IMPACT OF CLIMATE CHANGE ON HYDRO-ELECTRIC GENERATION IN THE ZAMBEZI RIVER BASIN

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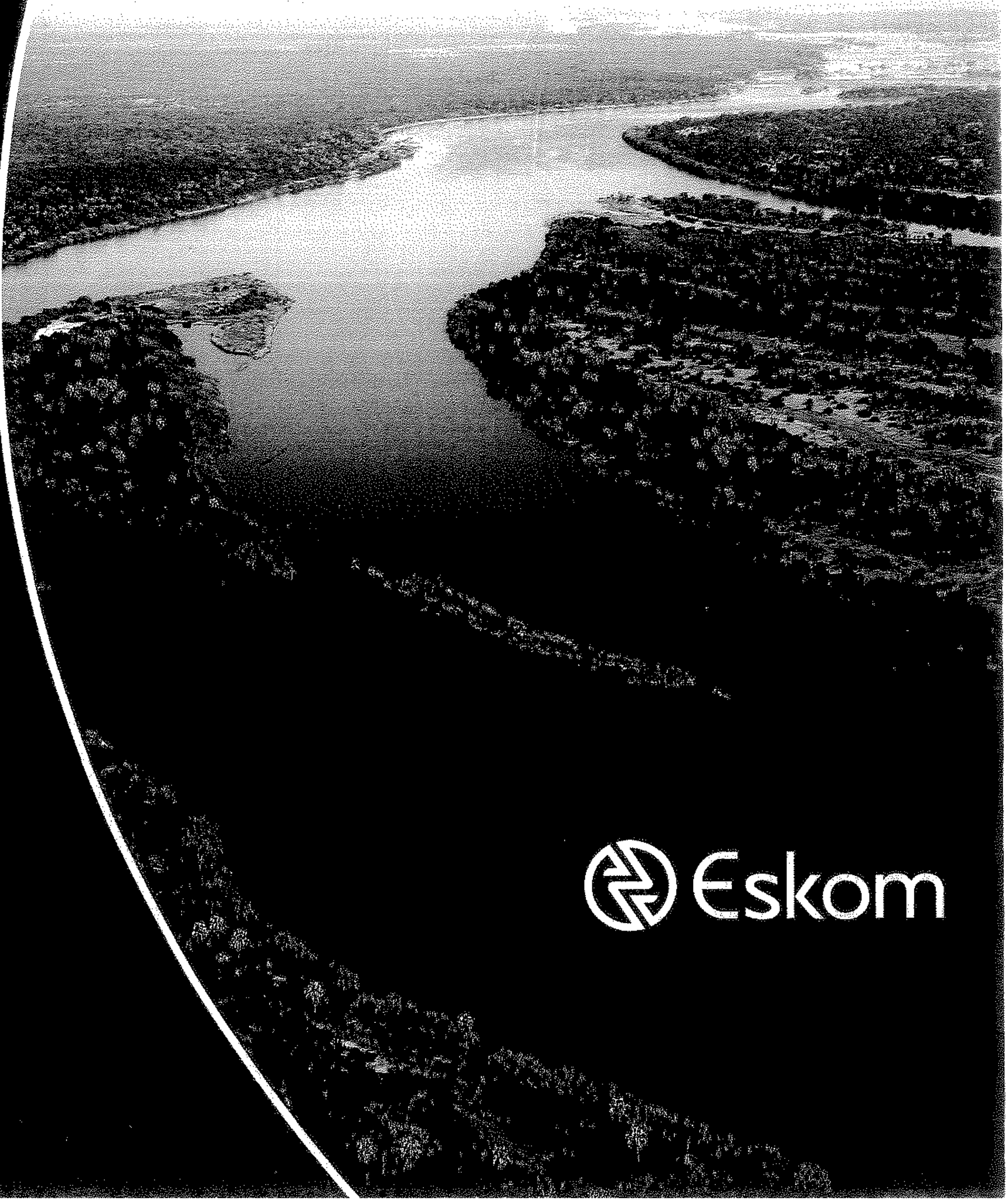

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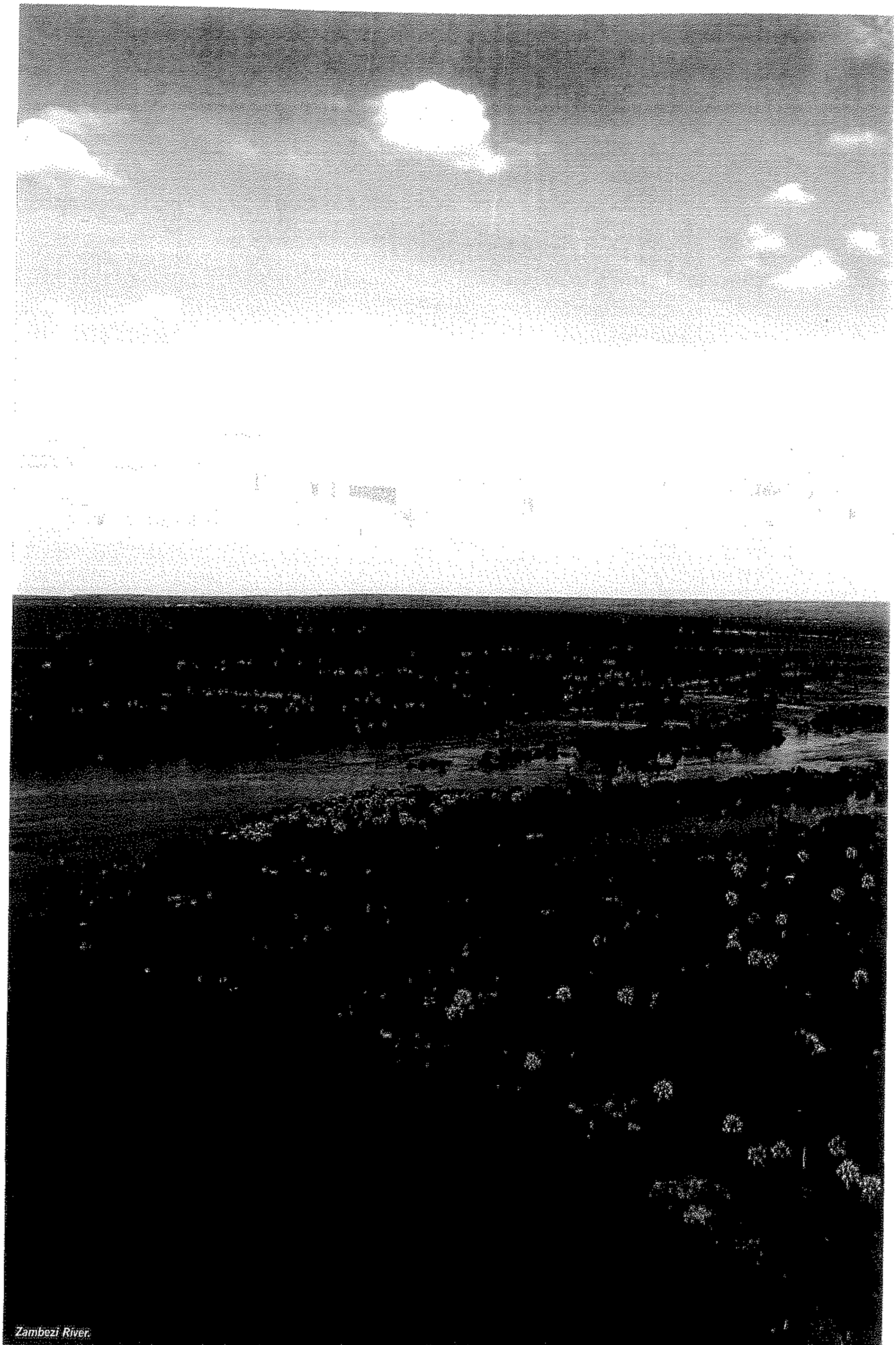

Zambezi River.

PREFACE

Eskom is a major partner in the South African Power Pool (SAPP), which exists to transfer electricity generated in the countries of the South African Development Community (SADC) among the member states of that organisation. This serves to promote efficiency through resource pooling and acts to foster commercial intercooperation within the region. Unlike South Africa, where coal is the predominant source of primary energy for power generation, many of the SADC countries have access to large scale hydro-electric resources and, further, there is sufficient capacity in the Zambezi and Congo river catchments to increase the installed hydro-electric generating capacity significantly in the future.

Although hydro-electric power generation provides a cost-effective way of mitigating greenhouse gas emissions, it is potentially very vulnerable to climate variability and change, particularly on the African continent where the major river systems are not subject to the periodic boost provided by annual seasonal snow melts. This vulnerability is amply demonstrated by recent historical data, which shows persistent droughts in the region.

Given these facts, together with the forecast for long-term economic growth within the SADC region, with the concomitant rise in energy demand, Eskom commissioned an interdisciplinary research programme into the impacts of climate change on hydro-electric power generation in the region. From the outset it was intended that this programme would utilise expertise from several SADC countries to ensure a mutual understanding of the situation among the members of the SAPP and to encourage collaboration and dialogue when planning new installed hydro-electric generating capacity. This publication draws from the extensive information obtained from a specific study aimed at assessing the impact of climate change on hydro-electric power generation within the Zambezi River Basin.

The study objectives included:

(i) An assessment of the historical baseline situation for the Zambezi River catchment.
(ii) The development of a water balance model and an estimate of the water demand under baseline conditions for both existing generating plant alone and existing plant combined with proposed new schemes.
(iii) Using derived climate change scenarios, the possible impacts of climate change on water run-off and thus hydro-electric power generation potential.
(iv) A preliminary consideration of possible adaptation measures that could be used to mitigate the impacts of climate change.

Although further research will be inevitable, the information provided in this publication can provide valuable material for planning the way ahead for expanding the hydro-electric generating potential within the SADC region. Eskom has been proud to assist in fostering research into hydro-electric power generation within the region and promoting cooperative research ventures with benefit to all the participants.

Dr Steve Lennon
Divisional Executive (Corporate Services)
Eskom Holdings Limited

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ACRONYMS

CCCMA	Canadian Centre for Climate Modelling and Analysis
CEEEZ	Centre for Energy Environment and Engineering Zambia
CR	Channel Reach Sub Model
CSIRO	Commonwealth Scientific Industrial Research Organisation
CSO	Central Statistical Office
DDC	Data Distribution Centre
DOS	Disc Operating System
DRC	Democratic Republic of Congo
ECZ	Environmental Council of Zambia
EDM	Electricidade de Mozambique
EGS	Environmental and Geographical Studies
ESCOM	Electricity Supply Commission of Malawi
FAO	Food and Agriculture Organisation
FSL	Full Supply Level
GCM	Global Circulation Model
HADCM3	Hadley Climate Model run by the Hadley Centre
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-tropical Convergence Zone
MAP	Mean Annual Precipitation
MAR	Mean Annual Run-off
Mm^3	Million cubic metres
mm	Millimetres
RU	Run-off sub model
RV	Reservoir sub model
SADC	Southern African Development Community
SAPP	Southern African Power Pool
SRES	Special Report on Emissions Scenarios
UNEP	United Nations Environment Programme
WRSM	Water Resource Simulation Model
ZESA	Zimbabwe Electricity Supply Authority
ZESCO	Zambian Electricity Supply Commission
ZRA	Zambezi River Authority

ACKNOWLEDGEMENTS

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CEEEZ wishes to recognise the invaluable contribution of the team members in this study, who comprised: Prof F.D. Yamba, Dr P. Zhou, Dr B. Cuamba, Mr C. Mzezewa, Mr C. Chikusa, Mr L. Nyahuma, Mrs S. Jain, Mr H. Walimwipi, and Mr G. Phiri.

We also wish to extend our gratitude to organisations and institutions that contributed to the success of this study. We are indebted to Zesco, Zambezi River Authority (ZRA), and the Meteorological and Water Affairs Departments in Zambia, Malawi, Mozambique and Zimbabwe, for providing us with the data utilised in the study.

ABOUT ESKOM

Eskom generates, transports and distributes approximately 95% of South Africa's electricity – making up 45% of the total electricity consumed on the African continent. Eskom is the world's eleventh-largest power utility in terms of generating capacity, ranks ninth in terms of sales, and boasts the world's largest dry-cooled power stations.

Eskom sells power directly to some 6 000 industrial, 18 000 commercial, 70 000 agricultural and three million residential customers. With an installed capacity of 43 GW, it owns and operates several coal-fired, gas-fired, hydro and pumped storage power stations, as well as one nuclear power station. Its 28 000 kilometres of transmission lines span the entire country and extend into most Southern African Development Community (SADC) countries. At the peak of the electrification programme, its distribution teams connected an average of 1 000 new homes every day – an achievement unprecedented anywhere else in the world.

Eskom is wholly owned by the South African government and has its headquarters in Johannesburg. The company is committed to aligning itself with international sustainability reporting initiatives and the government's programme to combat global climate change.

Further environmental and social information is available on the Eskom website **www.eskom.co.za.**

Part I:
Background and Methodology

Victoria Waterfall with the Zambezi flowing between Zambia and Zimbabwe.

1. BACKGROUND

1.1 INTRODUCTION

Although a great deal of research has been undertaken in global climate change world wide, very few studies have focused on regions. Studies are now emerging which place emphasis on continental regions. For example, a recent study [1] investigated the effects of increased greenhouse gas (GHG) emissions on the Southern Africa regions weather systems with emphasis on rainfall and temperature influences on water resources and agriculture. Further studies [2] have investigated the implications of climate change on run-off from major regions of Africa. Although hydro-electricity contributes moderately to the energy supply of Southern Africa, there are very few available studies that have examined the impact of climate change on energy use in the region [3].

The effects of climate change on river flows are uncertain, but any significant changes would have implications for hydro-electric generation. Climate change could affect the flow amounts and seasonality in most rivers, which could affect the amount of electricity generated annually by hydro-electric schemes and the timing of power production. Hydro-electric generation may be more sensitive to changes in river flows than other types of water systems. It is evident from recent drought occurrences in the SADC region [4] that there is a deficiency of water during drought periods, which consequently affects hydro-power generation and results in load shedding in most countries.

It is also clear that there is enough historical evidence of the persistent occurrences of droughts. According to the IPCC Third Assessment Report [5], water resources are a key area of vulnerability in Africa, affecting water supply for household use, agriculture and industry including hydro-electric power generation. The report states that Africa is the continent with the lowest conversion of precipitation to run-off, averaging 15% per annum. It concludes that most of Africa has invested significantly in hydro-electric power facilities. Reservoir storage in these facilities shows marked sensitivity to variations in run-off and periods of droughts. Thus storage and major dams have on occasion reached critical levels, threatening industrial activities. Model results of some reservoirs and lakes indicate that global warming will increase the frequency of such low storage volumes as a result of drought conditions.

The study reported in this book was supported by Eskom Holdings Limited, South Africa, to assess climate change/variability implications on hydro-electricity generation (covering those currently existing and possible future projects) in the Zambezi River Basin, under its Climate Change Impact Research programme. In the recent past, only one study [6] has been undertaken, focusing on climate change simulations for the proposed Batoka Gorge hydro-electric scheme on the Zambezi River Basin.

