) this can be achieved by managing release from Cahora Bassa when dam levels are within a specific range.
(c) this can be achieved by implementing the operating rule for Kamuzu Barrage to release flows close to the pattern of the inflow hydrograph when lake levels are within a specific range. Flood risk increases significantly as the Lake levels increase and as the response time required becomes less and less.

The main issues here are determining the flow rate for the outflow hydrograph, timing of start of release if the inflow hydrograph is known. Cahora Bassa already has the capacity to release environmental flows downstream within its current operational framework and water availability. This can also be done for small annual floods with minimal hydropower impact. However, to achieve larger ("medium-sized") annual floods (not extreme floods) that deliver more useful water to the floodplain, conjunctive management with Kariba offers more opportunity and more benefit. Kariba absorbs some of the risk by releasing water at the time when Cahora Bassa needs to release water downstream, so that all of the risk of reservoir reduction does not occur at Cahora Bassa site alone. Those medium floods from Kariba are also of benefit to the middle Zambezi, especially Mana Pools and Lower Zambezi National Park.

8.3.3 Scenario 3: Management of releases to reduce and delay peak of flood flow

In this scenario, the outflow hydrograph is always lower than the inflow hydrograph and it also reaches a lower peak much later. The amount of water discharged is less than the inflow. Some of the flood water is captured and retained in storage.

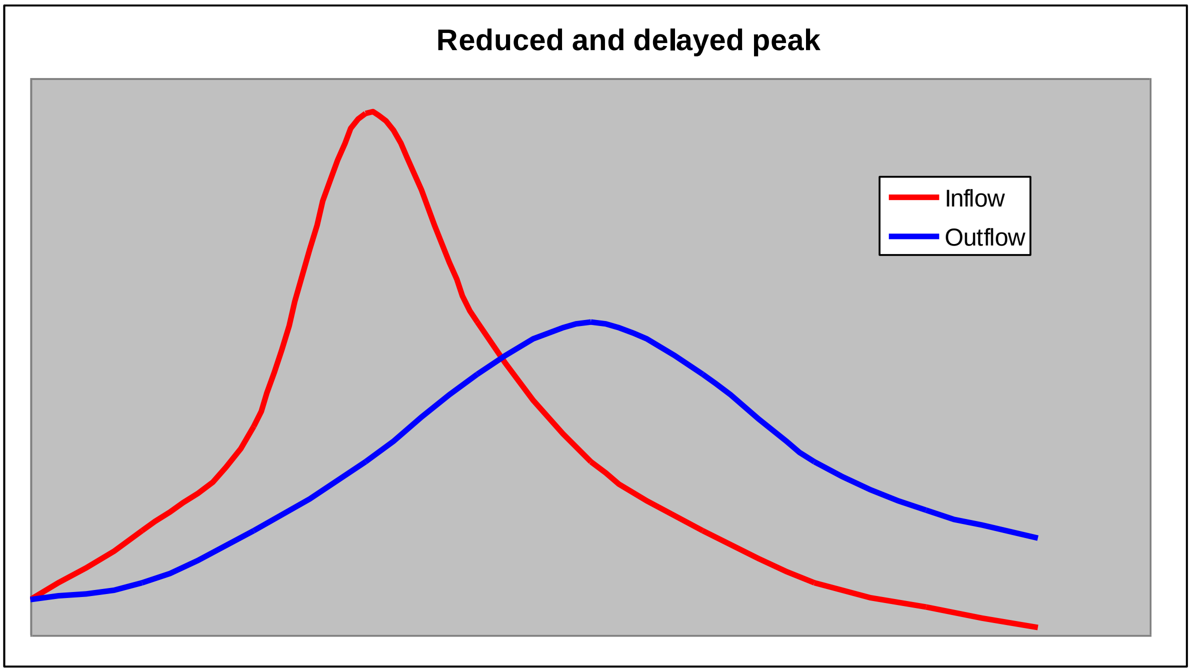


Figure 8.5: Concept of reduced and delayed peak

The following options can be presented:

(a) managing releases from Kariba when dam levels are within a specific range to retain some of the water in storage for current and future hydropower generation and other uses that depend on storage. Historical flows indicate that this has happened in the past.

(b) managing release from Cahora Bassa when dam levels are within a specific range to retain some of the water in storage for current and future hydropower generation and other uses that depend on storage. Historical flows indicate that this has happened in the past.

This hydrograph provides additional time to warn downstream users/riparians on the timing, flow pattern. The main issues here are determining the flow rate for the inflow and outflow hydrographs. From this study it is evident that the dams on the Kafue system do not have adequate capacity for this scenario. In addition the Kamuzu Barrage is not designed for this scenario.

8.3.4 Scenario 4: Management of releases to obtain floods for ecosystem maintenance

The main consideration here is to create flow patterns to meet the ecosystem requirements for the Zambezi delta. In this scenario the main dams can contribute releases which compound to create the required hydrograph. The timing and magnitude of the releases as well as contributions from downstream tributaries are quite important. In terms of dam operations this means that ecosystem requirements for a particular linked section of the river system may be achieved through the combined result of near real time implementing scenarios (1), (2) and (3) at different upstream dams. Synchronisation should also consider the contribution of new dams on unregulated tributaries to ecosystem maintenance.

8.4 Recommended concepts of synchronisation for improved dam management

The concepts on synchronization of dam operation to improve management of flood releases and environmental flows have been identified and discussed in section 8.3:

(i) Managing releases to **delay** peak of flood flow at a specific site
- allows for evacuation from flood plain, for example through a stepped flood release pattern. The rising and recession patterns would follow an acceptable hydrograph.
- provides for early warning through an early release within an acceptable range of flow to warn downstream riparian communities of the onset of flooding.

(ii) Managing releases to **reduce** peak of flood flow at a specific site
- reduces extend of flooding and may reduce flood damage.
- reduces risks to downstream dams

(iii) Managing releases to **reduce and delay** peak of flood flow at a specific site and
- allows for evacuation from flood plain (e.g. a stepped flood release pattern). The rising and recession patterns would follow an acceptable hydrograph.
- provides for early warning (e.g. an early release within an acceptable range of flow) to warn downstream riparian communities of the onset of flooding.
- reduces extend of flooding and may reduce flood damage.
- reduces risks to downstream dams
- secures water in storage for hydropower and other uses

(iv) Managing releases to obtain floods for ecosystem maintenance
- considers status of system and other objectives to combin**es different hydrographs** to match requirements in terms of ecosystems in terms of flow hydrograph, timing and frequency

Considering the variability and uncertainty in the hydrology of the Zambezi river basin these concepts form a sound basis for engagement on synchronization of dam operations. However to get to a level of implementation would require detailed modeling, monitoring and evaluation on an on-going basis. The review of the existing models in section 5.2.2 of this report and the review of the flow monitoring system in Annex 3 report indicate that they are both inadequate. The setting up of a modeling and monitoring systems to support dam synchronisation is therefore recommended and more details are provided in Intervention Sheet 2.2, in chapter 10 of this document.

It is recommended that training be provided to hydrologists, JOTC and SOF members on the concepts described in this chapter in order to improve their understanding and to capacitate them for effective participation in their meetings. This training should consider the requirements of different stakeholders. This recommendation is detailed in Intervention Sheet 2.2, in chapter 10 of this document.

9 Management of Sediments

9.1 Introduction

In this chapter the impact of existing dam operations on sediments and sedimentation are discussed, as well as the impact on sediment transport of bottom outlets on proposed new dams identified in the Zambezi basin in Chapter 7. These are evaluated in Annex 4 as an investment option.

9.2 Situation assessment

Kariba Dam has a maximum length of about 280 km and a capacity of 185.6 km^3, while Cahora Bassa has a maximum length of about 292 km and a capacity of 55.8 km^3. Both these dams do not have bottom outlets to flush out sediments. Although the spillways for both dams are openings under water it is currently impossible to release sediments from these reservoirs as both reservoirs are very long and most of sediment load settles on upstream parts of the reservoirs and on the edges. Their sediment trap efficiency is believed to be 100%. It is already evident that bottom outlets will have negligible value for sediment flushing for such dams and the need for these for dams of this size is debatable. Itezhi-Itezhi has a bottom outlet, but most sediments settle well upstream of the dam wall. The storage condition of the dams just before a major flood, which is affected by the operating rule, affects the distribution of sediments from the contributing rivers.

The transportation of nutrients as sediments is dealt with in detail in section 5.4 which deals with concepts and the purpose of environmental flows. The impact of historical releases on flow requirements for the environment and availability of sediments is discussed in detail in section 5.5. Improvements in environmental flow management can improve availability of sediments for fisheries, agriculture and growth of vegetation to support wildlife.