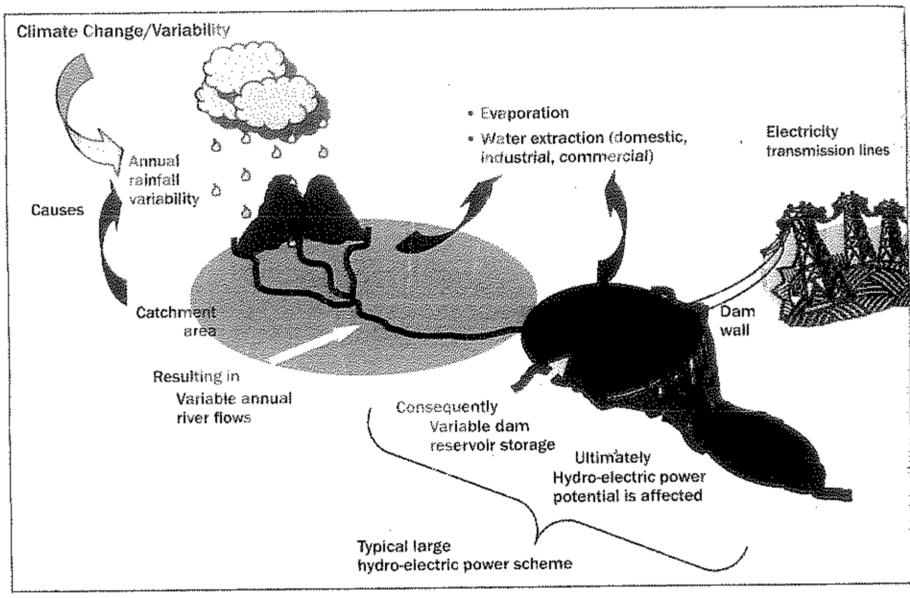


Figure 1.1: Climate change/variability effects on hydro-power potential.

1.2 CLIMATE CHANGE/VARIABILITY EFFECTS ON HYDRO-POWER POTENTIAL

A typical hydro-power system consists of a catchment with various river systems feeding into one main river. A dam wall is then constructed to store the water in a reservoir. From the reservoir, water is abstracted, normally through channels to mechanical turbines connected to generators for electricity generation. One of the main governing parameters on which basis the size of hydro-electric potential is assessed, is the flow. The river flow varies throughout the year in relation to the rainfall on the catchment. Ultimate river flow entering the channel for electricity generation is in turn affected by annual rainfall variability, evapo-transpiration in the catchment, and abstraction for domestic, commercial and industrial use. Climate change affects annual rainfall variability, which in turn affects river flows entering the reservoir, consequently affecting the hydro-electric potential of a given scheme.

1.3 STUDY BACKGROUND

In view of the effects of possible climate change on river flows in general and, in particular, recent historical data of persistent occurrences of droughts in the region on one hand, and implications for hydro-electric generation on the other, the study aimed to assess the impact of climate change on run-off and consequently hydro-electric generation in the Zambezi River Basin.

The Zambezi River Basin is the fourth-largest river basin of Africa, after the Congo/Zaire, Nile and Niger basins [7]. Its total area represents about 4,5% of the area of the continent and spreads over eight countries namely; Malawi, Mozambique, Zimbabwe, Zambia, Angola, Botswana, Namibia and Tanzania, as shown Figure 1.2. The Zambezi River flows eastwards for about 3 000 km from its source in Kalene Hills, north western Zambia, to the Indian Ocean, and consists of 13 main river basins. The main river basins are Borotse, Cuando/Chobe, Kabompo, Kafue, Kariba, Lwanginga, Luangwa, Lungwe Bungo, Mupata, Shire/Lake Malawi, Tete, Upper Zambezi and Zambezi Delta.

The aim and main objectives of the study undertaken by a multi-disciplinary research team were: to assess the effects of climate change/variability on run-off, reservoir storage capacities and hydro-power potential for both baseline (1970 – 2000) and projected (2010 – 2070) situations, and suggest corresponding adaptation/mitigation measures.

1.4 DETAILS OF MAJOR RIPARIAN STATES OF ZAMBEZI RIVER BASIN

1.4.1 ZAMBIA

The source of the Zambezi River is in the north western province of Zambia in an area around Kalene Hills (between 24° – 24°30' East and 11° – 11°30' South). From the source, it immediately flows through Angola and stretches a few kilometres before flowing back to Zambia through Western Province. It begins to widen as several tributaries join it.

1.4.1.1 Climate

Climate in Zambia is tropical, modified by altitude. Although Zambia lies in the tropics, the height of the plateau ensures that the climate is seldom unpleasantly hot, except in the valleys. There are three seasons, namely: cool, dry winter season from May to September, hot, dry season in October and November, and the rainy season, which is even hotter, from December to April. Winter months in Zambia are virtually rainless.

The circulation associated with the anticyclones to the south dries the mid levels of the atmosphere and suppresses any tendency to form rain-bearing clouds.

The southeast trade winds, blowing first across Madagascar and then Mozambique, carry little moisture into the mid-continent in June, blocked in large part by the Eastern Highlands [8].

There are about eight sub-basins of the Zambezi River in Zambia with some of them extending into parts of Angola, Zimbabwe and Mozambique. The sub-basins include Barotse River, Luangwa River, Kabompo River, Luanginga River, Chongwe River, Upper-Zambezi River,

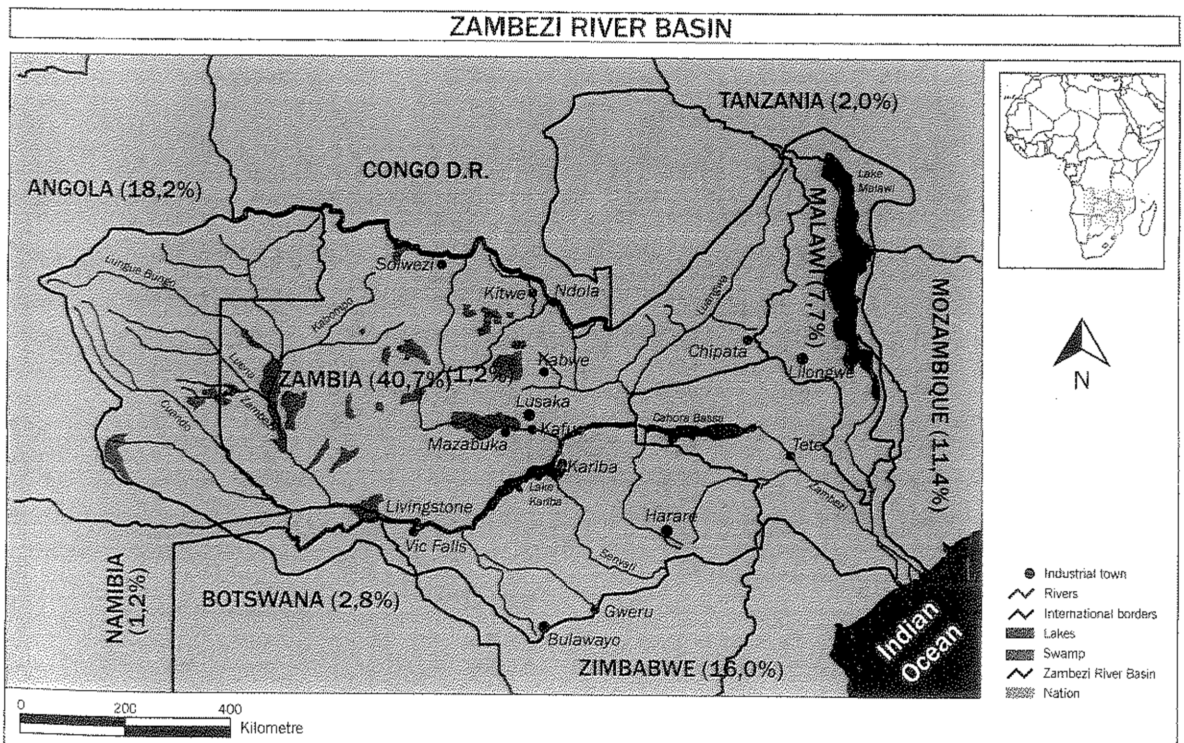


Figure 1.2: Zambezi Basin river systems.

Source: Zambezi River Authority (ZRA) GIS Office, Lusaka.

Lungue Bungo River, Kafue River and Kariba. Table 1.1 shows the location of sub-basins that constitute the Zambezi River Basin in Zambia with their respective catchment areas.

There are three major reservoirs in the Zambezi River Basin, which are essential to hydro-power generation in Zambia and these are, Lake Kariba, Itezhi-Tezhi, and Kafue Gorge. Itezhi-Tezhi and Kafue Gorge reservoirs lie within the Kafue River sub-basin while Lake Kariba lies in the Kariba sub-basin. The Mulungushi Reservoir, which is located in the Central Province lying on the Luangwa sub-basin, is another.

1.4.1.2 Hydro-power stations under baseline conditions in Zambia

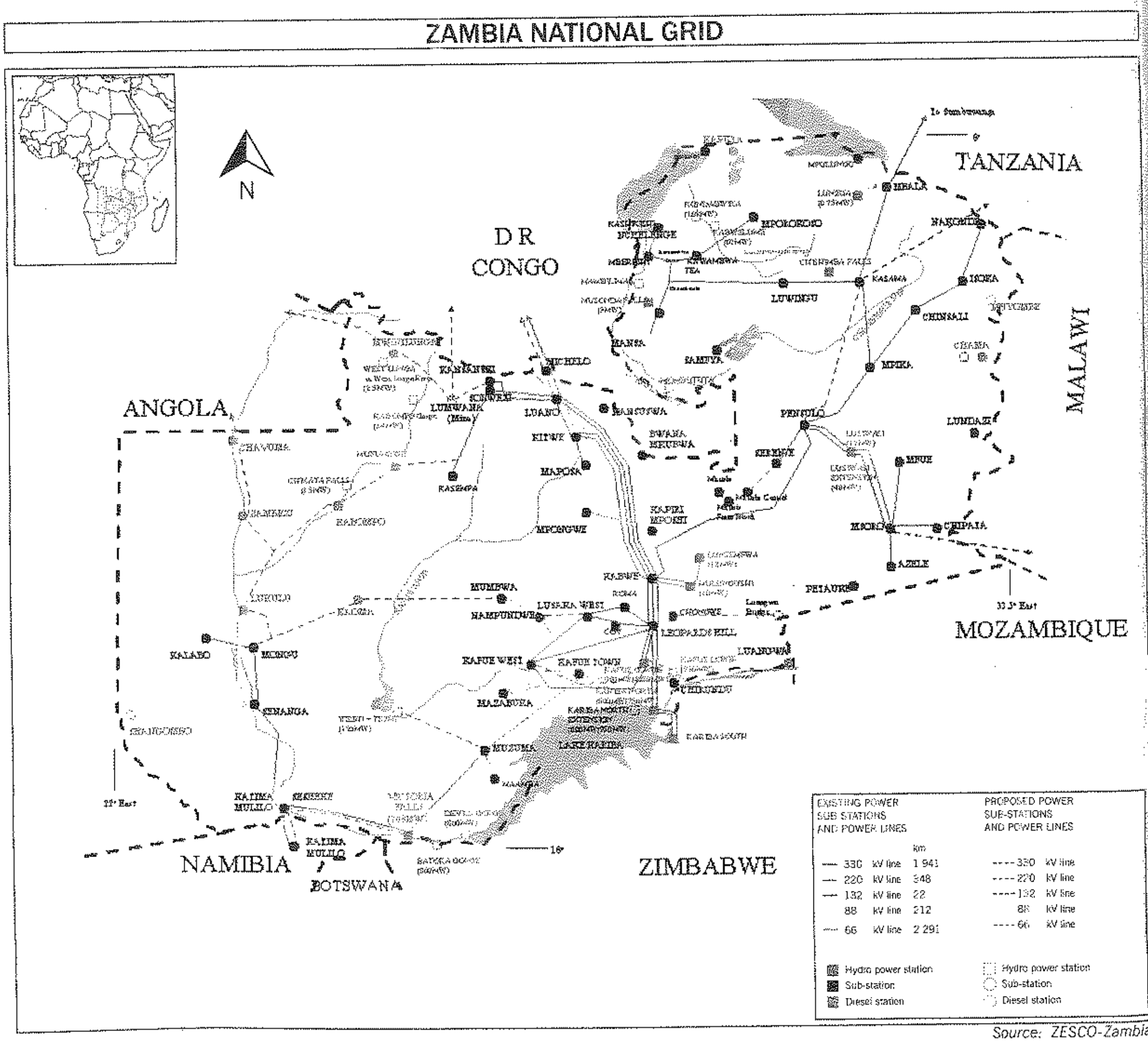
Zambia currently has only installed six major hydro-power plants in the sub-basins that make up the Zambezi River Basin. Table 1.2 shows the major hydro-power stations in the Zambezi River drainage basin in Zambia [9].

The most important installations are Kariba North Bank and Kafue Gorge, certainly their importance lies in their generating capacity. Hydro-power represents

Table 1.1: Catchment areas of Zambian sub-basins.

Name of catchment	Catchment area (km²)	Cross border catchment areas
Luangwa	147 622	
Kafue	150 971	
Barotse	93 403	
Luanginga	16 297	54 500,13 (including portions from Angola)
Kabompo	71 280	
Lungue Bungo	9 450	60 075,01 (including portions from Angola)
Chongwe	5 116	
Upper Zambezi	10 856	106 950,01 (including portions from Angola)
Cuando Chobe	145 359	Including portions from Namibia and Botswana
Luiana	54 843	

Source: Department of Water Affairs-Lusaka.



Source: ZESCO-Zambia.

Figure 1.3: Map of Zambia showing hydro-power development.

Table 1.2: Major hydro-power stations in Zambezi River drainage.

Name of power station	Name of sub-basin	Generating capacity (MW)
Victoria Falls	Kariba	108
Lusiwasi	Luangwa	12
Kariba North Bank	Kariba	600
Kafue Gorge	Kafue	900
Lunsemfwa	Luangwa	20
Mulungushi	Luangua	20

Source: Zesco-Lusaka.

99,8 per cent of the power produced by the Zambian Electricity Supply Commission (ZESCO). As for proposed hydro-power stations, a major reservoir, Katombora, is proposed for the Zambezi River some 60 km upstream of Victoria Falls, to regulate flows at the Victoria Falls station(s) and for the proposed Batoka Gorge hydro project. Construction of this reservoir and the proposed Batoka Gorge power station would enable Zambia's Kariba plant to be expanded from 600 MW to 900 MW [9].

Batoka Gorge power station, a bi-national hydro project between Zambia and Zimbabwe, about 50 km downstream of Victoria Falls, would include a 181 m high dam wall and would provide up to 800 MW of hydro capacity for both Zambia and Zimbabwe. Another proposed project on the Zambezi is Devils Gorge, at a site between Batoka Gorge and Kariba, which would have a capacity of 600 MW at each bank. Mupata Gorge, sited on the Zambezi just before the point at which it flows into Mozambique territory, would have an installed capacity of between 640 and 1 200 MW. There is potential for installing a second large hydro plant downstream of Kafue Gorge on the Kafue River, the Kafue Lower project (450 MW), just upstream of the confluence with the Zambezi River [9]. Figure 1.3 shows hydro-power development in Zambia.

Substantial water abstraction in the Zambezi River Basin in Zambia is done on the Kafue sub-basin. Other sub-basins whose water is abstracted considerably include Luangwa and Kariba sub-basins. Water abstracted is used for the following:

(i) Industrial activities (copper mines, food processing, chemical industry, etc).
(ii) Domestic (in major towns – Lusaka, Ndola, Kitwe, Kabwe, Livingstone, etc).
(iii) Irrigation (farming blocks, Nakambala Sugar Estate, etc).

Most of Zambia's industrial activities are concentrated along the railway line, particularly Copperbelt and Lusaka provinces. Zambia's major foreign exchange earner, copper, is mined in the Copperbelt province. Copperbelt and Lusaka provinces both draw water from the Kafue sub-basin to sustain their industrial and domestic needs. The most stressed sub-catchment in terms of water demand is the Kafue sub-basin. Water demand on the rest of the sub-basins that are part of the Zambezi River Basin in Zambia is almost negligible as the population density in these sub-basins is low, with little industrial activity.

1.4.2 ZIMBABWE

Zimbabwe covers an area of 391 000 km^2 and has a population of about 12 million. The total mean precipitation volume in Zimbabwe is 260 km^3, of which 20 km^3 is run-off. The Department of Water Development and Zimbabwe National Water Authority are responsible for water resources. There are now 223 large dams in operation. The total storage volume of all the country's reservoirs is more than 7,5 km^3.

1.4.2.1 Climate

Zimbabwe is located in the tropics. Temperate conditions prevail all year, as the climate is moderated by altitude and the inland position of the country. The hot and dry season is from September to October, and the rainy season from November to March. The best months to visit are April to May and August to September. Night-time temperatures can fall below freezing [8]. Table 1.3 shows the sub-basins that constitute the Zambezi River Basin in Zimbabwe with their respective catchment areas.

Table 1.3: Catchment areas of the sub-basins in Zimbabwe.

Name of Basin	Catchment area (km^2)
Gwayi River Basin	38 600
Sanyati River Basin	37 452
Manyame River Basin	9 740
Mazowe River Basin	4 538
Shangani River Basin	38 600
Angwa River Basin	656
Deka River Basin	2 950
Zambezi River Basin	361 000

Source: The Department of Water Development and Zimbabwe National Water Authority.

1.4.2.2 Hydro-power stations under baseline conditions in Zimbabwe

Zimbabwe Electricity Supply Authority (ZESA) is an electricity organisation that owns and operates all major power plants. The Zambezi River Authority is a bi-national organisation jointly owned by Zimbabwe and Zambia and is mandated to develop and manage resources on the section of the Zambezi River forming the common border between the two countries (about 760 km). The Authority is funded by both Governments equally, and each country is entitled to half the water available for power generation. The total installed capacity in Zimbabwe is 1 946 MW, of which 666 MW is hydro capacity at the Kariba South Bank station. No other hydro scheme is under construction or planned [10].

There are a number of proposed developments in the Zambezi River Basin, intended to develop fully the potential head between Victoria Falls and the Indian Ocean. A 390 MW plant could be installed on the south bank at Victoria Falls (on the Zimbabwe side), if the proposed reservoir is built. The Katombora regulating reservoir would have a live capacity of about 6 km^3 [10]. The Batoka Gorge project would include a 181 m high dam, with a lake of about 50 km, to be sited downstream of Victoria Falls, and could provide 800 MW of capacity each for Zimbabwe and Zambia.

1.4.3 MOZAMBIQUE

Mozambique, located in south-east Africa, covers an area of 802 000 km^2. The capital city is Maputo, while the other major towns are Beira, Nampula and the ports of Quelimane and Nacala. The official language is Portuguese [8]. The entry point of the Zambezi River into Mozambique is located at Zumbu, an area located 15,4° south and 30,3° east, with an altitude of 343 m above sea level.

1.4.3.1 Climate

The climate of Mozambique is primarily a lowland one, with higher precipitation, temperature, and cloud cover than the inland plateau. June is the cool season in Mozambique, especially inland, though the climate is moderated by the easterly flow from the 20° waters of the Mozambique Channel. The rainy season ends by April in the interior but may linger as long as June on some parts of the coast, especially over the Zambezi Delta.

Madagascar has some considerable influence on the weather on the mainland. The south-easterly trade winds flowing across the island lose much of their moisture on the windward side of the island and can recover only a part of the loss in the short trajectory over the Channel before reaching the coast of Mozambique [8].

The drainage area of the Zambezi River in Mozambique is about 181 273 km^2 and it contains 10 sub-basins namely, Luia, Revubue, Zambeze, Aruangua, Duangua, Messenguezi, Luenha, Chire, Cuacua and Zangue. Aruangua and Duangua sub-basins are shared between Zambia and Mozambique. Table 1.4 shows the sub-basins and their respective catchment areas.

1.4.3.2 Existing hydro-power stations in Mozambique

The main electricity authority is *Electricidade de Moçambique* (EDM), established by the state in 1977, two years after independence. EDM is responsible for generation, transmission and distribution (internally), but there are other companies that generate and distribute electricity. The main one is *Hidroelectrica de Cahora Bassa*, the biggest hydro-electric scheme in Southern Africa. Others include the Moatize Thermal Power Station (1 000 MW), the Cahora Bassa northern expansion (550 MW) and the Mepanda Uncua Hydro-Power Station (2 500 MW). Mozambique is one of the largest power producers in the SADC region. Hydro-electric power continues to be the main source of electrical power in Mozambique, but the harnessing of sea breeze and solar radiation are other possible sources of energy [10].

Table 1.4: Catchment areas of the sub-basins in Mozambique.

Name of sub catchment	Catchment area (km^2)
Luia	23 497
Revubue	15 655
Zambeze	82 908
Aruangua	3 664
Duangua	770
Messenguezi	2 230
Luenha	14 368
Chire	8 027
Cuacua	17 908
Zangue	10 016

Source: Mondlane University Mozambique

1.4.4 MALAWI

Malawi is a landlocked country with a geographical area of 118 484 km^2 and is located between latitudes 9°S and 17°S and between longitudes 33°E and 36°E. About 23,6 percent, or 28 000 km^2, of the area is occupied by Lake Malawi/Nyasa/Niassa), Africa's third largest freshwater lake [11].

The country shares its borders with the Republic of Tanzania to the north and northeast and is bounded by the Republic of Mozambique to the southeast, south and southwest. The western frontier is shared with the Republic of Zambia. Compared to other African countries, Malawi enjoys favourable biophysical characteristics such as its geomorphology, soils, climate, water resources and drainage. Stretching longitudinally from 852 km, with a breadth of no more than 160 km, the country has a wider resource base than other African countries of its size.

This resource base is adequate to support its population under conditions of sustainable resource use and management. The diverse natural resources found in the country are a rare wealth and are able to support agriculture for food production, water resources and sanitation programmes for a healthy society, tourism and industry for economic growth and social emancipation, energy and other services required for social and economic development.

1.4.4.1 Climate

The climate of Malawi is influenced by the country's geographical position. Lying northward of the sub-tropical high-pressure belt, the country is affected by south-easterly winds for about six months of the year. The dominant wind system influencing the country's climate is the position of the Inter-tropical Convergence Zone (ITCZ), which oscillates north and south bringing with it the changes in seasons as it moves. Thus, when there is strengthening of the south easterlies towards the ITCZ, which normally lies over the central region of the country, increases in cloud cover occur resulting in rainfall. Local topography also determines climatic conditions. Due to Malawi's topography and the range in altitude between locations, climatic conditions may be complex. Variations between wet and dry places and between hot and cold areas are therefore not uncommon due to this characteristic.

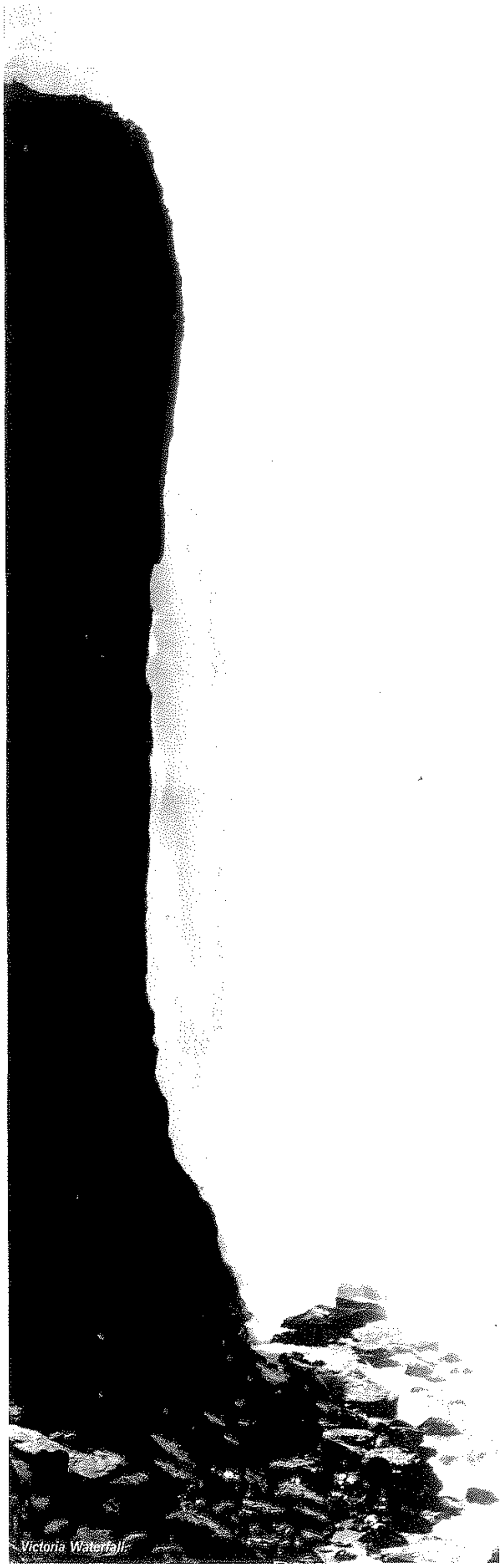
Malawi is endowed with huge water resources in the form of Lake Malawi/Nyasa/Niassa, Lake Chilwa, Lake Malombe and other smaller lakes, and many rivers and streams. The prevalence of moderate to high annual rainfall makes Malawi one of the few SADC countries that boasts adequate water resources for social and economic development, even though there are internal disparities in access. The country's average annual renewable water resource of 17,54 km^3 is higher than that of other countries bigger than its geographical size in the region, such as Botswana (2,90 km^3), Namibia (6,20 km^3) and Zimbabwe (14,10 km^3) [11].

Surface and groundwater satisfy domestic and industrial water requirements. The Lake Malawi/Nyasa/Niassa catchment is, by and large, asymmetrical due to the fact that the eastern side of the catchment has been downthrown by faulting. The western part consists of a series of blocks stepping eastward parallel to the main fault. As a result, the major rivers found within the basin both in the east and west of the lake flow towards it.

1.4.4.2 Hydro-power stations under baseline conditions in Malawi

The supply of electricity in Malawi is entirely under the control of the national electricity supply authority, Electricity Supply Commission of Malawi (ESCOM). ESCOM controls generation, transmission and distribution of electricity in Malawi. ESCOM is a statutory body established by government. Only 4% of Malawi's population has access to electricity, which is lower than all other SADC member countries.

The great bulk of ESCOM's operations consist of an interconnected network extending from the southernmost tip of the country to a distance of about 100 km from the most northern point, the country being about 900 km long and less than 200 km wide. The remaining portion is covered by two isolated diesel generating stations in the north of the country. The commission is actively expanding the network and has ambitious plans to increase generation.


Victoria Waterfall

2. METHODOLOGY

Assessment of the Zambezi River Basin's existing and projected hydro-power potential variations against climate change/variability required a definition of the Zambezi River Basin, modelling and network formulation based on the water balance model, assessment of water demand under baseline and projected conditions, use of Global Circulation Models (GCM) for precipitation projections, and water balance models to determine run-off. These processes were followed by assessment of the effects of run-off on storage capacity and hydro-electric power potential.

2.1 DEFINITION OF ZAMBEZI RIVER BASIN

The Zambezi Basin is located between 8° to 20° south latitude, and 16,5° to 36° east longitude, draining an area of about 1 385 million km^2. It covers about 25% of the total area of its eight riparian states (Figure 2.1): Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe.

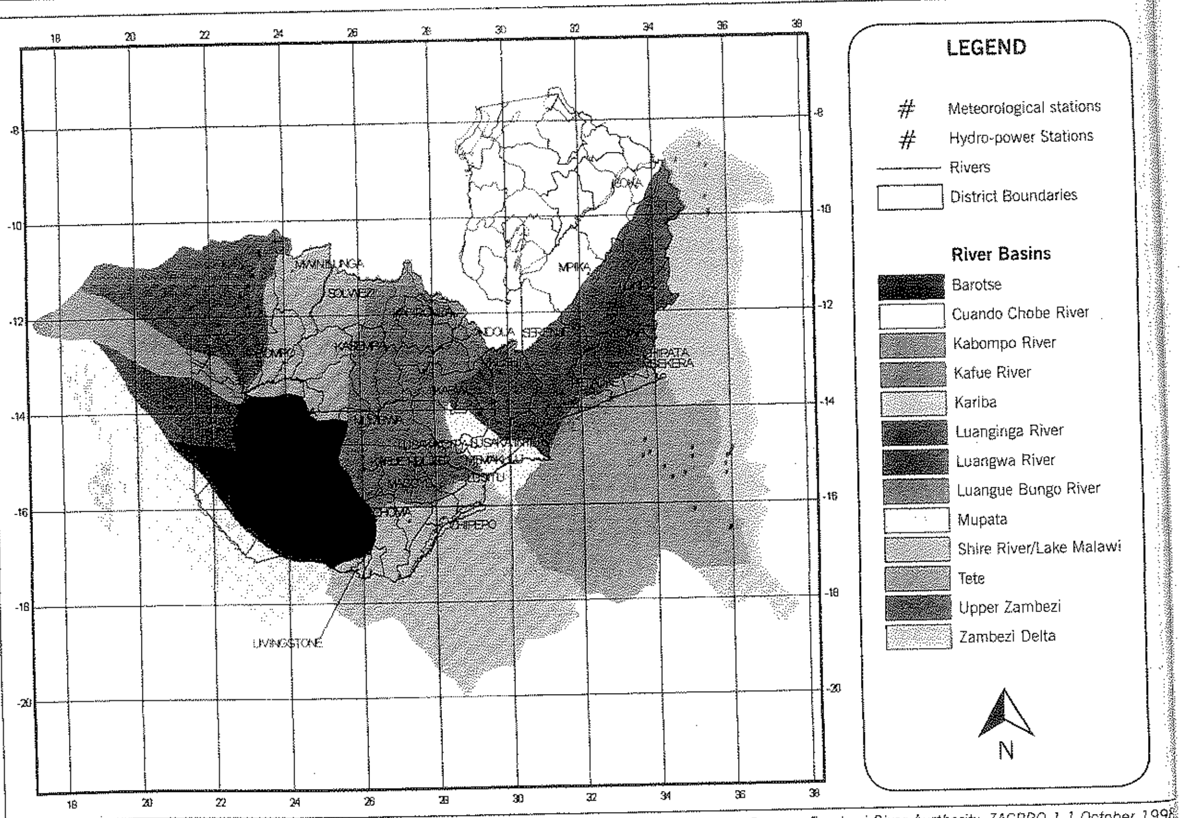
The Zambezi River rises on the central African plateau in the Kalene Hills in north western Zambia at 1 585 m above sea level flowing to the delta in Mozambique before flowing into the Indian Ocean. The river's major tributaries include the Luena and Lungue-Bungo in Angola, Chobe in Botswana, Shire in Malawi, Luiana in Namibia, Kabompo, Kafue and Luangwa in Zambia and Manyame, Sanyati and Gwayi in Zimbabwe.

The existing hydro-power facilities considered under the study included Kafue Gorge, Victoria Falls, Lake Kariba in Zambia and Cahora Bassa in Mozambique. Further proposed hydro-electric scheme sites were studied, and these included the Batoka and Mupata Gorges on the Zambia/Zimbabwe Zambezi river boundaries (Figure 2.2) and Mepanda Uncua in Mozambique. Other proposed sites included Kafue Lower in the Kafue tributary in Zambia.