The tributaries downstream of the major dams carry fine sediments to the main stem of the Zambezi River, but deposition of these fine sediments on the floodplains can only happen when the floods in the tributaries coincide with floods in the main stem of the Zambezi River. Increased in the intensity of rainfall due to climate change discussed in Chapter 2 will result in increased sediment loads.

9.3 Concepts for improved dam management

Bottom outlets are included in a dam either to cope with floods during dam construction or to facilitate the management of the reservoir thereafter. Bottom gates also allow for drawing down the water level much more than spillways placed higher in the dam body. When bottom outlets are present, it is possible to release not only flow but also sediment, allowing for sediment management in the reservoir.

For the new dams that have been identified for construction bottom outlets will be included in the designs. For example, a bottom outlet has been provided for on the new Gwayi-Shangani Dam, and will release sediments especially if significant floods are experienced at the start of the rainfall season coinciding with low dam levels. This could be beneficial to the ecology possibly limited to the extent of Kariba Dam only.

10 Recommended Concepts and Interventions for Dam Management

This document presents new insights into the operation of the Zambezi River as a system, which consider variability and uncertainty in climate patterns as well as climate change patterns; the role of weltlands in flood management, the history of flooding the pursuit to maximise hydropower generation. Cogent arguments are presented on the need to move dam operations from focusing on individual dam safety and hydropower generation to a broader basin-wide perspective where all the dams in the basin are considered conjunctively. This is involves defining additional objectives and setting up new modes of operation and cooperation. To contribute towards achievement of the desired balance in meeting the different and sometimes conflicting objectives the following concepts were developed on this study:

(a) An effective institutional set up will be needed to promote good governance, communication and enhancement of dam operations in the Zambezi River Basin.
(b) Improved, regulated releases from the main reservoirs in the Zambezi River Basin will be realized from negotiating and achieving revised operating rules that will address basin-wide objectives and apply methods that incorporate management of hydrological risks.
(c) Hydropower infrastructure on the Lake Malawi/Shire River System can be designed/developed/rehabilitated/operated/maintained while maintaining the ecological integrity of the system and mitigating flooding.
(d) Floodplains and wetlands in the Zambezi River Basin retain their functions
(e) New dams in the Zambezi River Basin will contribute to more effective dam synchronisation and improved flood management for the whole system.

The specific actions recommendations to support these concepts based on the findings and recommendations presented in Chapters 1-9 of this report are presented in sheets 2.1 to 2.11 and can be summarized as follows:

1. Promote the establishment of a Zambezi Basin System Operators' Forum
2. Support capacity building to facilitate better understanding of dam synchronisation and new modes of dam operation
3. Establish and implement a basin-wide flood and drought risk management plan
4. Facilitate the adoption of new modes of dam operation
5. Develop operating rules for new dams
6. Estimate and implement Zambezi Environmental Flows
7. Improve the quality of observed flow data for application on dam management
8. Simulate flow time series for the Zambezi River System
9. Develop climate change scenarios for the Zambezi River Basin
10. Improve the understanding of the hydrology and functioning of wetlands in the Zambezi River Basin
11. Implement a pilot project involving the Kariba, Itezhi-Tezhi, Kafue and Cahora Bassa dams on synchronisation, conjunctive operation of dams for introduction of e-flows and flood release management.

These intervention sheets are not project proposal sheets. They are based on the findings of the Technical Study "Dam Synchronisation and Flood Releases in the Zambezi River Basin". Before implementation further consultation with stakeholders and specific details will be required.

Figure 10.1 shows how the relationship between the concepts and recommendations. In preparing these sheets, it should be noted that a key assumption has been the future ratification of the ZAMCOM agreement by all basin states. As management of the Zambezi River basin is currently limited to piecemeal management by the 8 basin states, implementation of basin-wide strategies is unlikely to be successful until the full ratification of the ZAMCOM agreement has been achieved. Other specific assumptions have been listed for each recommendation or intervention.

The sheets include a number of standardised fields. A brief description of these fields is provided below:

Intervention sheet # - the number of the recommendation/ intervention linked to specific focus areas. Interventions starting with "2" are linked to Concepts and "Recommendations for Dam Management".

Timeframe – the timeframes presented here are approximate and are limited to short term (0-2 years), medium term (2-5 years) and long term (>5 years).

Budget range – to facilitate implementation of the proposed interventions, a budget range has been included to assist with obtaining funding. Four budget ranges have been considered, as follows: < US$ 0.5 million, US$ 0.5-2 million, US$ 2-5 million and > US$ 5 million. It should be noted that the costs presented in this field are rough order cost estimates prepared in most cases from an educated assessment of the likely cost for implementation of each respective intervention.

Linkages – this field details the locations within the report where further information on each recommendation/ intervention can be obtained.

Concept – this field outlines the overall concept to which the proposed intervention is expected to contribute.

Justification – this field explains the rationale behind the proposed recommendation/ intervention.

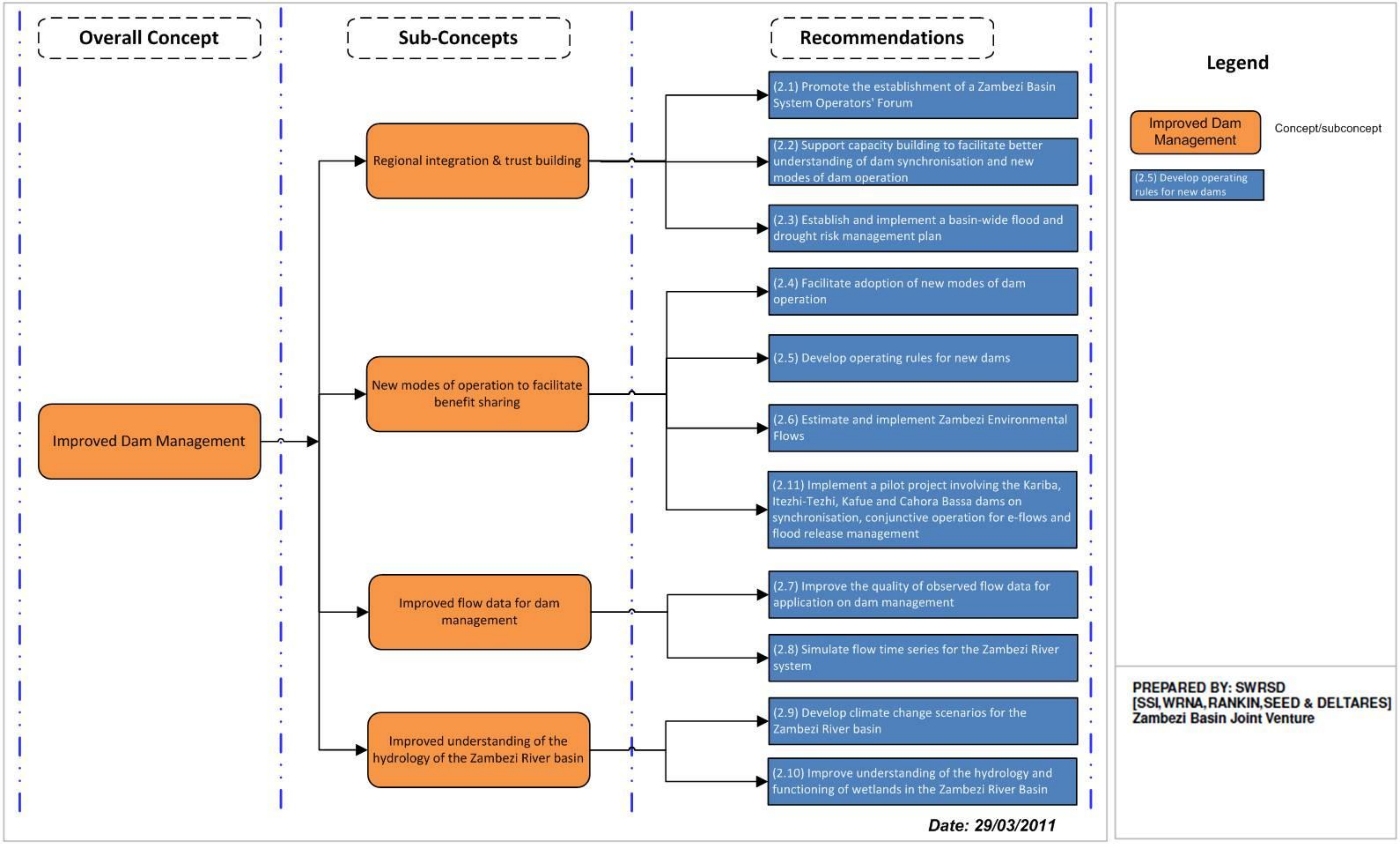
Actions/ responsibilities – this field lists the specific actions that are required for achievement of the proposed recommendation/ intervention and the responsibility for implementation. Although the SADC Secretariat and the basin states are generally listed as the responsible parties for implementation, the appointment of either consultants, equipment suppliers or contractors will be required as part of the implementation procedure for each recommendation/ intervention.

Benefits/ beneficiaries – this field was included to demonstrate the expected benefits arising from implementation, as well as the likely beneficiaries. Particular attention was given to specifying whether the beneficiaries would be limited to a single country or multiple countries.

Means of implementation – this field briefly describes the expected process for implementing the proposed recommendation/ intervention, such as the expected implementing parties and the actions to be implemented.

Specific assumptions/ risks – this field includes any specific assumptions or risks associated with this specific recommendation.

Comments – any remaining comments or issues not covered by the other standard fields are captured in this field.



PREPARED BY: SWRSD
[SSI, WRNA, RANKIN, SEED & DELTARES]
Zambezi Basin Joint Venture

Date: 29/03/2011

TRANSBOUNDARY WATER MANAGEMENT IN SADC: DAM SYNCHRONISATION AND FLOOD RELEASES IN THE ZAMBEZI RIVER BASIN PROJECT

ANNEX 2 FIG 10-1 CONCEPTS AND RECOMMENDATIONS FOR DAM MANAGEMENT

giz
On behalf of:
Federal Republic of Germany
The Federal Government
UKaid
from the Department for International Development
Australian Government
Aid Program

PROMOTE THE ESTABLISHMENT OF A ZAMBEZI RIVER BASIN SYSTEM OPERATORS' FORUM

Intervention Sheet #	**2.1**	**Time Frame:**	Short term to Medium term	**Budget range:**	US$ 0.5-2 million,

Linkages	Annex 2, Chapter 5	
Concept:	The System Operating Forum, the existing JOTC, and resuscitated Meetings of Hydrologists will promote good governance, communication and enhancement of dam operations in the Zambezi River Basin.	
Purpose	To improve cooperation and exchange of information between institutions involved in and/or affected by management of dam operations in the Zambezi River Basin	
Justification:	The major dam operators and power producers on the Zambezi river namely ZRA, HCB, ZESA and ZESCO have a platform for cooperation called the Joint Operation Technical Committee (JOTC). ZINWA and ARA Zambeze are also part of the committee. This corporation arrangement also includes an MOU to provide for executive decisions to consider recommendations from this technical committee. The JOTC is focused on the operations of the Kariba, Kafue and Cahora Bassa dams. In the past hydrologists working on the Zambezi Basin met once a year following the SARCOF meeting. This meeting allowed these specialists to engage and interpret recommendations from SARCOF into practical forecasts. These meetings have since stopped, and should be resuscitated. The management of the Zambezi River Basin in a system-wide context will entail the accommodation of other uses of the river such as hydropower production, flood protection, agriculture and the environment. This study identified the need for a broader forum of stakeholders, and recommends the establishment of a System Operating Forum (SOF). This includes organizations responsible for Disaster Management, Water Management, Environmental Management, Local Government and Civic Society. This broader forum will enhance sharing of data between operators and other stakeholders. It will facilitate close liaison with different ongoing programs by various organizations as well as updating the ZAMWIS database. The second Advisory Group meeting deliberated on the continuation of the AG meetings to take the form of the SOF. Most of the members of the AG are in support of the SOF and can see its benefits, therefore the transformation of the AG into a fully operational the SOF can be achieved within a very short time, not exceeding two years. The SOF will provide a platform for interested and affected stakeholders to contribute to the effective management of the Zambezi River System and improve communication.	
Actions/ Responsibility	• Facilitate signing and adoption of a revised MOU to improve cooperation between Dam Operators. Encourage and support active participation of the riparian states in implementing the MoU.	Interim ZAMCOM Secretariat /SADC Secretariat/JOTC/Riparian states
	• Establish a System Operating Forum. This includes setting up its Terms of References and thereafter supporting annual meetings to monitor operations and facilitate the realization of agreed interventions.	Interim ZAMCOM Secretariat /SADC Secretariat /Dam Operators and other stakeholders including Departments of Water
	• Establish the challenges that led to discontinuation of the annual meeting if hydrologists in the Zambezi River Basin. Resuscitate and thereafter support these meetings.	Interim ZAMCOM Secretariat /SADC Secretariat/Departments of Water, Dam Operators and Water Management Agencies
Benefits/ Beneficiaries:	• Improved communication	All stakeholders but main beneficiaries are Dam Operators and Disaster Management Agencies
	• Trust through sharing of information on operations	All stakeholders but main beneficiaries are Dam Operators and Hydrologists
	• New knowledge from review of operations	All stakeholders but main beneficiaries are Dam Operators
	• Improved conditions for synchronized and conjunctive operation of the Zambezi water system	All stakeholders but main beneficiaries are Dam Operators

Means of implementation:	• The meeting of hydrologists continues to focus on providing hydrological information to Dam Operators, Water Managers, Disaster Management and other stakeholders • JOTC continues to focus on technical issues related to dam operations. • A forum (the SOF) open to all stakeholders engages them on issues related to the operation of the whole of the Zambezi River system • Meetings of the Interim ZAMCOM Secretariat, SADC Secretariat, JOTC members, Hydrologists and SOF Members • Consultancy services to provide support during the JOTC, and meeting of hydrologists • Consultancy services to provide support during the set-up period for the SOF
Specific assumptions/risks	• Zambia, Mozambique and Zimbabwe governments sign MoUs for establishment of the JOTC and the Meetings of Executive Managers for the major dams. • SOF sets up and adopts its Terms of References and members agree on how it will operate • SOF members make recommendations on system operation without bureaucratic hindrance from governments and other stakeholders • SOF, JOTC members and Hydrologists willing to meet running costs as a minimum
Comments	Important drivers for realization of this Concept: • Facilitation by Interim ZAMCOM Secretariat • Participation of stakeholders

<table>
<tr><th colspan="6">SUPPORT CAPACITY BUILDING TO FACILITATE BETTER UNDERSTANDING OF DAM SYNCHRONISATION AND NEW MODES OF DAM OPERATION</th></tr>
<tr><td>Intervention Sheet #</td><td>2.2</td><td>Time Frame:</td><td>Short term</td><td></td><td><US$ 0.5 million,</td></tr>
<tr><td>Linkages</td><td colspan="5">Annex 2, Chapters 5 and 8</td></tr>
<tr><td>Concept:</td><td colspan="5">Capacitated stakeholders engage meaningfully in meetings of the System Operating Forum, JOTC, and Hydrologists and promote good governance, communication and enhancement of dam operations in the Zambezi River Basin.</td></tr>
<tr><td>Purpose</td><td colspan="5">To introduce hydrologists, dam operators, water managers, disaster management, and civil society to dam synchronisation concepts and new modes of operation of water resources in the Zambezi River system.</td></tr>
<tr><td>Justification:</td><td colspan="5">The Zambezi River System has important socio-economic and environmental functions and it is resident to over 40 million people. There is growing recognition that the development and operation of water resources in this system needs to consider these different functions. Synchronisation of dam operations and adoption of new modes of operation can contribute to this objective. The meetings of Hydrologist, JOTC and SOF are important for monitoring the implementation of recommended interventions and sharing of information. For effective participation of stakeholders in these meetings, training workshops are necessary. This training will consider the requirements of different stakeholders.</td></tr>
<tr><td rowspan="3">Actions/ Responsibility</td><td colspan="3">Training workshop for Dam Operators and Power Producers (the JOTC)</td><td colspan="2">Interim ZAMCOM Secretariat</td></tr>
<tr><td colspan="3">Training workshop for hydrologists, ecologists and water managers</td><td colspan="2">Interim ZAMCOM Secretariat</td></tr>
<tr><td colspan="3">Training workshop for Disaster Management and Civil Society</td><td colspan="2">Interim ZAMCOM Secretariat</td></tr>
<tr><td rowspan="3">Benefits/ Beneficiaries:</td><td colspan="3">• Improved and shared knowledge on the Zambezi River System and its functions</td><td colspan="2">All stakeholders but main beneficiaries are Dam Operators and Disaster Management Agencies</td></tr>
<tr><td colspan="3">• Improved and shared knowledge on dam synchronisation and new modes of dam operation</td><td colspan="2">All stakeholders but main beneficiaries are Dam Operators and Disaster Management Agencies</td></tr>
<tr><td colspan="3">• Commitment to adoption of new modes of dam operation and participation in SOF, JOTC, meetings of Hydrologists.</td><td colspan="2">All stakeholders but main beneficiaries are Dam Operators and Disaster Management Agencies</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">• Training needs assessment and development of training materials
• Conducting and evaluating of training workshops.</td></tr>
<tr><td>Specific assumptions/risks</td><td colspan="5">• Stakeholders are willing and available to attend training workshops
• Participants are willing to keep costs of attending training workshops low</td></tr>
<tr><td>Comments</td><td colspan="5"></td></tr>
</table>