2.2 MODELLING AND NETWORKING FORMULATION

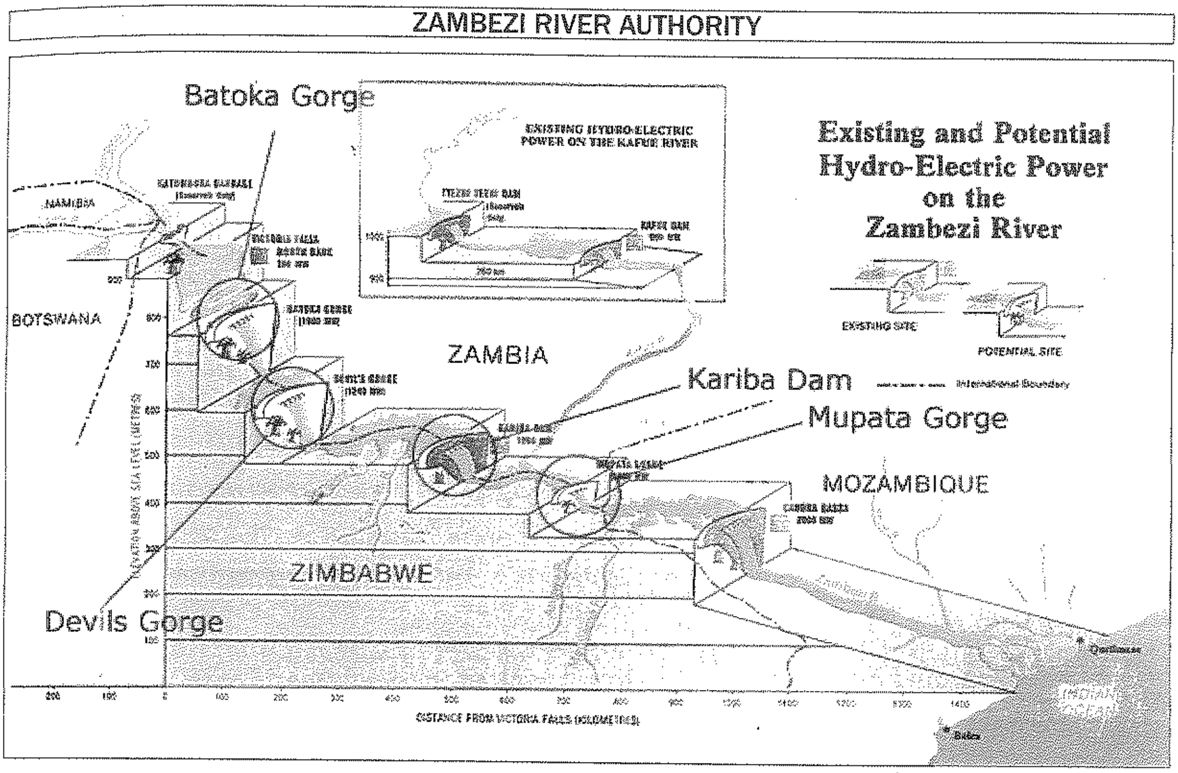
In order to model the Zambezi River Basin, various hydrological features and other features relevant to the study in the Zambezi River Basin were identified. These included main reservoirs, main tributaries, irrigated areas, surface water abstraction, etc. Modelling was done on baseline as well as projected scenarios. Baseline modelling was based on the baseline network depicting existing features while the projected scenario was modelled on the projected network depicting existing and proposed hydro-power schemes.

MAP SHOWING THE ZAMBEZI BAISIN AND ITS SUB-COMPONENTS



Source: Zambezi River Aurthority, ZACPRO 1.1 October 1998
Data manipulation and Desktop mapping by Allan D.Mulando

Figure 2.1: Zambezi River Basin – by sub-basin.



Source: Zambezi River Authority-Lusaka.

Figure 2.2: Schematic layout of the proposed and existing hydro-electric power schemes.

The modelling process involved:

(i) Identification and location of hydrological features (i.e. main reservoirs, main tributaries).
(ii) Determination of the sub-basins' boundaries and their respective catchment areas.
(iii) Identification and location of other relevant features to water balance modelling (i.e. irrigated areas, water abstraction for towns and industries).
(iv) Identification and location of gauging stations on tributaries of the Zambezi River Basin.

This was followed by drawing the network diagram containing the above mentioned features using Corel DRAW®. Figure 2.3 shows the baseline network diagram derived from the methodology described.

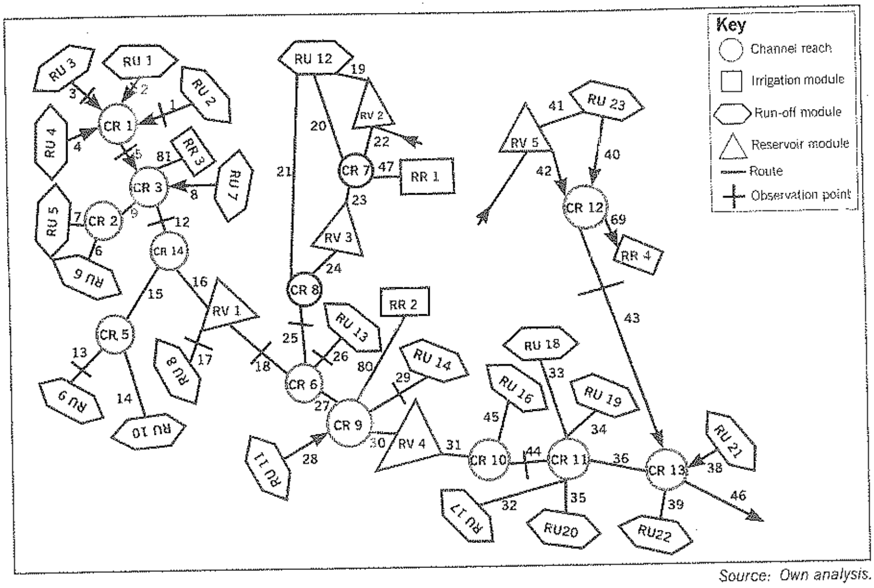
The features are drawn according to their location in the Zambezi River Basin. The network diagram therefore is the diagrammatic representation of the Zambezi River Basin. In the network diagram, a hexagon represents a run-off module, a circle represents channel reach module, a triangle represents a reservoir, a rectangle represents an irrigation module, and a straight line represents a route linking modules together. A crossed straight line represents a gauging station. In order to derive the network diagram, the following were needed:

(i) Topographic maps of the scale 1:750 000 to determine catchment boundaries.
(ii) A hydrological map of the Zambezi River Basin to determine locations of sub-basins and dam reservoirs and place them in the network model.
(iii) A software package called CorelDRAW® used to draw the network.
(iv) GIS maps showing gauging stations on rivers in the Zambezi River Basin.

2.3 NETWORK CONNECTIVITY DESCRIPTION

Drawing the network helps to determine which, and how many, sub-models will be needed to describe the physical system. The network also describes interconnections among modules and routes. Considering the baseline network shown in Figure 2.3, the starting point is at the run-off sub-model RU1 (i.e. Upper Zambezi). From the network, it can be observed that one route emerges from run-offs RU1, RU2 (Kabompo sub-basin), RU3 (Lwanginga sub-basin) and RU4 (Lungue Bungo). Routes 2, 1, 3 and 4 connect RU1, RU2, RU3 and RU4, respectively, to CR1. Each of these routes acts as an inflow route into CR1 and all of them culminate into this channel reach. This implies that all the water from run-offs 1-4 flows into CR1. Route 5 provides an outflow to CR1 and stretches from this channel reach to another channel reach, CR3.

Route 7 is linked with RU5 (Cuando Chobe sub-basin) while route 6 links with RU6 (Luiana sub-basin) and both routes flow into CR2. Route 9 emerges from CR2 and terminates in a downstream module called CR3. CR3 is a recipient of water flow from upstream modules through inflow routes 9, 8 and 5. Water from RU7 (Barotse sub-basin) flows into CR3 through route 8. Water flows further downstream



Source: Own analysis.

Figure 2.3: Baseline network diagram.

from CR3 to CR14 through outflow route 12. It must be noted that water flow through route 12 is a summation of flow through routes 9, 8 and 5 after losses in CR3 due to evapo-transpiration, abstraction, etc. (see Figure 2.3).

Gwayi run-off (RU9) and Shangani run-off (RU10) flow into CR5 through routes 13 and 14 respectively. Channel 5 connects to CR14 via route 15. Run-off from Sanyati sub-basin (RU8) pours straight into Lake Kariba through route 17. Thus routes 12 and 15 provide a means of flow into CR14. There is one route (16) emerging out of CR14 and terminating into Lake Kariba (RV1). In essence, all the 15 tributaries upstream of Lake Kariba have their waters flowing into the lake and these tributaries include, Kabompo, Upper Zambezi, Luia, Lungue Bungo, Cuando Chobe, Luiana, Gwayi and Shangani. Sanyati River is also considered among tributaries whose waters pour into Lake Kariba.

Water from reservoir (RV1) flows via route 18 to CR6. Route 18 transports the turbine discharge from Lake Kariba Dam reservoir as well as the occasional spillway flow to a confluence of Zambezi River main and the Kafue River. CR6 is the conjunction of water flow from Lake Kariba and Kafue River with routes 18 and 25 providing inflow to the channel respectively. The Kafue sub-network constitutes run-off 12 (RU12), Itezhi-Tezhi reservoir (RV2), Kafue Gorge reservoir (RV3), irrigation sub-model (RR1), CR8 and CR7. Three routes emerge from run-off 12(RU12) and these are 19, 20 and 21. Route 20 connects RU12 to CR7 while route 19 links RU12 with RV2. Route 21 emerges from RU12 and terminates into CR8. Some water from CR8 is abstracted through route 47 into an irrigation module RR1. RR1 is a representation of all the irrigated areas in the entire Kafue sub-basin. Route 47 provides a means of passage for all the water demanded for irrigation purposes in the irrigated area of the sub-basin.

Water from CR8 flows via route 25 and joins CR6. Run-off from Chongwe sub-basin also pours into CR6 through route 26. Route 27 connects CR6 with CR9. There are three inflow routes that flow into CR9 and these include routes 27, 28 and 29. Run-offs 15 (Manyame) and 13 (Luangwa) empty their waters into CR9. A connection between CR6 and CR9 is facilitated by a sole link called route 27. At this stage, the run-off has increased greatly owing to the contribution of run-offs from all the upstream tributaries. Route 30 emerges from CR9 and plunges into Cahora Bassa Lake (RV4) after which the lake is emptied through turbine discharge and occasional spillway flow. The turbine discharge flows via route 31 into CR10. Route 45 stretches from Luia run-off 16 (RU16) and joins CR10. It can be observed at this point that there are two routes whose arrows are pointing into CR10 and one arrow away. Route (44), whose arrow points away, is an outflow route for CR10.

CR11 has inflow routes from route 44, Revuboe run-off (RU18), Mażowe run-off (RU17), Lwenha run-off (RU20) and Zambezi (RU19). CR module 13 is the module that occupies the last position in the network and it has four inflow routes. It is in this channel that the run-off from the Shire River of Malawi joins the Zambezi River main on the network model. Shire run-off is represented by RU23 on the network model. Route 41 stretches from run-off 23 (RU23) into RV5 (Lake Malawi). This indicates that some water from run-off sub-model 23 goes into CR12 and some to reservoir RV5. Some of the water from reservoir 5 flows via route 42 to CR12. This is the spillage from reservoir module six. Route 69 carries water from CR12 to irrigated areas (designated RR4). Some water from RU23 flows via route 40 into CR module 12. Route 43 connects CR12 to CR13 where its waters flow into Zambezi River main. Route 38 emerges from run-off 21 (Gwacua) and terminates into CR13. The run-off Zangue (RU22) flows into CR13.

The network terminates in the Indian Ocean, which is a zero sink module. All the flow from all sub-basin flows culminates into route 46 and flows into the Indian Ocean. It should be noted that the transverse strips, such as the one seen in route one, represent a gauging station weir. A gauging station or observation point provides a means of measuring the amount of water that passes through a certain point per second.

These points lie on several points in the network. There are 13 points with credible data that were used in this research. There are other gauging stations which have not been shown in the network because the data is not consistent and there were some data gaps.

The following are the names of gauging stations that were included in the network:

(i) Kasaka on Kafue river
(ii) Kalabo on the Luanginga River
(iii) Watopa on the Kabompo River
(iv) Chavuma on the Upper Zambezi sub-basin
(v) Zambezi River main at Senanga
(vi) Big Tree Station near Victoria Falls
(vii) Gwayi
(viii) Sanyati
(ix) Chirundu just after Lake Kariba
(x) Luangwa at Great East Road Bridge
(xi) Manyame
(xii) Shire River at Liwonde
(xiii) Chongwe
(xiv) Tete on the Zambezi sub-basin.

The network in Figure 2.4 shows the projected network diagram that was used to model the projected water balance. Its description is similar to that for the baseline case but it has additional reservoirs (Batoka, Devils Gorge, Kafue Lower, Itezhi-Tezhi, Mupata and Mepanda Uncua), which represent proposed hydropower schemes.

The projected network consists of 22 run-off modules and 13 channel modules as in the baseline situation. However, under the projected network diagram there were nine major existing and proposed dam reservoirs, and 53 routes. The interconnectivity of the above mentioned modules and routes makes up the system diagram on which premise modelling, calibration and simulation of the Zambezi River Basin were undertaken.

2.4 USE OF GCM MODELS

A GCM is a global, three-dimensional computer model of the climate system that can be used to simulate human-induced climate change. GCMs are highly complex and they represent the effects of such factors as reflective and absorptive properties of atmospheric water vapour, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures and ice boundaries. The most recent GCMs include global representations of the atmosphere, oceans, and land surface. The data generated is stored in huge databases like those of the data distribution centre (DDC). The IPCC DDC provides climate data simulated by GCMs. The Environmental and Geographical Studies (EGS) department of the University of Cape Town is maintaining a database of the monthly mean climate data generated by the following GCMs.

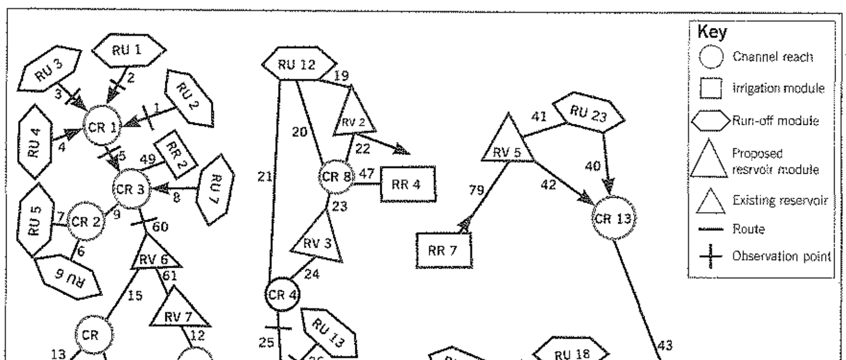
To determine precipitation projections, three GCMs were used: CCCMA run by the Canadian Centre for Climate Modelling and Analysis; CSIRO run by the Commonwealth Scientific Industrial Research Organisation based in Australia, and HADCM3 (Hadley Climate Model) run by the Hadley Centre in UK.

The Greenhouse gas emissions scenario used was based on SRES A2. The A2 storyline assumes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a heterogeneous world with less rapid and more diverse technology, but with strong emphasis on community initiative and social innovation to find local, rather than global solutions [12].

Projected rainfall data involved creating a 30 year monthly precipitation time series for periods 2010 to 2040 and 2040 to 2070 for every sub-basin. The precipitation data for each sub-basin was extracted by obtaining baseline time series (O) of monthly total precipitation for each sub-basin in the period 1970 to 2000 from Meteorological Departments in the region (Malawi, Mozambique, Zambia and Zimbabwe).