<table>
<tr><th colspan="6">ESTABLISH AND IMPLEMENT A BASIN-WIDE FLOOD AND DROUGHT RISK MANAGEMENT PLAN</th></tr>
<tr><td>Intervention Sheet #</td><td>2.3</td><td>Time Frame:</td><td>Medium term to Long term</td><td>Budget range:</td><td>US$ 2-5 million</td></tr>
<tr><td>Linkages</td><td colspan="5">Annex 2, Chapter 5; Intervention No. 2.1 and Annex 3 Report</td></tr>
<tr><td>Concept:</td><td colspan="5">The establishment and implementation of flood and drought risk management plan will improve resilience of concerned and affected stakeholders in the Zambezi River System.</td></tr>
<tr><td>Purpose</td><td colspan="5">To reduce vulnerability of system functions and infrastructures to floods and drought.</td></tr>
<tr><td>Justification:</td><td colspan="5">The Zambezi River System is prone to floods and droughts. Historical impacts of these extreme events on system functions, infrastructure and livelihoods have been severe. The reality of climate change means that the frequency and severity of these extreme climatic conditions will worsen the situation. A review of the current practice/operation and institutional set-up of the Zambezi River System shows that there is scope to incorporate flood and drought mitigation measures in policy, planning and institutional strengthening in order to reduce the vulnerability of the system to floods and droughts; mitigation measures and policies in riparian states need to be harmonized to include basin-wide action plan. Reservoirs, through keeping some water in storage to manage risks associated with climate variability and uncertainty. Management of releases tries to avoid loss of water and power (which can translate to loss of revenue and livelihoods), loss of power to consumers (who may not have alternative sources of power or may be exposed to unfavorable power tariffs). Key strategies for reducing vulnerability include increasing resilience through diversification of sources of power, establishment a risk management fund, improved preparedness, adaptation and procedures for use of advanced knowledge on the onset of floods/droughts, their magnitude, duration and potential impacts. This can be achieved by establishing and implementing a flood and drought risk management plan.</td></tr>
<tr><td rowspan="2">Actions/ Responsibility</td><td colspan="3">Identify the existing management plans, integrate them and develop a flood and drought risk management plan which defines regional actions, time frames, roles and costs. The plan should incorporate the zoning of flood prone areas and also set out the principles to be considered as well as how costs and benefits will be shared</td><td colspan="2">Interim ZAMCOM Secretariat /Dam Operators/Disaster Management Agencies/Water Resources Managers</td></tr>
<tr><td colspan="3">Monitor implementation of the flood and drought risk management and preparedness plan at basin scale, continuously update the plans in terms of adequacy, and identify new risks on an ongoing basis.</td><td colspan="2">Interim ZAMCOM Secretariat /Dam Operators/System Operating Forum/ JOTC/Water Resources Managers/Disaster Management Agencies</td></tr>
<tr><td rowspan="3">Benefits/ Beneficiaries:</td><td colspan="3">• Improved and shared knowledge of risk of droughts and floods</td><td colspan="2">All stakeholders but main beneficiaries are Dam Operators and Disaster Management Agencies</td></tr>
<tr><td colspan="3">• Improved preparedness and management of droughts and floods</td><td colspan="2">All stakeholders but main beneficiaries are Dam Operators and Disaster Management Agencies</td></tr>
<tr><td colspan="3">• Improved resilience /reduced vulnerability of system functions to floods and droughts</td><td colspan="2">All stakeholders including subsistence farmers other water users</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">• Replication and integration of existing initiatives
• Strengthening existing disaster management activities.
• Stakeholder engagement in development of plan</td></tr>
<tr><td>Specific assumptions/risks</td><td colspan="5">• The concept and important of a system-wide risk management is understood and accepted by stakeholders
• Existing institutions have adequate capacity to implement actions identified in the risk management plan
• Accessibility of the flood prone areas in Angola improves significantly</td></tr>
<tr><td>Comments</td><td colspan="5">Progress in implementation of the Risk Management Plan, identification of new risks and necessary interventions to be considered at SOF meetings</td></tr>
</table>

<table>
<tr><th colspan="6">DEVELOP OPERATING RULES FOR NEW DAMS</th></tr>
<tr><td>Intervention Sheet #</td><td>2.4</td><td>Time Frame:</td><td>Short term to Medium term</td><td>Budget range:</td><td>US$ 0.5-2 million,</td></tr>
<tr><td>Linkages</td><td colspan="5">Annex 2, Chapter 7; Annex 4 Report</td></tr>
<tr><td>Concept:</td><td colspan="5">New dams in the Zambezi River Basin will contribute to more effective dam synchronization and improved flood management for the whole system.</td></tr>
<tr><td>Purpose</td><td colspan="5">To ensure that new dams on the Zambezi River system contribute to basin-wide operating objectives.</td></tr>
<tr><td>Justification:</td><td colspan="5">The flood plains of the Zambezi main stem are important for livelihood activities including food production. Individual Zambezi riparian countries have already identified a number of sites on the unregulated tributaries where dams for hydropower and irrigation schemes can be developed. These dams may be more accessible to users and have less environmental and socio-economic impacts than larger dams. They can also contribute to management of flush floods and they can be equipped to measure discharges and this data can be used in decision-making of the whole Zambezi River system. Rainfall, storage, inflow, outflow and evaporation data collected at dams is often quite reliable. The Zambezi main stem also has a number of sites which are suitable for hydropower production. The increasing deficit in electricity supply in the SADC Secretariat Region favors development of these dams. New dams can make conjunctive and synchronized operation more attractive for operators of existing large dams. The elements of such operating rules should meet water requirements for power generation, environmental flow requirements, agriculture, fisheries, etc where applicable. The HEC-3 Reservoir Operation Model developed by NIRAS-BRL for the World Bank , The WEAP model available in the ZAMWIS database, The ZRA flow forecasting model, the Hugo Model and the HDAM Graphs developed by WRNA were considered on this study. They all require further development to incorporate the new modes of operating dams on the Zambezi river system.</td></tr>
<tr><td rowspan="5">Actions/ Responsibility</td><td colspan="3">Review and update guidelines for operation of dams of low live storage/MAR ratio that may be developed on the Zambezi and its tributaries to incorporate basin wide objectives</td><td colspan="2">Ministries of Water and Interim ZAMCOM Secretariat/Dam operators</td></tr>
<tr><td colspan="3">Review designs of new dams and ensure that they incorporate the new modes of dam operation as mentioned in the justification above.</td><td colspan="2">Ministries of Water and Interim ZAMCOM Secretariat/Dam operators</td></tr>
<tr><td colspan="3">Develop reservoir and system operation models for new dams on the Zambezi River Basin</td><td colspan="2">Ministries of Water and Interim ZAMCOM Secretariat</td></tr>
<tr><td colspan="3">Monitor rainfall, inflows, outflows, storage and evaporation at new dams and capturing into ZAMWIS as standard best practice.</td><td colspan="2">Interim ZAMCOM Secretariat/Dam operators/Departments of Water and Catchment Management Authorities</td></tr>
<tr><td colspan="3">Develop operating rules for new dams which consider system-wide objectives</td><td colspan="2">Ministries of Water, Dam Operators and Interim ZAMCOM Secretariat</td></tr>
<tr><td rowspan="3">Benefits/ Beneficiaries:</td><td colspan="3">• Flexibility in the operation of main stem dams</td><td colspan="2">Dam Operators</td></tr>
<tr><td colspan="3">• Improved confidence and cooperation between different stakeholders</td><td colspan="2">Dam Operators and Disaster Management Agencies</td></tr>
<tr><td colspan="3">• Improved and more secure livelihoods</td><td colspan="2">Land and water users in the Zambezi Basin</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">• Studies to develop the guidelines and review designs.
• Studies to develop system operation models
• Effective monitoring of water resources and updating of ZAMWIS database</td></tr>
<tr><td>Specific assumptions/risks</td><td colspan="5">• New multi-purpose dams are implemented.
• New dams incorporate the processes recommended in the IHA Sustainability Assessment Protocol</td></tr>
<tr><td>Comments</td><td colspan="5">Important drivers for realization of this Concept:
• Hydrologists implement models developed
• System Operating Forum meeting evaluate contribution of new dams to basin-wide objectives</td></tr>
</table>

DEVELOP AND IMPLEMENT MULTI-OBJECTIVE DAM OPERATING RULES					
Intervention Sheet #	**2.5**	**Time Frame:**	Short term to Medium term	**Budget range:**	US$ 0.5-2 million,

Linkages	Annex 2, Chapters 5;and 6, Interventions No. 2.1 & 2.2; Annex 3 Report (recommendation sheet 1.1)	
Concept:	Improved, regulated releases from the main reservoirs in the Zambezi River Basin need clear guidelines that on how to address basin-wide objectives and apply methods that improve management of hydrological risks.	
Purpose	To provide guidelines for the operation of the dams on the Zambezi River Basin which address basin-wide operating objectives	
Justification:	Current dam operations leave some other important objectives and are typically for one year. Apart from dam safety and hydro power generation, other objectives to be considered include flood management, environmental requirements, irrigation, and flood-plain agriculture, among others. The fulfillment of multi-purpose operating objectives will require improved information, development of multi-objective, multi-year operating rules and synchronization of dam operations. Improved operation of dams and barrages contribute to maintenance of the ecological integrity of Zambezi River system and mitigation of flooding. Monitoring of implementation of the operating rules will result in progressive realization of benefits and adjustments where necessary.	
Actions/ Responsibility	Develop guidelines for developing and implementing multi-objective and multi-year operating rules.	Specialists and Dam and Barrage Operators
	Develop guidelines for synchronization of dam releases and conjunctive operation of dams	Specialists and Dam and Barrage Operators
	Develop multi-objective, multi-year operating rules for early warning decision support.	Specialists and Dam and Barrage Operators
	Investigate incorporation of inflow uncertainty in costing of water in storage, pricing, storage space and releases	Dam Operators, Interim ZAMCOM Secretariat
	Determine (where not available) and adopt minimum operating levels to connect to SAPP and possible power sales/purchases	Power Producers
	Facilitate application of guidelines in the operation of dams/barrages for with new operating rules including sediment and weed management.	Dam/Barrage Operators, Interim ZAMCOM Secretariat
	Monitor implementation of multi-year, multi-objective operating rules	Interim ZAMCOM Secretariat and stakeholders
Benefits/ Beneficiaries:	• Reduced risk to dam operations from improved modes of operation	All stakeholders but main beneficiaries are Dam and Barrage Operators
	• Reduced flood damage upstream and downstream of major dams	All stakeholders but main beneficiaries are Dam and Barrage Operators and Disaster Management Agencies
	• Improved sediment and weed management	All stakeholders but main beneficiaries are power producers
	• Improved water and energy security. Dam management requirements considered in interconnection with SAPP	All stakeholders but main beneficiaries are Power producers and consumers
Means of implementation:	• Studies to develop the guidelines and operating rules • Data capture and meetings to support implementation and monitoring activities	
Specific assumptions/risks	• Dam Operators and power producers are fully engaged, make the necessary changes and adopt the new modes of operation • A risk management plan exists to support decisions by dam operators and power producers. • Availability of power from SAPP during drought periods • Adoption of revised MOU for JOTC facilitates conjunctive and synchronized operation of dams as well as information exchange	

Comments	Important drivers for realization of this Concept: • Progress monitoring and reporting at System Operating Forum meetings.

<table>
<tr><th colspan="6">ESTIMATE AND IMPLEMENT ZAMBEZI ENVIRONMENTAL FLOWS</th></tr>
<tr><td>Intervention Sheet #</td><td>2.6</td><td>Time Frame:</td><td>Medium term to Long term</td><td>Budget range:</td><td>>US$ 5 million,</td></tr>
<tr><td>Linkages</td><td colspan="5">Annex 2, Chapters 4 , 5 and 6</td></tr>
<tr><td>Concept:</td><td colspan="5">The management of the Zambezi River System takes into consideration environmental flow requirements.</td></tr>
<tr><td>Purpose</td><td colspan="5">To improve availability of data on environmental flow requirements</td></tr>
<tr><td>Justification:</td><td colspan="5">Environmental flows contribute to the maintenance of ecosystems such as rivers, wetlands, estuaries and near coast marine systems, which provide a great variety ecosystem of goods and services. Aquatic ecosystems need water and other inputs such as debris and sediment to stay healthy. Depriving a river or a groundwater system of these flows damages the entire ecosystem, and also threatens the people and communities who depend on it. Current dam operations on the Zambezi consider a single objective. Apart from dam safety and hydro power generation, other objectives to be considered include flood management, environmental requirements, irrigation, and flood-plain agriculture, among others. The inclusion of environmental management objectives in operating rules will require improved information on environmental flows. Data on environmental flows is generally unavailable and there is need to implement a process to establishing them as outlined is chapter 4 of Annex 2. The WWF is supporting a project o establish environmental flows for parts of the Zambezi river Basin including the Kafue system and other wetlands. Establishment of environmental flows for the rest of the basin will complement this effort. The proposed Kholombidzo Dam will regulate Lake Malawi outflows and Shire River flows to further secure flow for hydropower production. The dam is intended to manage fluctuations in flow required for hydropower production and other downstream activities. Furthermore, there is scope for the dam to be sized and operated to control floods beyond the regulating level of the Kholombidzo Dam. However, during floods and depending on lake levels prior to the flooding, the water impoundment may extend all the way to the lake creating a vast reservoir area which will impact negatively on the integrity of the system.</td></tr>
<tr><td rowspan="2">Actions/ Responsibility</td><td colspan="3">Establish estimates of environmental flows for the Zambezi Basin</td><td colspan="2">Interim ZAMCOM, All the Departments of Water.</td></tr>
<tr><td colspan="3">Evaluate the Kholombidzo Dam design and make recommendations for incorporation of flood management and environmental releases in the design and operation of the.</td><td colspan="2">DIWD Malawi</td></tr>
<tr><td rowspan="4">Benefits/ Beneficiaries:</td><td colspan="3">• Improved knowledge environmental flows</td><td colspan="2">All stakeholders but Dam Operators and Disaster Management Agencies are main users of this information</td></tr>
<tr><td colspan="3">• Lake Malawi/Shire River system ecosystems preserved</td><td colspan="2">All stakeholders and water users</td></tr>
<tr><td colspan="3">• Reduced flood damage around Lake Malawi and on the Shire River system</td><td colspan="2">All stakeholders and water users</td></tr>
<tr><td colspan="3">• Reduced operating risks to hydro power plants</td><td colspan="2">ESCOM</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">• Specialists studies
• Evaluation by Departments of Water, Departments of the Environment, Interim ZAMCOM Secretariat, Specialists, JOTC, Hydrologists and SOF.</td></tr>
<tr><td>Specific assumptions/risks</td><td colspan="5">• Availability of data of suitable format, quality and length</td></tr>
<tr><td>Comments</td><td colspan="5"></td></tr>
</table>

<table>
<tr><th colspan="6">IMPROVE OBSERVED FLOW DATA FOR APPLICATION ON DAM MANAGEMENT</th></tr>
<tr><td>Intervention Sheet #</td><td>2.7</td><td>Time Frame:</td><td>Medium term</td><td>Budget range:</td><td>US$ 0.5-2 million</td></tr>
<tr><td>Linkages</td><td colspan="5">Annex 1, Annex 2, Chapters , 5, 6 and 7; Interventions No. 2.1 & 2.2; Annex 3 Report (recommendation sheet 1.2)</td></tr>
<tr><td>Concept:</td><td colspan="5">Availability of accurate observed flow data can significantly improve the operation of the main reservoirs in the Zambezi River Basin.</td></tr>
<tr><td>Purpose</td><td colspan="5">To improved observed flow data for stations used in the operation of dams on the Zambezi River Basin</td></tr>
<tr><td>Justification:</td><td colspan="5">The available historical flow records in the ZAMWIS have a lot of gaps. Some of the data has not been converted to flow and is presented as stage readings. There are rating curves for the respective gauge stations and there is need to develop them. Some of the data has gaps which can be filled using scientific patching methods. The usefulness of ZAMWIS as a source of flow data can only be realized if this data is improved and the database is continuously updated and maintained.</td></tr>
<tr><td rowspan="3">Actions/ Responsibility</td><td colspan="3">Clean, patch available observed data. Carry out statistical analysis of stream flows to inform dam operations [</td><td colspan="2">Specialists and Dam/Barrage Operators/ Water Resources Management Agencies or Authorities</td></tr>
<tr><td colspan="3">Update rating curves and calculate flow from observed gauge records</td><td colspan="2">Specialists and Water Resources Management Agencies or Authorities</td></tr>
<tr><td colspan="3">Activate and maintain ZAMWIS. This is linked to Annex 3 Report (recommendation sheet 3.2)</td><td colspan="2">Interim ZAMCOM Secretariat</td></tr>
<tr><td rowspan="2">Benefits/ Beneficiaries:</td><td colspan="3">• Improved and up to date observed stream flow data available in a suitable form to use in tools that generate operating rules.</td><td colspan="2">Dam Operators, Water Resources Management Agencies or Authorities and Hydrologists</td></tr>
<tr><td colspan="3">• Reduced risk to Dam Operators through application of more reliable observed data</td><td colspan="2">Dam Operators, Water Resources Management Agencies or Authorities and Hydrologists</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">• Studies to patch data by hydrologists and specialists
• Dam/Barrage Operators and
• Field measurements and analysis to generate rating curves by hydrologists and specialists
• Activation and maintenance of ZAMWIS by Interim ZAMCOM Secretariat, Dam Operators, Water Resources Management Agencies or Authorities and Hydrologists</td></tr>
<tr><td>Specific assumptions/risks</td><td colspan="5">• Recognition of the importance of improving observed data by Dam Operators, Water Resources Management Agencies or Authorities and Hydrologists</td></tr>
<tr><td>Comments</td><td colspan="5">Important drivers for realization of this Concept:
• Dam Operators, Water Resources Management Agencies or Authorities and Hydrologists</td></tr>
</table>