This was followed by extracting HADCM3, CCCMA, CSIRO precipitation data for the control period 1970 – 2000 (C) and results between the former and the latter compared closely. Based on this correlation, future period (F1) 2010 – 2040 and (F2) 2040 to 2070 for a grid box of size according to the sub-basin was done. The respective extracted gridded data for control (C) and future (F) from HADCM3, CCCMA, CSIRO were averaged to obtain the overall control (C) and future (F).

The overall (averaged) control (C) and future (F) data were then used to determine the future monthly precipitation using Equation 2.1.



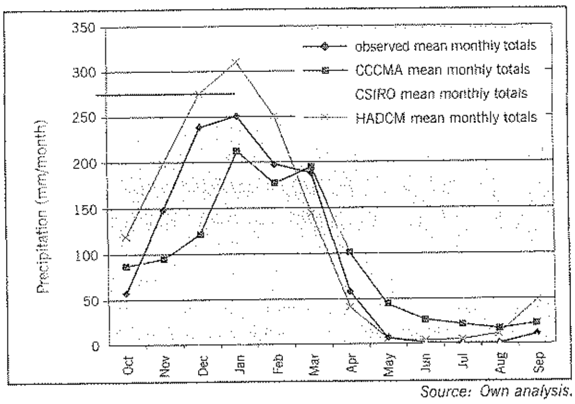
Source: Own analysis.

Figure 2.4: Projected network diagram (i.e. including proposed reservoirs).

$$P_P = O + \left(\frac{F - C}{C}\right) \tag{2.1}$$

P_P = *Projected precipitation (monthly)*
O = *Baseline (observed) time series*
F = *Future gridded data*
C = *Control*

From the GCMs' grid data projections, future monthly rainfalls were generated for the period 2010 – 2070 together with their anomalies. Of the three GCMs considered, some generated monthly means that were higher than the observed monthly means while others produced monthly means that were below the observed monthly means. Figure 2.5, representing one of the sub-basins, shows a comparison of observed and model monthly means for the period 1970 – 2000 for the three GCM models that were considered.



Source: Own analysis.

Figure 2.5: Observed and model monthly means for the period 1970 – 2000, for Kabompo.

Because of these differences, confidence could not be based on a single GCM. The average of the monthly mean precipitation for CCCMA, CSIRO and HADCM3 for the control period was found to generally characterise the observed monthly mean precipitation as shown in Figure 2.6. This was done for all the sub-basins of the Zambezi River Basin and fed into the water balance model.

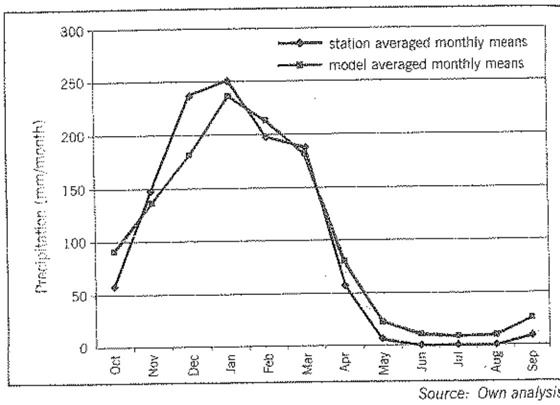
2.5 USE OF WATER BALANCE MODELS

2.5.1 *GENERAL WATER BALANCE MODEL DESCRIPTION*

Water balance modelling depends on hydro-meteorological data and surface water run-off conditions in catchment areas. The river catchments considered in this study have a reliable coverage of rainfall, temperature and pan evaporation (PE) measurements. In its simplest form, a water balance model of a drainage basin can be described by Equation 2.2 [13].

$$P = Q + E \pm S \pm G \tag{2.2}$$

P = *Precipitation or rainfall*
S = *Surface and sub-surface run-off*
Q = *Change in soil moisture*
G = *Change in groundwater*
E = *Evapo-transpiration*



Source: Own analysis.

Figure 2.6: Station and model averaged monthly means for 1970 – 2000, for Kabompo.

The aim is to determine Q after accounting for evapotranspiration losses, soil moisture and groundwater flows. The mean monthly rainfall, temperature and run-off considered over the entire period of observed records are assumed to represent the baseline scenario of the period 1970 to 2000. Various models can be used to simulate observed run-off from the average monthly rainfall and pan evaporation figures of the catchment.

The simulated run-offs are derived from historical monthly rainfall and mean monthly pan evaporation and then compared to measured run-off records for the same period. This is the model calibration process, which assesses agreement between measured and modelled results and also allows derivation of soil moisture and groundwater parameters/coefficients for the catchment.

2.5.2 *WATER RESOURCE SIMULATION MODEL*

In this study, the water balance model used was Pitman's model, known as Water Resource Simulation Model (WRSM) [13], which is software used to simulate hydrological systems. Two versions of the software were employed in this research: the Water Resource Simulation Model 90 (WRSM 90), DOS version and the Water Resource Simulation Model 2000, Windows version. The Windows version allows the user to create and edit the network and modules within the program as opposed to the DOS version where the files had to be created externally. The DOS files, however, are still compatible with the Windows version.

WRSM 2000 is of modular construction, with four different modules linked by means of routes. The routes represent lines along which water flows, such as river reaches. Most hydrological systems can be represented by means of the four types of modules, linked using routes. Each module is connected to the other modules by means of routes. Routes can be visualised as loss free river reaches, canals or pipelines connecting the various modules, to form a coherent network. A route is always bounded by two modules, namely, a source module and a sink module. Flow along the route will be from the source to the sink. The terms modules or sub-models have the same meaning. As stated earlier, WRSM 2000 is totally modular. This means that a number of modules can be linked together in any feasible way to form a network. The functioning of the modules or sub-models is described below [13].

The run-off module is the heart of WRSM 2000. The following features are taken into account: pan factors are read in as data, i.e. they are not built into the program. This enables the user to adopt pan-factor figures, provided suitable 'crop factors' are available for natural vegetation.

The growth of afforestation and impervious areas is represented by reading in values for up to ten different years. The module also has the facility to send fixed portions of the total run-off along various routes. This feature enables one to economise on run-off modules in relatively homogenous areas [13].

The main function of the channel module is to collect the inflows to it from various routes and to redistribute these flows along the outflow routes. Inflows can be in the form of predefined flows or calculated outflows from any of the four types of module. Channel modules can therefore be sink modules for routes from other channel modules. Outflows can also be predefined flows but are more often calculated demands from adjacent irrigation modules.

The principal outflow route represents the main river channel and surplus flow is passed along this route after all demands are satisfied. Channel modules also make provisions for bed losses and evaporative losses from a wetland area. If there is a wetland to be simulated, the module requires as input a set of twelve monthly pan factors. A rain file and Mean Annual Precipitation (MAP) must also be specified so that the net evaporative loss can be computed [13].

The reservoir module can be used to represent a single reservoir or an equivalent dam made up of any number of small dams. Allowance is made for the single dam to be constructed (and raised) in any year during the simulation period and for the number of small dams to change over time by inputting values of storage and surface area for up to ten different years. Evaporation is calculated in a similar way to that for wetlands and one has complete flexibility in the choice of pan type and associated pan factors. The reservoir module collects inflows and distributes outflows in a manner similar to that described for the channel module. The one essential difference is the effect of storage, which means that the reservoir must be filled before outflow can take place along the principal outflow (i.e. spillage route) [13].

In the case of the irrigation module, the following features are taken into account:

(a) Changes of irrigation area over time can be represented by inputting values for up to 10 years.
(b) Choice of pan type and pan factor left to user.
(c) The MAP of the irrigation area and its rainfall pattern need not be the same as catchment (run-off module) in which it lies geographically.
(d) A limit (in mm) can be placed on the abstraction in any one year and effective rainfall factors can be read in for each month [13].

Gauging stations are associated with routes and contain data about historically observed flows. Gauging stations are used to compare the simulated flows with observed flows in a route, so that the calibration of the network can be achieved. It is important to distinguish a gauging station on a route from defined flow in a route. Gauging stations are used for comparison only whereas defined flows push or pull the flows in the model. The main function of a network is to specify the order in which the modules must be solved. In addition, the network is used to set the time period for simulation, to indicate the DATA-Result folders to be used, and to specify the routes and reservoirs that are to be reported in the summary file. The summary file is an easy-to-check file in which flows in the specified routes or storage in the specified reservoirs are stored on a monthly basis during a simulation run [13].

A rain file is a file that contains a monthly rainfall time series expressed as percentages of MAP for a sub-basin or a catchment area. Rain files should not be confused with rain gauge files. A rain file usually combines the data of multiple rain gauges into a single time series and, in addition, the values are expressed as a percentage of the MAP for the area or catchment. Operation of WRSM 2000 is facilitated by a Windows Style Main Menu that gives a number of options to the user, including running the simulation, viewing statistics, plotting graphs, changing model parameters and writing results to output devices. The model stores all information internally, so that any number of runs can be undertaken without terminating the program. This facility, in conjunction with the ability to look at several gauging points in a network, speeds up the calibration process considerably [13].

2.5.3 OPERATION OF WRSM

The main data requirements for a water balance model include rainfall, river flows, reservoirs capacities, and proposed hydro-power installations. In addition, for the water balance model to run, it requires input data from the network diagram and water demand described in Sections 2.3 and 2.6, respectively.

The detailed data requirements for the run-off sub-model include:

(i) Catchment area of sub-basins (km^2).
(ii) Maps showing locations of meteorological stations in the Zambezi River Basin so as to group meteorological stations according to sub-basins, which in turn helps to determine the monthly average precipitation over a sub-basin.
(iii) Mean annual precipitation (mm).
(iv) Monthly pan evaporation.
(v) Rain file for each sub-basin.

In this study, monthly rainfall for a period of 30 years (1970 – 2000) was considered for each of the 22 sub-basins of the Zambezi River Basin.

The main reservoirs considered in the Zambezi River Basin are Lake Kariba, Lake Malawi, Itezhi-Tezhi, Kafue Gorge and Cahora Bassa. Preliminary data was also collected on reservoirs on proposed hydro-power schemes. The following is the data required for the purpose of modelling the reservoir modules:

(i) Mean annual precipitation (mm).
(ii) Rain file.
(iii) Reservoir lake levels (m) for a period of 30 years (1970 – 2000).
(iv) Reservoir volumes (Mm^3) (1970 – 2000) derived from the reservoir level-reservoir volume charts, reservoir surface areas (km^2) derived from the reservoir level-reservoir surface area charts, pan evaporation, full supply volume (Mm^3), and full supply surface area (km^2) [14].

Most of the tributaries that make up the Zambezi River Basin are measured in terms of river flows. For the purpose of this study, historical data of monthly mean time series of river flows were collected for gauged tributaries of the Zambezi River for the period 1970 to 2000. Some tributaries are not gauged while others are gauged but with a number of data gaps. However, gauging stations of tributaries with consistent data of up to five years were considered in the network diagram and were used in the simulation process. On the other hand, the water balance model estimated monthly run-offs for tributaries with no historical data on river flows. Tributaries of the Zambezi River are measured at various points and the names of the points considered in the study include: Kasaka on Kafue River, Kalabo on Luanginga River, Watopa on Kabompo River, Chavuma on Upper Zambezi sub-basin, Zambezi River main at Senanga, Big Tree Station near Victoria Falls, Gwayi, Sanyati, Chirundu just after Lake Kariba, Luangwa at Great East Road Bridge, Manyame, Shire River at Liwonde, Chongwe and Tete on the Zambezi sub-basin.

2.5.4 *CREATION OF NETWORK FILE AND CALIBRATION*

2.5.4.1 *Creation of network file in the WRSM*

Based on the network diagram of the Zambezi River Basin, a NETWORK FILE is created in the WRSM software package. A network file acts like a backbone on which all the .dat files are hooked. The .dat files represent modules such as run-off, irrigation, reservoirs, etc. Historical data such as rainfall, river flows, etc are in turn hooked on to the .dat files. Data formatting involves converting rainfall into rain files in the MS-DOS environment and formatting historical river flows into the required input format in a MS-DOS environment. The rest of the data is inserted accordingly in the network. Thus, data input involved inserting formatted rainfiles, mean monthly river flows, pan evaporation, etc into .dat files. All the raw and formatted data on the Zambezi River can be accessed from the Zambezi Database [13]

2.5.4.2 *Calibration and simulation*

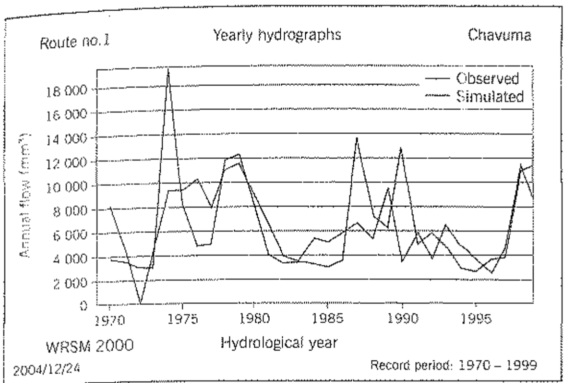
Calibration is a process in which calibration parameters are adjusted to create a balance between measured (observed) and simulated run-off in the water balance model of the Zambezi River Basin. Once the WRSM is calibrated, it can be used for estimating future run-offs of sub-basins in the projected scenario and estimating run-offs of ungauged tributaries in the baseline.

Calibration is achieved by comparing simulated mean annual run-off (MAR) with measured mean annual run-off. If there is a difference between the two values, calibration parameters are adjusted until a satisfactory equivalence is realised. The process involves inputting calibration parameters initially and running the software. If the simulated MAR does not match the observed MAR, one or more parameters are adjusted and the software is run again. This cyclic process is repeated until simulated MAR is almost equal to that of the observed values.

The list of parameters used for calibration in the WRSM includes:

POW – Power of soil moisture/subsurface flow equation.
SL – Soil moisture state when subsurface flow = 0.
ST – Soil moisture capacity in mm.
FT – Subsurface flow at soil moisture capacity.
GW – Maximum groundwater flow in mm/month.
Z_{MIN} – Minimum catchment absorption in mm/month.
Z_{MAX} – Maximum catchment absorption in mm/month.
PI – Interception storage (mm).
TL – Lag of flow (excluding groundwater).
GL – Lag of groundwater flow (in months).
R – Coefficient in evaporation/soil moisture equation.

The closeness of observed MAR to simulated MAR alone does not give an indication of accuracy of the simulation in the broader perspective of a 30 year period. There are other indicators that show the degree of accuracy and assist in deriving a simulation that is as close to the observed data as possible and these are: mean annual run-off (MAR), standard deviation of annual flows (S), coefficient of variability (S/Mar), coefficient of skewness, autocorrelation coefficient of annual flows, mean of logs of annual flows, standard deviation of logs of annual flows, seasonal index and variability. In the network, there are observation points that are provided and they represent gauging stations on a river. These points show the measured monthly flow of a river at a particular point in the river networks of the basin for a period of time (1970 to 2000). Figure 2.7 shows an example of a WRSM result of simulated and observed yearly hydrograph



Source: Own analysis.

Figure 2.7: Hydrograph of yearly run-off from upper Zambezi sub-basin.

for the upper Zambezi sub-basin and gives a clearer but generalised picture of the flow regime on the river.

Over the baseline period of 30 years, the upper Zambezi sub-basin produced an annual mean run-off of about 6 407 Mm^3 from its 106 950 km^2 catchment. Figure 2.7 shows WRSM generated plots for simulated and observed annual run-offs.

A period from the year 1970 to 1973 experienced a low run-off of less than 4 000 Mm^3. The scenario changed however from 1972 to 1979, where a considerable increase in run-off was experienced. The highest run-off value was 12 000 Mm^3.

Table 2.1: Flow statistics for network gauging stations.