SIMULATE FLOW TIME-SERIES FOR THE ZAMBEZI RIVER SYSTEM					
Intervention Sheet #	**2.8**	**Time Frame:**	Medium term to long term	**Budget range:**	US$ 0.5-2 million
Linkages	Annex 1, Annex 2, Chapters 2, 5, 6 and 7 ; Annex 3				
Concept:	Improved flow data is available for system operations				
Purpose:	To make available improved basin wide flow data from rainfall-runoff analysis and flow routing methods.				
Justification:	The stochastic nature of rainfall brings uncertainty and variability and as such risks associated with such analysis needs to be established and minimized. Time series of flow need to be sufficiently long (greater than 30years) to be of practical use in water resource management. Reliable long-term rainfall records exist for many stations in the Zambezi River basin. Rainfall-runoff analysis and flow routing are important tools in the operation of the Zambezi River System. They are applied for planning of new developments and to provide advance knowledge necessary for operation of dams/barrages.				
Actions/ Responsibility:	Develop models and undertake rainfall-runoff analysis and flow routing for important stations identified in Chapters 6 and 7 of this study using methods that accommodate heterogeneity and allow comparison across the basin. [		Dam Operators, Catchment Management Agencies and Interim ZAMCOM Secretariat		
	Develop and implement methods to quantify and communicate uncertainty in runoff estimates across the basin.		Dam Operators, Catchment Management Agencies and Interim ZAMCOM Secretariat		
Benefits/ Beneficiaries:	Reliable flow data available for dam management and other applications.		Dam Operators, Catchment Management Agencies		
	Information on uncertainty and variability in runoff estimates across the basin		Dam Operators, Catchment Management Agencies and Disaster Management agencies		
Means of implementation:	• Rainfall runoff studies by hydrologists and specialists • Studies to estimate uncertainty and variability by hydrologists and specialists				
Specific assumptions/risks	Cooperation of Dam Operators in providing available observed data.				
Comments					

<table>
<tr><th colspan="6">CLIMATE CHANGE SCENARIOS FOR THE ZAMBEZI BASIN</th></tr>
<tr><td>Intervention Sheet #</td><td>2.9</td><td>Time Frame:</td><td>Medium term to long term</td><td>Budget range:</td><td>US$ 2-5 million</td></tr>
<tr><td>Linkages</td><td colspan="5">Annex 2, Chapter 3</td></tr>
<tr><td>Concept:</td><td colspan="5">Better information on possible future climate conditions will contribute to improved dam and wetland management</td></tr>
<tr><td>Purpose</td><td colspan="5">To improve understanding of possible future change in the climate of the Zambezi River Basin and their implications on dam and wetland management</td></tr>
<tr><td>Justification:</td><td colspan="5">Most studies on climate change consistently state that the Zambezi will become drier in the next 20 to 50 years. This means that climate change is a potential threat to water availability and, to a lesser degree, to an increase in potential flood and drought occurrences. Climate change and variability have also become a major concern for the Zambezi River Basin.</td></tr>
<tr><td rowspan="4">Actions/ Responsibility</td><td colspan="3">Develop new climate change scenarios relevant to dam management and wetland hydrology for the Zambezi River basin for a period of 20 to 50 years</td><td colspan="2">Interim ZAMCOM Secretariat and Specialists</td></tr>
<tr><td colspan="3">Investigate impact of climate change impacts on extreme flows in the Zambezi River Basin and the impact on dam operations.</td><td colspan="2">Dam Operators, Catchment Management Agencies and Interim ZAMCOM Secretariat</td></tr>
<tr><td colspan="3">Investigate impacts of various climate change scenarios on the functions of the Barotse wetland and make recommendations</td><td colspan="2">Department of Water – Zambia</td></tr>
<tr><td colspan="3">Investigate impacts of various climate change scenarios on the functions of the Lower Shire wetland and make recommendations</td><td colspan="2">DIWD Malawi</td></tr>
<tr><td rowspan="2">Benefits/ Beneficiaries:</td><td colspan="3">Information on possible future climate conditions</td><td colspan="2">Dam Operators, Catchment Management Agencies</td></tr>
<tr><td colspan="3">Information on possible impacts of climate change on wetland hydrology</td><td colspan="2">Departments of Water, Departments of Environment. Wetland riparians, Conservation Agencies</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">• Specialist climate change scenario and impact studies
• Evaluation of impact studies by Interim ZAMCOM, SADC Secretariat, Conservation Agencies and Climate Change Specialists</td></tr>
<tr><td>Specific assumptions/risks</td><td colspan="5">Willingness to consider and review information on climate change scenarios and impacts.</td></tr>
<tr><td>Comments</td><td colspan="5">• Progress monitoring and reporting at System Operating Forum meetings.</td></tr>
</table>

<table>
<tr><th colspan="6">IMPROVE UNDESTANDING OF THE HYDROLOGY AND FUNCTIONING OF WETLANDS IN THE ZAMBEZI RIVER BASIN</th></tr>
<tr><td>Intervention Sheet #</td><td>2.10</td><td>Time Frame:</td><td>Medium term to long term</td><td>Budget range:</td><td>US$ 2-5 million</td></tr>
<tr><td>Linkages</td><td colspan="5">Annex 2, Chapter 4</td></tr>
<tr><td>Concept:</td><td colspan="5">The Barotse, Luangwa and Shire wetlands retain their hydrological functions</td></tr>
<tr><td>Purpose</td><td colspan="5">To improve understanding of the hydrology and functioning of the Barotse wetlands</td></tr>
<tr><td>Justification:</td><td colspan="5">The Zambezi river Basin has a number of significant wetlands. The WWF is supporting projects on the Kafue and other wetlands. There is a an on-going programme to rehabilitate the degraded Luangwa wetlands. The Barotse, Luangwa and Lower Shire wetlands are important for management of floods and they also perform very important socio-economic and environmental functions. It is likely to be impacted on by land use patterns and climate change. The Barotse is in the upstream part of the Zambezi and its drainage influences the Zambezi flows. More specifically its pre-wet season state can affect its response to rainfall and runoff events. The wetlands face a number of threats rooted in poverty and high demographic growth rates. The degradation of the wetland functions may continue into the future unless the impacts are quantified and appropriate interventions are identified and implemented. The Luangwa is a major contributor of floods into Cahora Bassa dam. They Lower Shire wetlands are impacted on by land use patterns, climate change, and flow regulation from hydropower production activities in the Middle Shire. Furthermore the impact of the proposed activities to enhance hydropower production on wetlands functions is unknown. The degradation of the wetland functions may continue into the future unless the impacts are quantified and appropriate interventions are identified and implemented.</td></tr>
<tr><td rowspan="4">Actions/ Responsibility</td><td colspan="4">Undertake hydrology study of the Barotse wetland based on historical conditions and available Landsat images</td><td>Department of Water – Zambia, ZRA and Interim ZAMCOM Secretariat</td></tr>
<tr><td colspan="4">Carry socio-ecological studies for the Barotse wetland and water demands and make recommendations on their sustainable use.</td><td>Department of Water – Zambia</td></tr>
<tr><td colspan="4">Undertake hydrology study of the Lower Shire wetlands based on historical conditions and available Landsat images</td><td>DIWD Malawi and Interim ZAMCOM Secretariat</td></tr>
<tr><td colspan="4">Carry socio-ecological studies for the Lower Shire wetlands and water demands and make recommendations on their sustainable use.</td><td>DIWD Malawi</td></tr>
<tr><td rowspan="3">Benefits/ Beneficiaries:</td><td colspan="4">• Improved knowledge of hydrological functioning of the Barotse and Shire Wetlands</td><td>All stakeholders but Dam Operators and Disaster Management Agencies are main users of this information</td></tr>
<tr><td colspan="4">• Improved knowledge of uses of the Barotse and Shire Wetlands</td><td>All stakeholders</td></tr>
<tr><td colspan="4">• Contribution to sustainable use of the wetlands</td><td>All stakeholders, wetland and water users</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">• Specialist hydrology studies
• Specialist socio-ecological studies
• Evaluation of hydrology and socio-ecological studies by Departments of Water – Zambia and Malawi and Interim ZAMCOM Secretariat, SOF, JOTC members, hydrologists and specialists</td></tr>
<tr><td>Specific assumptions/risks</td><td colspan="5">• Availability of data of suitable format, quality and length</td></tr>
<tr><td>Comments</td><td colspan="5"></td></tr>
</table>

<table>
<tr><th colspan="6">IMPLEMENT A PILOT PROJECT INVOLVING THE KARIBA, ITEZHI-TEZHI, KAFUE AND CAHORA BASSA DAMS WITH CORE ACTIVITIES SUCH AS DAM SYNCHRONISATION, CONJUNCTIVE OPERATION OF DAMS, INTRODUCTION OF E-FLOWS AND FLOOD MANAGEMENT</th></tr>
<tr><td>Intervention Sheet #</td><td>2.11</td><td>Time Frame:</td><td>Short term to medium term</td><td>Budget range:</td><td>>US$ 5 million</td></tr>
<tr><td>Linkages</td><td colspan="5">Annex 2, Chapters 5, and 8</td></tr>
<tr><td>Concept:</td><td colspan="5">Operators of main dams in the Zambezi River Basin negotiate and agree to operate their dams for optimal outcomes.</td></tr>
<tr><td>Purpose</td><td colspan="5">To operate the dams on the Zambezi River Basin to address flood management and environmental flow requirements.</td></tr>
<tr><td>Justification:</td><td colspan="5">The major dams of the basin have, to date, been operated more of less independently, without regard to requirements of other stakeholders in the basin. Similarly, all dams have been managed without any provision for environmental flows and other socio-economic considerations for downstream or other riparian users. Floods and droughts are part of the history of the Zambezi with and without dams. Large floods and severe droughts are a fact of life in the Zambezi system. Dams impound floods and modify downstream flows and the lake environment. However releases can be managed to minimize upstream and downstream impacts. The need to widen the range of possible flow regimes in the Zambezi River system downstream of major dams in order to provide for more uses/users was established on this study. The goals of system optimization, water security and benefit sharing were also discussed in detail. Synchronisation and conjunctive operation are two terms which are very closely associated with modern scientific trends in dam management to achieve these goals. Synchronisation relates to timing of actions (near real time) in order to achieve or avoid an outcome which is certain to occur at a known position in space and time. Conjunctive operation relates to getting different parts of a system to support each other or to support other systems in order to meet requirements such as quantity and/or quality and cost of water. The changes in state which influences the triggers for conjunctive operation do not happen suddenly, and are not near real time, but are measurable and predictable. Thus Dam Operators require support to set up and implement a practical pilot project which builds their confidence on synchronised and conjunctive operation of dams.</td></tr>
<tr><td>Actions/ Responsibility</td><td colspan="4">Development of a feasibility report on a pilot project for synchronized and conjunctive operation of Kariba, dams on the Kafue sub-system and Cahora Bassa for management of flood releases and provision of environmental flows</td><td>Dam Operators, Interim ZAMCOM Secretariat</td></tr>
<tr><td></td><td colspan="4">Facilitate synchronised operation of Kariba, dams on the Kafue sub-system and Cahora Bassa for management of flood releases.</td><td>Dam Operators, Interim ZAMCOM Secretariat</td></tr>
<tr><td></td><td colspan="4">Facilitate conjunctive and synchronized operation for introduction of environmental flows for the middle and lower Zambezi from Kariba, the Kafue subsystem and Cahora Bassa dams.</td><td>Dam/Barrage Operators, ZAMCOM Secretariat</td></tr>
<tr><td></td><td colspan="4">Monitor implementation of pilot project</td><td>Interim ZAMCOM Secretariat and stakeholders</td></tr>
<tr><td>Benefits/ Beneficiaries:</td><td colspan="4">• Operations of Kariba, dams on the Kafue sub-system and Cahora Bassa result in optimum hydropower production, dam safety, supply of water to other users including the environment</td><td>All stakeholders but main beneficiaries are Dam and Barrage Operators</td></tr>
<tr><td></td><td colspan="4">• Reduced flood damage upstream and downstream of major dams</td><td>All stakeholders but main beneficiaries are Dam and Barrage Operators and Disaster Management Agencies</td></tr>
<tr><td>Means of implementation:</td><td colspan="5">• Feasibility study for the pilot project
• Implementation of a pilot project involving Kariba, dams on the Kafue sub-system and Cahora Bassa
• Data capture and meetings to support implementation activities</td></tr>
<tr><td>Specific</td><td colspan="5">• This should be considered a short to long term intervention to allow testing of a wide</td></tr>
</table>

assumptions/risks	range of scenarios which depend on weather/hydrological patterns. • Dam Operators and power producers are fully engaged, make the necessary changes and adopt the new modes of operation • A risk management plan exists (including funds) to cover for unforeseen loss of storage and power. • Availability of power from SAPP during drought periods • Adoption of revised MOU for JOTC facilitates conjunctive and synchronized operation of dams as well as information exchange
Comments	Important drivers for realization of this Concept: • Progress monitoring and reporting at System Operating Forum meetings.

References

Aduah, M.S. (2007). Multitemporal remote sensing for mapping and monitoring floods an approach towards validation of the KAFRIBA model, Kafue Flats, Zambia. MSc thesis, International Institute for Geo-information Science and Earth Observation, (ITC), the Netherlands.

Allen, R. G., Pereira, L.S., Raes, D, and Smith, M (1998), *FAO Irrigation and Drainage Paper No. 56 - Crop Evapotranspiration*, Food and Agriculture Organization.

Arnell, N.W., 1999: Climate change and global water resources. Global Environmental Change, 9, S31-S50. As cited in IPCC Report, 2007.

Balek, J. Water balance of the Zambezi Basin. Technical Report 15. Lusaka, Zambia: National Council for Scientific Research, 1971b.

Batoka Joint Venture Consultants, 1993: Batoka Gorge Hydro Electric Scheme Feasibility Study. Section 13. Reservoir operation studies. Final Report. Harare: Zambezi River Authority.

Beilfuss, R., and dos Santos, D. (2001). Patterns of hydrological change in the Zambezi Delta, Mozambique: Working paper 2, Program for the sustainable management of Cahora Bassa dam and the lower Zambezi

Beilfuss, R. Personal communication and spreadsheets of data over 21st April to 30th April. 2010.

Beilfuss R, C. Bento, P. Hancock, B. Kamweneshe, K. McCann, M. Morrison, L. Rodwell. Water, wetlands & wattled cranes: A regional monitoring & conservation program for Southern Africa.

Richard Beilfuss, et. al. (2000) Paul Dutton & Dorn Moore (2000). IUCN ZD Land cover and land use change in the Zambezi Delta in Zambezi Basin Wetlands Volume III: Chapter 2.

Budyko, M. I. Climate and life, edited by D. H. Miller, Academic Press, 1974

Cambula, P., 1999: Impacts of climate change on water resources of Mozambique. Republic of Mozambique. Final Report of the Mozambique/U.S. Country Study Program Project on Assessment of the Vulnerability of the Economy of Mozambique to Projected Climate Change, Maputo, Mozambique, (unpublished). As cited in IPCC[1] Report (2001).

Chavula, G.M.S. and Chirwa, A.B., 1996: Effects of Climate Change on Water Resources of Malawi: Vulnerability assessment and adaption strategies. In: USA Country Studies Program to address Climate Change: Support to Malawi for Vulnerability and Adaption Studies. As cited in Norconsult, 2003.

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Koli, W.-T. Kwon, R. Laprise, V.M. Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton. 'Regional climate projections. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change', S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 847-940, 2007.