Gauging station	Observed mean annual run-off (Mm^3)	Simulated mean annual run-off (Mm^3)
Upper Zambezi River at Chavuma	16 703,8	16 743,4
Kabompo at Watopa station	6 601	6 601,6
Lwanginga-Kalabo station	1 776,6	1 7625
Senanga on Zambezi main	27 016,9	27 314,7
Big Tree gauging station	31 691	33 095,9
Gwayii	673,4	692,7
Sanyati	1 749,9	1 765,7
Zambezi main at Chirundu	41 943,5	38 250,7
Kafue at Kasaka	37 116	37 017,6
Chongwe	159,04	159,9
Manyame	1 038,7	1 054,8
Luangwa at GER bridge	23 437,5	23 221
Shire at Liwonde	13 701,3	13 745,7
❶Tete gauging station	67 922,6	95 288,08

Source: Own analysis.

❶ *The measured flows at Tete on Zambezi River main are suspected of being erroneous.*

Table 2.1 indicates some selected flow statistics from the routes with gauging stations. It compares observed and simulated mean annual run-offs on each of the routes with gauging stations. There were 14 observation points on 14 different routes in the network.

The network simulation was run once again and all the necessary output simulations were noted, and regarded as the baseline situation. With this relatively close correlation, the water balance model adopted in this study was to generate run-off under projected scenarios.

2.6 WATER DEMAND EFFECTS

2.6.1 GENERAL CHARACTERISTICS

Water demand effects (water use or water demand) have an effect on run-off and therefore should be considered as part of the ultimate run-off determination. The terms 'water use' and 'water demand' are often used interchangeably. However, they have different meanings. In the context of the study, **water use** can be distinguished into three different types.

The first is withdrawals or abstractions where water is taken from a surface or groundwater source and, after use, returned to a natural water body, e.g. water used for cooling in industrial processes that is returned to a river. Such return flows are particularly important for downstream users in the case of water taken from rivers.

Second, consumptive water use or water consumption that starts with a withdrawal or an abstraction but in this case without any return flow. Water consumption is the water abstracted that is no longer available for use because it has evaporated, transpired, been incorporated into products and crops, consumed by man or livestock or otherwise removed from freshwater resources. Water losses during the transport of water between the points of abstraction and the point of use (e.g. resulting from leakage from distribution pipes), are excluded from the consumptive water use figure. Examples of consumptive water use include steam escaping into the atmosphere and water contained in final products i.e. it is water that is no longer available directly for subsequent use.

Third, non-consumptive water use including water bodies for navigation, instream flow requirements for fish, recreation, effluent disposal and hydro-electric power generation [15].

Water demand is defined as the volume of water requested by users to satisfy their needs. In a simplified way, it is often considered equal to water consumption, although conceptually the two terms do not have the same meaning. This is because in some cases, especially in rural parts of southern Africa, the theoretical water demand considerably exceeds the actual consumptive water use [15].

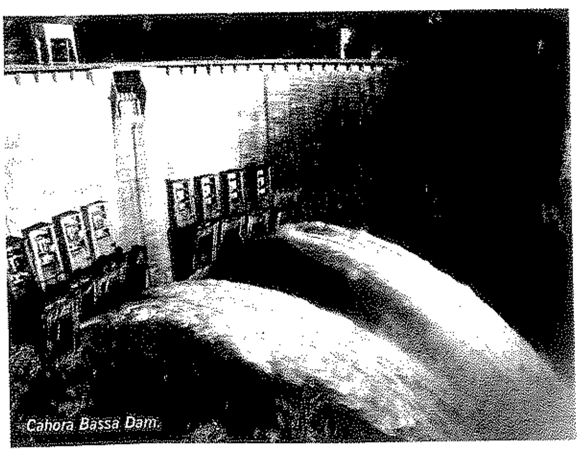
An important purpose of water management is to match or balance the demand for water with its availability through suitable water allocation arrangements. At a basin and sub-basin level, there are a large number of often conflicting water uses including: irrigation, domestic use in urban centres, domestic use in rural areas, livestock, industrial use, commercial use, the environment (e.g. in-stream flow requirements for aquatic life and wildlife), institutions (e.g. schools, hospitals), hydro-power, cooling (e.g. for thermal power generation), waste and wastewater disposal, fisheries, recreation and navigation.

Water Demand Models that predict future water demand and use are increasingly important in sub-catchment and catchment management. It is generally easier to forecast water demand and use for the short term than for the long-term. For short-term forecasts, it is possible to make assumptions that some factors will not have changed significantly from the present. However, for long term forecasts, there is a greater degree of uncertainty as to how water demand and use will change. It is important that uncertainties resulting from a lack of information are explicitly reflected in the demand forecasts. At a catchment level demand, forecasting should be carried out for each of the major demand sectors including environment, urban and rural domestic, industry and agriculture. There is no absolute level of accuracy that is appropriate in all demand forecasting circumstances. As a consequence, the level of accuracy of the forecast should be sensitive to its purpose. There are many influences that affect water demand and water use. Some of the most commonly cited factors relate to population, level of service, tariff levels, demand management measures and increased efficiency in water use and climatic conditions [15].

2.6.2 *WATER DEMAND FORECASTING METHODS*

A number of forecasting methods are commonly used to predict future water demand and use. These include; judgmental forecasts, extrapolation of historical data, forecasts based on population growth and *per capita* consumption, trend analysis, component analysis, multiple linear regression analysis and multiple non-linear regression analysis [15].

In this study, water demand forecasting was based on baseline water demand and growth rate. In the SADC region, water demand is projected to rise by at least 3% annually until the year 2020, a rate about equal to the region's population growth rate [16]. Water demand for the year 2000 was used as a premise on which forecasting or future discounting was done at a 3% annual growth rate. The projected water demand in the sub-basins of the Zambezi River Basin was done according to sectors (i.e irrigation and industrial/domestic water use). Projected water use for irrigation and industrial/domestic were separate. These projections were undertaken on the premise of the 3% annual growth in water use in the SADC region estimated by UNEP.



Cahora Bassa Dam.

2.7 EFFECTS OF INSTALLATION OF PROPOSED POWER STATIONS ON RUN-OFF

The effects of the installation of proposed new power stations on run-off are determined using the water balance model equation described in section 2.5.

$$P = Q + E \pm S \pm G \qquad (2.3)$$

P = *Precipitation or rainfall*
Q = *Surface and sub-surface run-off*
E = *Evapo-transpiration*
S = *Change in soil moisture*
G = *Change in groundwater*

The aim is to determine Q after accounting for evapo-transpiration losses, soil moisture and groundwater flows. Before installation of new power stations namely, Batoka, Devils, Mupata Gorge, and Mpanda Uncua, the river flow is largely being influenced by surface and sub-surface run-off, evapo-transpiration losses, change in soil moisture, precipitation and change in groundwater around the existing dams, Kariba and Cahora Bassa. However, when new installations are considered there are increased losses due to the same effects especially evapo-transpiration losses due to increase of surface areas of the new installed infrastructure. This in turn contributes to a reduction of run-off going into the existing power stations, in this case Kariba Dam and Cahora Bassa. The losses in run-off are determined by the same system flow equation used before the installation of new power stations.

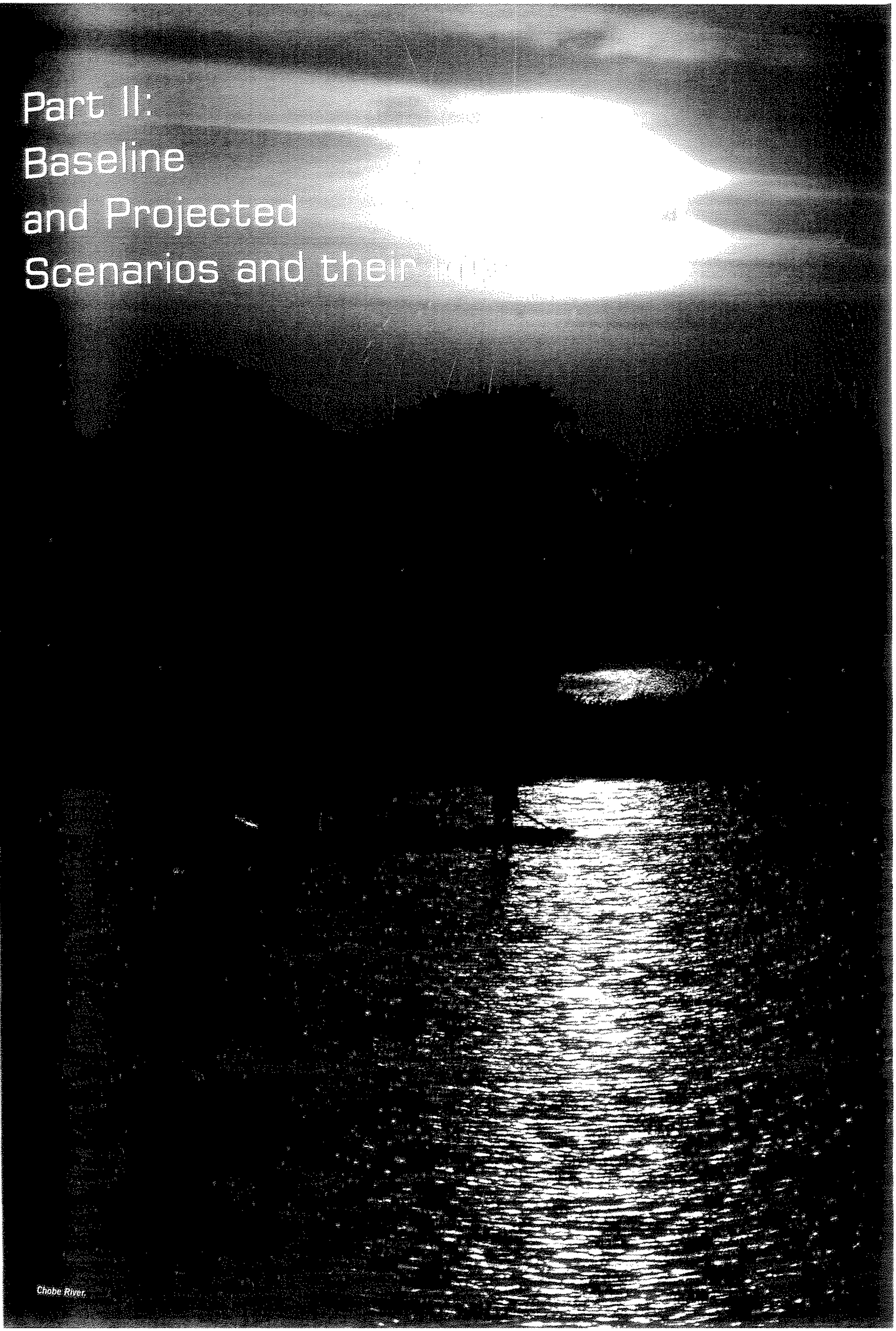
2.8 CALCULATION OF HYDRO-POWER POTENTIAL

Projected power potential was assumed as the gross hydro-power potential. It was estimated from knowledge of the effective heads of each of the dam reservoirs, annual run-off entering the reservoirs, density of the water and the gravitational force as given in the Equation 2.4

$$P_{Gross} = \frac{\rho_{water} \times g \times H_{gross} \times Q}{10^6} \qquad (2.4)$$

P_{Gross} = *Gross power (MW)*
ρ_{water} = *Density of water (kg/m³)*
g = *Acceleration due to gravity (m²/s)*
H_{Gross} = *Gross head (m)*
Q = *Annual run-off into the reservoir (m³/s)*

Part II: Baseline and Projected Scenarios and their



Chobe River.

3. BASELINE SCENARIO IMPACTS

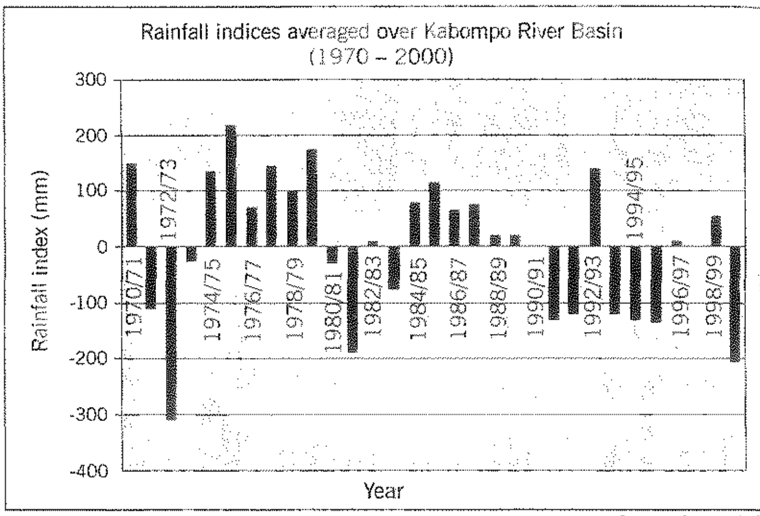
The baseline is defined as the period between the years 1970 and 2000 in which various historical data were collected and analysed using WRSMs and algorithms in Microsoft Excel. The purpose of this exercise was to assess the dynamics of the hydrological cycles in the Zambezi River Basin, for the period of 30 years, in relation to hydro-electric power generation. From this assessment, measurable effects of climate change/ variability through annual rainfall on run-off, reservoir storage capacity and hydro-electric power generation in the Zambezi River Basin were established.

In order to assess the effects of climate change/variability through annual rainfall over the baseline period, a correlation was undertaken with run-off, reservoir storage and hydro-power generation in both dry and wet years. Generally, the wet and dry years were common to all sub-basins in Zambia and to some extent similar to those in Zimbabwe, Malawi and Mozambique. Sometimes, years considered to be wet on a regional basis turned out to have low rainfall locally in some sub-basins. The identified wet years regionally were 1977/78, 1980/81 and 1997/98, while the dry years were 1972/73, 1981/82, 1983/84, 1991/92, 1994/95 and 1997/98 [4].

3.1 SEASONAL CHANGES OVER 30 YEAR BASELINE PERIOD

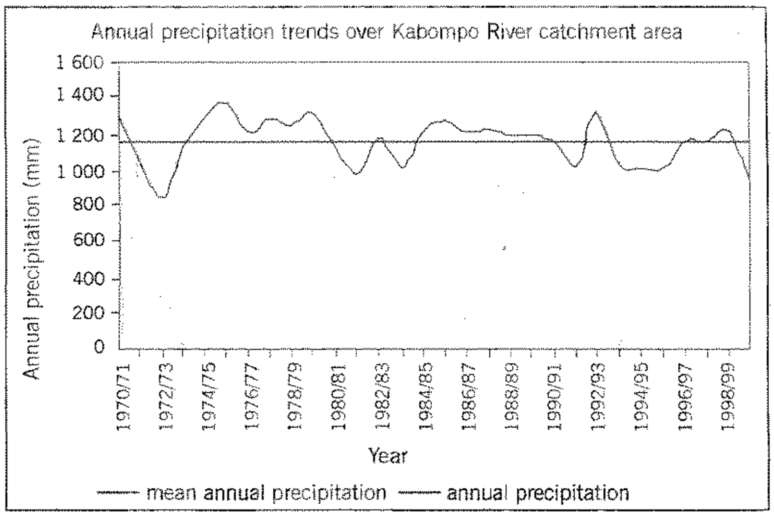
Figures 3.1 to 3.4 present statistically calculated rainfall indices which depict seasonal changes over the baseline period of 30 years (1970 – 2000), focusing on selected sub-basins Kabompo, Lwanginga and Luangwa as part of the Zambezi River Basin.