Dyson, M., Bergkamp, G., Scanlon, J. (eds). Flow: The Essentials of Environmental Flows. IUCN, Gland, Switzerland and Cambridge, UK.

Fauchereau, N., S. Trzaska, Y. Richard, P. Roucou and P. Camberlin, 2003: Sea-surface temperature co-variability in the southern Atlantic and Indian Oceans and its connections with the atmospheric circulation in the southern hemisphere. Int. J. Climatol., 23, 663-677. As cited in IPCC, 2007.

Gerrits, A. M. J., H. H. G. S. A. E. J. M. Veling, and Pfister, L (2009), Analytical derivation of the Budyko curve based on rainfall characteristics and a simple evaporation model, *Water Resour. Res.*, *45*, W04403, doi:10.1029/2008WR007308.

Government of Malawi (2003a) Ministry of Water Development, Integrated Water Resources Development Plan for Lake Malawi and shire river system "Lake Malawi Level Control" stage 2, Final Feasibility Report, Volume I – Main report

Government of Malawi (2003b) Ministry of Water Development, The Integrated Water Resources Development Plan for Lake Malawi and Shire River System - " Lake Malawi Level Control" - Stage 2 - Volume II – Part B Technical Assessments of Alternative Dams at Kholombidzo

Government of Malawi (2003c) Ministry of Water Development, Integrated Water Resources Development Plan for Lake Malawi and shire river system "Lake Malawi Level Control" Stage 2, Final Feasibility Report, Volume II – Part C – EIA of Upgraded Liwonde Barrage

Hargreaves, G. H., and Samani, Z. A. (1982), Estimating Potential Evapotranspiration, *J. Irrig. and Drain. Div.*, *108*(3), 225-230.

HDAM, Hydrological Drought Assessment Model, WR Nyabeze and Associates, 2011, www.wrnyabeze.com

Hudson, D.A. and R.G. Jones. Regional climate model simulations of present day and future climates of Southern Africa. Technical Note 39, Hadley Centre, Bracknell, 42 pp, 2002.

IPCC[1], 'Third Assessment Report : Climate Change 2001 (TAR) : Impacts, Adaption and Vulnerabilty', Chapter 10 : Africa, 2001.

IPCC[2], 'Special Report on the Regional Impacts of Climate Change : An Assessment of Vulnerability'. Chapter 2 : Africa, 2001.

IPCC, Climate Change 2002 : 'Impacts, Adaptions and Vulnerability', 2001. Cited in Norconsult, 2003.

IPCC, Fourth Assessment Report : 'Climate Change 2007 (TAR) : Impacts, Adaption and Vulnerabilty', Chapter 10 : Africa, 2007.

King, J.M. and Brown, C.A.(2010), Integrated Basin Flow Assessments: concepts and method development in Africa and South-east Asia. Special Issue of Freshwater Biology 55(1):127-146.

Klaassen J.G. 2003, Regulation and synchronisation of dam operation for environmental flows in the Zambezi River- Preliminary analysis. WWF phase 1 report

KNMI, (Koninklijk Nederlands Meteorologisch Institute) webite (accessed April, 2010) http://www.knmi.nl/africa_scenarios/published_JCLI2317.pdf, 2007.

Li-EDF-KP Joint Venture Consultants (Lahmeyer-Knight Peisold-Electricite' de France), 1999: Mepanda Uncua and Cahora Bassa North Project. Preliminary environmental and social impact assessment. Main report and technical annexes. Maputo: Unidade Tecnica de Implentacao de Projectos Hidroelectricos.

Mazvimavi, D. and Wolski, P.. 'Long Term Variations of Annual Flows of the Okavango & Zambezi Rivers', 2006.

Mwelwa E. 2004, The Application of the monthly time step Pitman Rainfall-Runoff Model to the Kafue River Basin of Zambia.., MSc Thesis, December 2004.

New, M. Climate change and water resources in the south-western Cape, South Africa. S. Afr. J. Sci., 98, 369-373, 2002.

New, M., Lister, D., Hulme, M., and Makin, I., 2002: A high-resolution data set of surface climate over global land areas. Climate Res., 21, 1-25.

Norconsult 'The integrated Water Resources Development Plan for Lake Malawi and Shire River System – "Lake Malawi Level Control" – Stage 2 – Volume III : Paper III-g : Hydrology - Past, Present and Future Conditions', 2003.

Ragab, R. & Prudhomme, C., 2002: Keynote paper: Climate Change and Water Resources Management in Arid and Semi-arid Regions: Prospective and Challenges for the 21st Century. Biosystems Engineering (2002) 81(1), 3-34. As cited in Norconsult, 2003.

Richard, Y., N. Fauchereau, I. Poccard, M. Rouault and S. Trzaska, 2001: 20th century droughts in Southern Africa: spatial and temporal variability, teleconnections with oceanic and atmospheric conditions. Int. J. Climatol., 21, 873-885. As cited in IPCC, 2007.

Ruosteenoja, K., T.R. Carter, K. Jylhä and H. Tuomenvirt. Future climate in world regions: an intercomparison of model-based projections for the new IPCC emissions scenarios. Finnish Environment Institute No. 644, Helsinki, 83 pp, 2003.

SAPP website (http://www.sapp.co.zw/). Accessed April 2010.

Seyam I. M, A. Y. Hoekstra, G. S. Ngabirano & H. H. G. Savenije. Globalization & Water Resources Management: The changing value of water. August 6-8, AWRA/IWLRI – University of Dundee International Specialty Conference, 2001.

Shela, O.N., 2000. 'Naturalisation of Lake Malawi levels and Shire River flows: challenges of water resources research and sustainable utilisation of the Lake Malawi-Shire River system'. In: Proceedings of the 1st WARFSA/Waternet Symposium: Sustainable Use of Water Resources, Maputo, 1–2 November 2000, pp. 1–12.2000. Cited in Mazvimavi & Wolski, 2006.

Shawinigan-Lavalin and Hidrotécnica Portuguesa. 1990a. Simulation of Kafue Gorge Power Plant operation: Hydroelectric Hydrological Assistance Project - Phase 1.SADCC 3.0.4.

Shawinigan-Lavalin and Hidrotécnica Portuguesa. 1990b. Simulation of the joint operation of major power plants in the Zambezi Basin: Hydroelectric Hydrological Assistance Project - Phase 1.SADCC 3.0.4.

Strzepek, K. and A. McCluskey. District level hydro-climatic time series and scenario analysis to assess the impacts of climate change on regional water resources and agriculture in Africa. Centre for Environmental Economics and Policy in Africa (CEEPA) Discussion Paper No.13, University of Pretoria, Pretoria, 59 pp, 2006.

SWECO, 1971. Kafue River Hydroelectric Power Development Stage II. Itezhitezhi Reservoir and extension of Kafue Gorge upper power station. Preinvestment study. Stockholm, Sweden. As cited in Beilfuss, R. Patterns of Hydrological Change in the Zambezi Delta, 2001.

Tadross, M.A., B.C. Hewitson and M.T. Usman. The interannual variability of the onset of the maize growing season over South Africa and Zimbabwe. J. Climate, 18, 3356-3372, 2005a. As cited in IPCC, 2007.

Tumbare[1], M.J. 'Infrastructure Management in a Changing Environment : The Case of Kariba Dam,' in Petermann T., (ed.), 2008, Towards Climate Change Adaptation - Building Adaptive Capacity in Managing African Transboundary River Basins, InWent, ISBN: 978-3-939394-28-0, Chapter 7 (Pgs 141-159), 2008.

Tumbare[2], M. J. 'Cyclic Hydrological changes of the Zambezi River Basin : Effects and Migratory Measures' in Tumbare M. J. (ed), 2000, Management of River Basins and Dams: The Zambezi River Basin, AA Balkema Publishers, Rotterdam, ISBN 90 5410490 2 (ISBN 905809 338 7 soft bound edition) (Pgs 201-209), 2000.

Usman, M.T. and C.J.C. Reason, 2004: Dry spell frequencies and their variability over southern Africa. Climate Res., 26, 199-211. As cited in IPCC, 2007.

World Bank. The Zambezi River Basin, A Multi-Sector Investment Opportunities Analysis, 2010.

Vörosmarty, C.J. and B. Moore, 1991. 'Modelling basin scale hydrology in support of physical climate and global biochemical studies: an example using the Zambezi River. Surveys in Geophysics', 12, 271-311. Cited in IPCC Report, 2007.

Winsemius, H.C., 2009: Satellite data as complementary information for hydrological models, Delft, University of Technology, VSSD press, ISBN: 978-90-6562-207-5.