The zero in the rainfall indices graphs signifies the average rainfall for the sub-basin over the baseline period of 30 years. The bars above the zero line indicate annual rainfall above the 30 year mean while



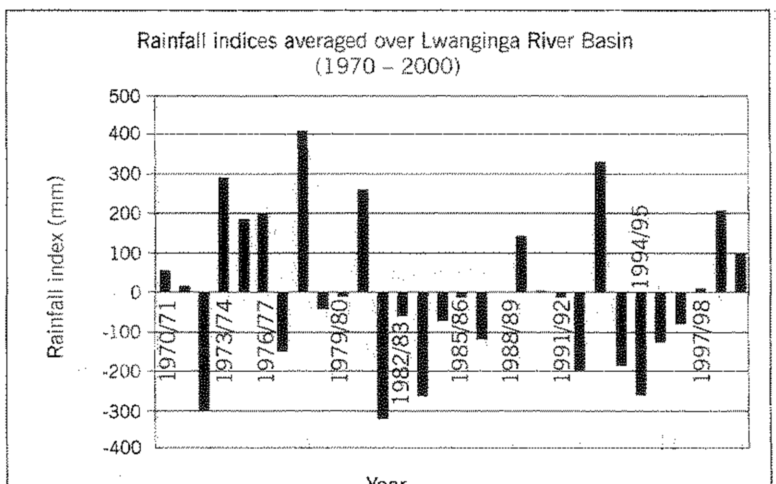
Source: Own analysis.

Figure 3.1: Precipitation anomalies (Kabompo).



Source: Own analysis.

Figure 3.2: Precipitation trends (Kabompo).



Source: Own analysis.

Figure 3.3: Precipitation trends (Lwanginga).

those below the zero line signify rainfall below the annual mean. From Figure 3.1, the following can be deduced for Kabompo:

(i) The zero on the rainfall index axis depicts the mean rainfall in 30 years (1 151 mm).
(ii) In the first decade (1970 – 1980), seven years are above the mean and three years below.
(iii) In the second decade (1980–1990), six years are above the mean and four below.
(iv) The third decade (1990 – 2000) exhibits 50% above the mean with 50% below.

Figure 3.5 shows the mean annual rainfall averaged over 30 years for all sub-basins of Zambezi River Basin. High and low rainfall sub-basins are clearly identifiable from Figure 3.5. Mean annual rainfall is generally higher on the northern part of the Zambezi Basin, with a mean annual rainfall over 30 years of 1 151 mm.

3.2 RUN-OFF EFFECTS

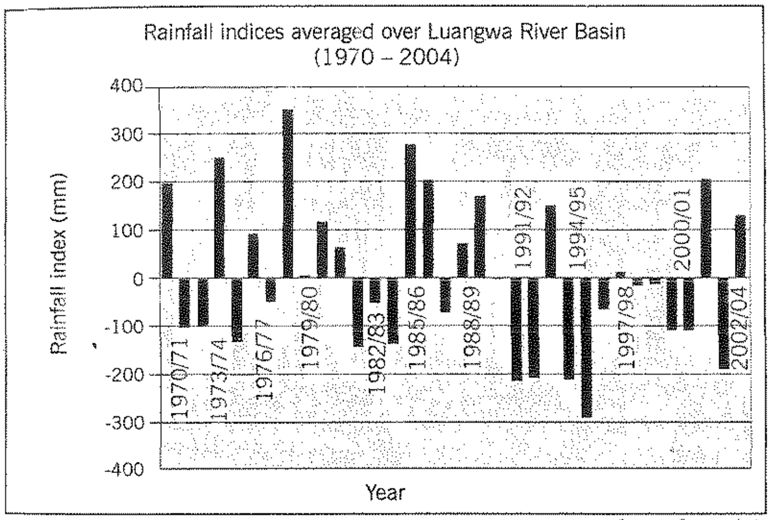
The main sub-basins considered in the study are the Kafue, Upper Zambezi, Kabompo, Lwanginga, Cuando Chobe, Luiana, Lwangwa, Barotse, Lunge Bungo, Chongwe, Shire, Mazowe, Gwayii, Shangani, Sanyati, Manyame, Luia, Zambeze, Luenha, Guacua and Zangwe. The sub-basins in Zambia can further be divided into smaller sub-basins, specifically the Kafue and Luangwa River Basins. The main tributaries of the Zambezi River such as Kafue, Kabompo, Lwangwa, Upper Zambezi originate in the Zambezi-Zaire watershed. The study assessed run-off effect parameters over the baseline period (1970 to 2000) in all the sub-basins identified. Detailed results of the assessments (catchment area, mean annual average rainfall, mean run-off) for selected sub-basins are provided in Table 3.1.

Based on the results in Table 3.1, Figure 3.6 provides a percentage distribution of the mean annual run-off of sub-basins.

The sub-basin with the largest contribution to the Zambezi River Basin run-off is Kafue (31,8%), followed by Luangwa (20,1%), Upper Zambezi (14,3%) and Malawi/Shire (11,8%). From Figure 3.6, it is evident that a bigger percentage of run-off is from the sub-basins located in Zambia and those partially shared with Angola. Of those located in Zimbabwe, Sanyati sub-basin has the highest run-off contribution of 1,5%. The sub-basins located in Mozambique have Zambezi as the highest run-off contributor with a percentage of 2%.

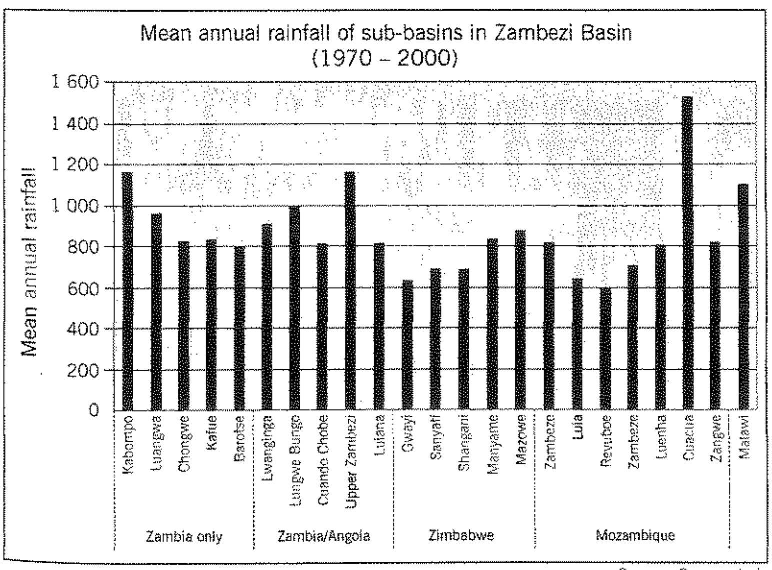
Further analysis was undertaken to correlate run-off from selected sub-basins against identified wet and dry years over the baseline period. Some of the features in this analysis need to be compared with the network diagram in Figure 2.3.

The **Kabompo** sub-basin has a catchment area of 71 280 km² and is located in a high rainfall zone in Zambia. The mean annual rainfall over the sub-basin is 1 151 mm. The sub-basin churns a mean annual run-off of 6 601 Mm³ through Watopa Gauging Station. It had a maximum of 11 478 Mm³ in the 1977/78 rainy season and a minimum of 3 939 Mm³ in the 1994/95 rainy season, almost half the mean run-off.



Source: Own analysis.

Figure 3.4: Precipitation anomalies (Luangwa).



Source: Own analysis.

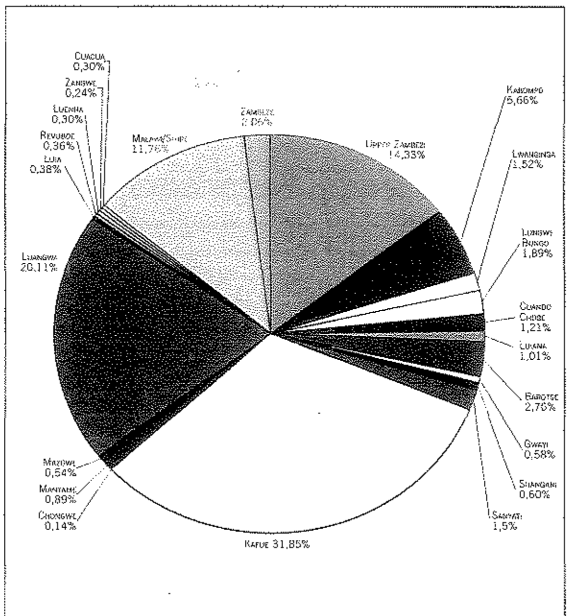
Figure 3.5: Mean annual rainfall of sub-basins of the Zambezi River Basin.

Table 3.1: Run-off effect parameters.

Sub-basin	Catchment area (km²)	Mean annual rainfall (mm)	Mean annual run-off (Mm³)
Kabompo	71 280	1 151	6 601
Upper Zambezi	106 950	1 151	16 703
Lwanginga	54 500	901	1 776
Lungwe Bungo	60 075	998	2 207
Cuando Chobe	145 359	812	1 408
Luiana	54 843	812	1 177
Barotse	93 403	812	3 222
Gwayi	38 600	636	673
Shangani	38 600	681	696
Sanyati	62 945	678	1 749
Kafue	150 971	855	37 116
Chongwe	5 116	836	159
Manyame	44 019	828	1 038
Mazowe	27 489	859	630
Luangwa	147 622		23 437
Luia	23 497	643	437
Revuboe	16 655	575	425
Luenha	14 368	813	353
Zangwe	10 016	816	280
Guacua	17 908	1 513	347
Shire/ Lake Malawi	118 484	1 105	13 701

*Mm^3-million cubic metres

Source: Own analysis.

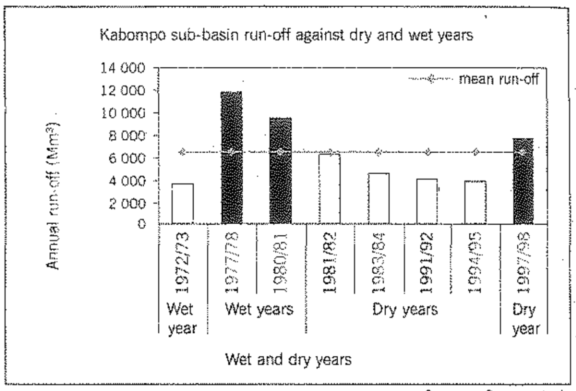


Source: Own analysis.

Figure 3.6: Percentage contribution of each sub-basin to the Zambezi River Basin mean annual run-off.

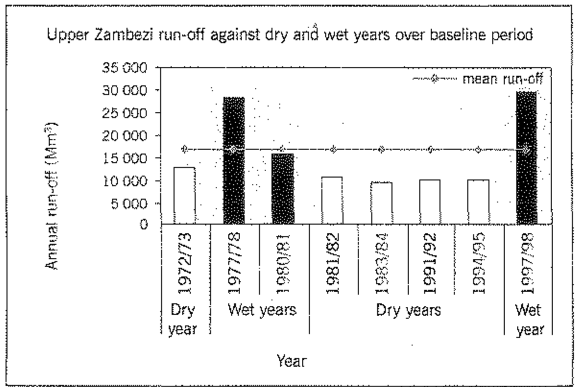
It is evident from Figure 3.7 that the wet years had an annual run-off above the mean over the baseline period while the dry years had run-off below the mean.

The **Zambezi** River originates within the Upper Zambezi sub-basin in Kalene Hills. The Upper Zambezi has a catchment area of 106 950 km², about 90% of the catchment area lies in Angola while the other 10% is located in Zambia. This sub-basin receives a mean annual rainfall of 1 151 mm and it generates a mean annual run-off of 16 703 Mm³ through Chavuma gauging station. The maximum run-off was recorded to have occurred in the 1979/80 rainy season, amounting to 30 237 Mm³ and the minimum was 6 589 Mm³ in



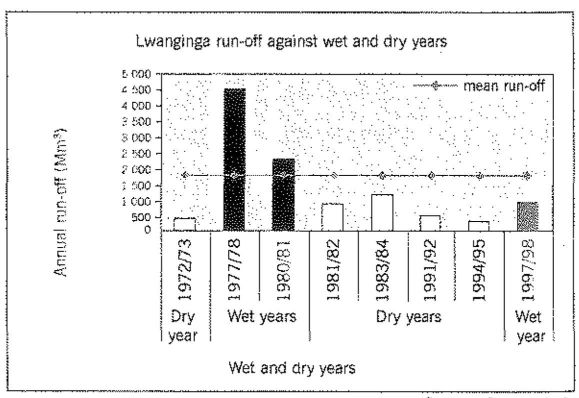
Source: Own analysis.

Figure 3.7: Kabompo sub-basin run-off against dry and wet years.



Source: Own analysis.

Figure 3.8: Upper Zambezi sub-basin run-off against dry and wet years.



Source: Own analysis.

Figure 3.9: Lwanginga sub-basin run-off against dry and wet years.

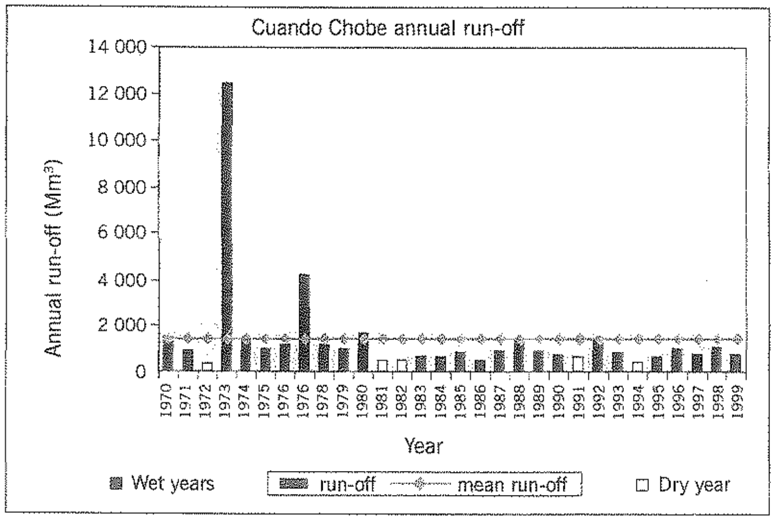
1996/97. Figure 3.8 shows some selected dry and wet years in terms of rainfall in relation to run-off of the Upper Zambezi sub-basin. All the identified dry years had run-off below the annual mean as opposed to wet years whose annual run-off was above the mean over the baseline period.

The **Lwanginga** River is located south west of the Upper Zambezi sub-basin. It has a catchment area of 54 500 km² of which 30% is located in Zambia and 70% in Angola. A mean rainfall of 901 mm is received by the catchment area annually. With this amount of mean annual rainfall, the sub-basin in turn drains a mean annual run-off of 1 776 Mm³ through Kalabo gauging station into the Zambezi main. The maximum run-off was recorded in 1988/89, amounting to 5 545 Mm³ with the minimum recorded in 1994/95 as 387 Mm³.

Figure 3.9 reveals a situation similar to the cases considered in the previous analysis. It is evident that wet years resulted in above average run-off and dry years over Zambia resulted in below average run-off. There is an interesting feature in this sub-basin in that the 1997/98 rainy season, which was generally understood to be a wet year in Zambia, did not necessarily result in above average run-off. This clearly demonstrates the distinction of local, regional and global climate. On a regional basis, 1997/98 is taken as a wet year but locally in the Lwanginga sub-basin there was insufficient rainfall to generate run-off above average.

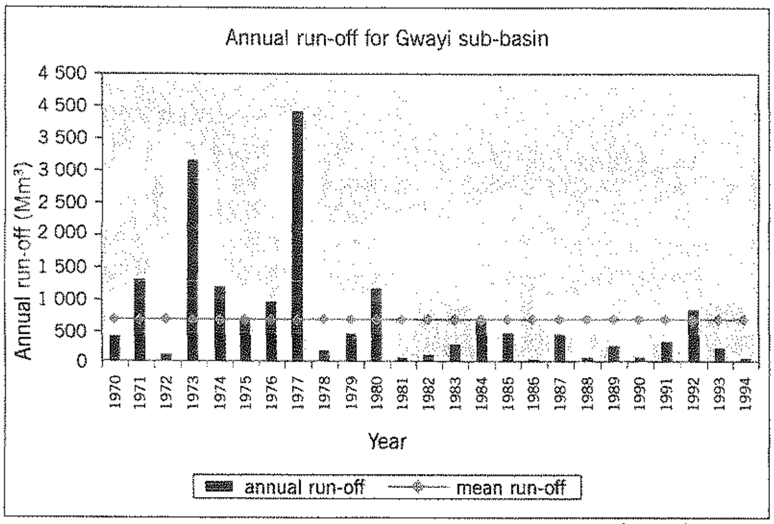
The **Cuando Chobe** sub-basin occupies an area of 145 359 km² shared between Angola, Zambia, Botswana and Namibia, though it only takes small portions from Botswana and Namibia in the Caprivi Strip. It collects a mean annual rainfall of 812 mm and converts part of it into a mean annual run-off of 1 408 Mm³, which drains into the Zambezi main.

The river is not gauged and thus does not have historical flows. The annual run-offs provided in Figure 3.10 were derived from the water



Source: *Own analysis.*

Figure 3.10: Annual run-off of Cuando Chobe.



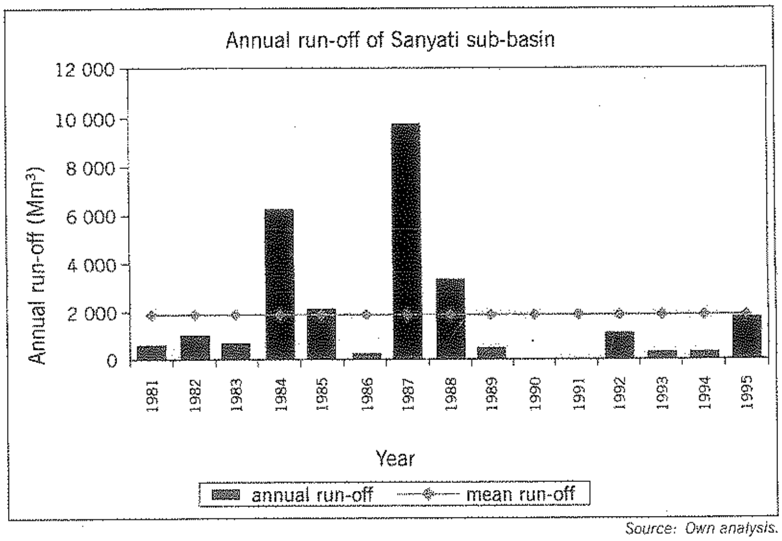
Source: *Own analysis.*

Figure 3.11: Annual run-off for Gwayi sub-basin over the baseline period.

balance model (WRSM 2000). This approach can be used to generate missing data in future analysis and research. The wet years of 1977 and 1980 show run-off above the mean with the exception of 1997/98. All identified dry years had run-off below the annual mean. Cuando Chobe and Lungwe Bungo are adjacent to each other and both of them show run-off below the mean in the wet year 1997/98 rainy season. The local rainfall in these two sub-basins in this particular year was in fact below average.

The **Gwayi River Basin** is located entirely in Zimbabwe and occupies a catchment area of 38 600 km². Generally, Zimbabwe has less annual rainfall than Zambia and thus it is expected that all its sub-basins have a lower rainfall relative to those located in Zambia, Malawi and Mozambique. The sub-basins located to the north east and east (i.e Manyame and Mazowe) of Zimbabwe have a higher annual rainfall relative to the rest of the sub-basins (i.e Gwayi, Sanyati, and Shangani).

The Gwayi river receives a mean annual rainfall of 636 mm. It releases a mean annual run-off of 673 Mm³ through its gauging station located at Kamativi. Between 1970 and 1993, August to October generally, the sub-basin had little or no run-off. Over this period, the only months with guaranteed run-offs were January, February and March. The highest annual run-off was recorded in the 1977/78 rainy season and amounted to



Source: Own analysis.

Figure 3.12: Annual run-off for Sanyati sub-basin.

3 879 Mm^3. On the other hand, the least run-off was recorded as 21 Mm^3 in the 1989/90 rainy season as can be observed in Figure 3.11. It can also be observed that in some years there is almost no run-off.

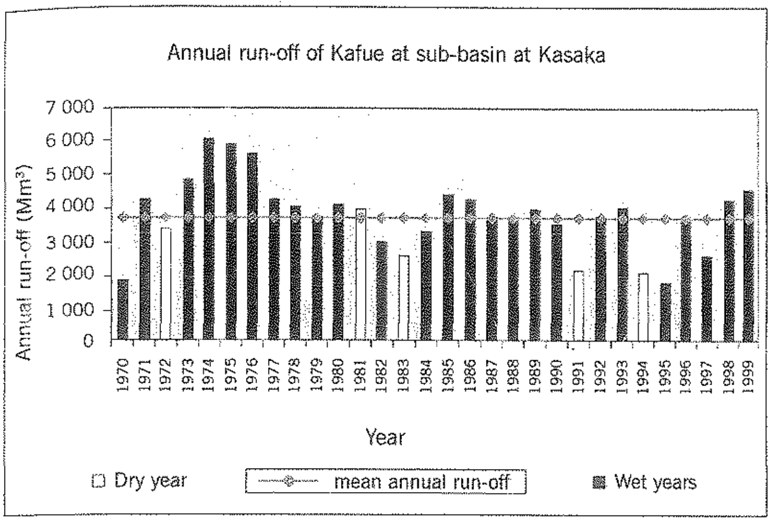
The **Sanyati River Basin** drains right into Lake Kariba. It receives a mean annual rainfall of 678 mm on its 62 945 km^2 catchment area. A mean annual run-off of 1 749 Mm^3 passes through its gauging station at Copper Queen into Lake Kariba. The river basin had historical flows only from 1981 to 1995. In the year 1989/90, there was no run-off from August to January. In the 1990/91 rainy season, there was no flow at the gauging station on Sanyati from April to January. Similarly, the season 1991/92 had no run-off from May to October. Figure 3.12 shows the trends of annual run-off for the Sanyati River.

The source of the **Kafue** River is in the Copperbelt Province of Zambia in the Zambezi/Zaire watershed. It stretches from the Zambia/DRC border down to the Zambia/Zimbabwe border near Chirundu. Two main hydrological features relevant to hydro-power generation in Zambia are located in the basin, namely Kafue Gorge and Itezhi-Tezhi Dam reservoir. It joins the Zambezi River main near Chirundu. The Kafue sub-basin has several tributaries especially on the upper north of the sub-basin. It provides the highest annual run-off contribution to Zambezi River main. The catchment area of the Kafue sub-basin is 150 971 km^2 and a mean rainfall of 855 mm is received by its vast area annually. The upper north of the sub-basin is located in the high rainfall zone (over 1 000 mm) of Zambia and the middle part around Central Province is a medium rainfall zone (between 800 – 1 000 mm). The lower parts of the basin as the river joins the Zambezi River main from the low rainfall zone (less than 800 mm). The catchment area converts rainfall it receives annually into an annual run-off of 37 116 Mm^3 at Kasaka gauging point, taking into account evapo-transpiration losses and other factors. The highest flow was recorded in the 1974/75 rainy season and amounted to 59 567 Mm^3 while the lowest was recorded in the 1995/96 rainy season at 16 819 Mm^3.

From Figure 3.13, it is clear that the identified dry years in Zambia had the effect of reduced run-off (i.e. below the mean) with the exception of the 1981/82 rainy season, which was around the mean annual run-off over a period of 30 years. On the other hand, all the wet years had run-offs above the mean except the 1997/98 rainy season, which had rainfall below the mean. This can be attributed to several factors from rainfall to water usage in the sub-basin by power and water utilities companies, mining and irrigation. It must be noted that Zambia's main industries (mines, manufacturers, etc) and major towns, including the capital Lusaka are located in this sub-basin.

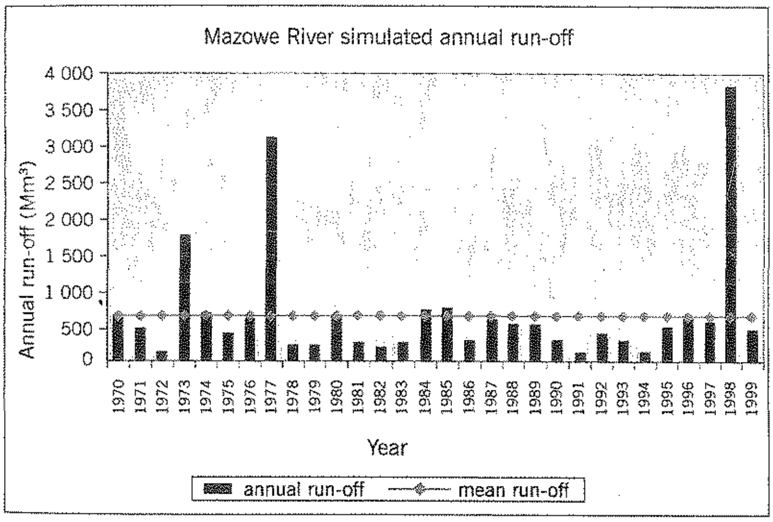
The **Mazowe** River originates in Zimbabwe and joins the Zambezi main in Mozambique after Tete. It has a catchment area of 27 489 km^2 that stretches from Zimbabwe into Mozambique. It must be stated that since only a small portion lies in Mozambique, it is regarded as negligible and was therefore not considered in the study. Mazowe sub-basin has the highest mean annual rainfall, 859 mm, among the sub-basins in Zimbabwe. Gwayi sub-basin has the lowest mean annual rainfall of 636 mm. Mazowe River Basin does not have historical river flows for the whole baseline period, however, the water balance model as in other cases of ungauged rivers did provide the simulated run-offs for the entire baseline period. The annual run-off of Mazowe is shown in Figure 3.14. Mazowe River merges with Lwenha just before it joins the Zambezi River main. An annual run-off of 630 Mm^3 was estimated by the water balance model.

The **Lake Malawi/Nyasa/Niassa** catchment is, by and large, asymmetrical due to the fact that the eastern side of the catchment has been downthrown by the faulting western part. It consists of a series of blocks stepping eastward parallel to the main fault. As a result, the major rivers found within the basin both in the east and west of the lake flow towards it. Songwe, North Rukuru, South Rukuru, Dwangwa, Bua, Lilongwe, Diamphwe and Linthipe, are the principal rivers found on the northern highlands and the central plateau of the country and all flow eastwards to the lake. This faulting has also induced similar characteristics for those rivers that flow into the Shire River, the main drain plug of Lake Malawi/Nyasa/Niassa, with rivers such as Rivi Rivi, Nkulumadzi and others flowing eastwards to pour their waters into the Shire and down to the Zambezi.



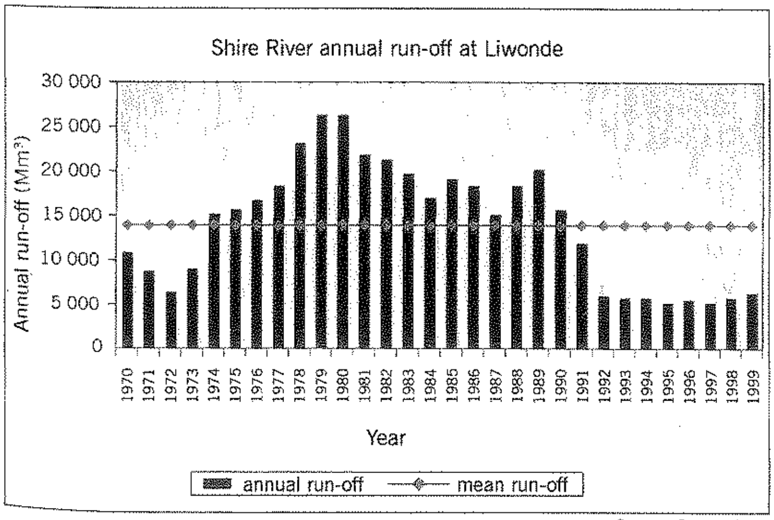
Source: Own analysis.

Figure 3.13: Annual run-off for Kafue sub-basin.



Source: Own analysis.

Figure 3.14: Annual run-off for Mazowe sub-basin.



Source: Own analysis.

Figure 3.15: Shire River annual run-off at Liwonde.

The Malawi basin area in this study was taken to be the whole geographical area of Malawi with a catchment of 118 484 km² for the purpose of modelling. The mean annual rainfall for the sub-basin over the baseline period is 1 105 mm. The sub-basin drains into the Zambezi River main through Shire River in Mozambique with a mean annual run-off of 13 701 Mm³.

Figure 3.15 shows that the Shire River flowed below the mean from 1970 to 1973. Between 1974 and 1990, the river's annual run-off was above the mean, with the maximum of 26 006 Mm³ occurring in this range in the year 1979. From 1990 to 2000, there was significant drop in run-off with all the years in this bracket having run-off below the mean. The lowest flow, amounting to 5 044 Mm³, was recorded in 1997. The water balance model revealed that the river flows were high in the month of May, estimated at 10% of the annual average over 30 years. On the other hand, the flows were observed to drop in October to about 5% of the annual average.

3.3 RESERVOIR EFFECTS

In order to assess the effects of climate change/variability through run-off over the baseline period, a correlation was undertaken with reservoir storage and hydro-power generation in both identified dry and wet years. This was undertaken in the four main water bodies of the Zambezi River Basin; Lake Kariba, Itezhi-Tezhi, Lake Malawi and Cahora Bassa.

3.3.1 LAKE KARIBA DAM RESERVOIR

Lake Kariba dam was built in the late 1950s, it has a gross capacity of 185 km³. The impoundment of water started in December 1958. The power station has an installed capacity of 1 266 MW, with 666 MW on the south bank (Zimbabwe) and 600 MW on the north bank (Zambia) (Table 3.2).

Table 3.2: *Kariba hydro-electric scheme characteristics.*

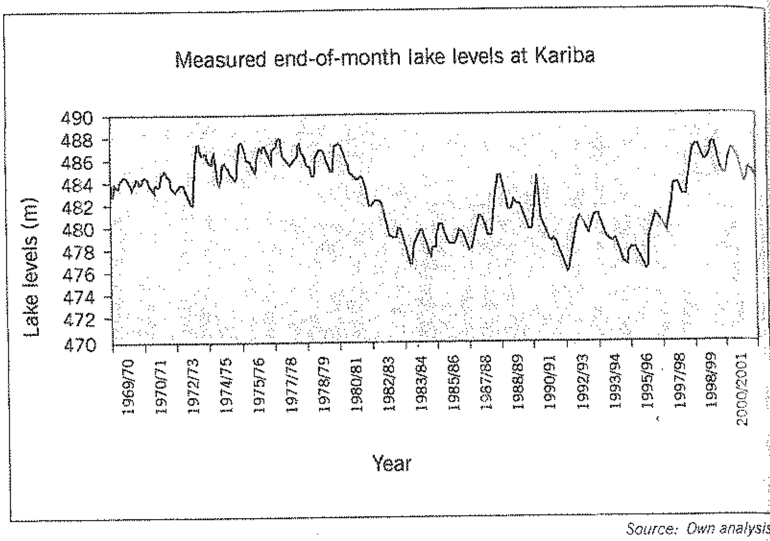
A Kariba Dam wall	
Type	Arch double curvature
Height	128 m
Crest length	617
Thickness	Maximum width 24 m Minimum width 13 m
Volume of concrete	1 032 Mm³
Flood gates	Six gates (9 m high x 8,8 m wide)
Discharge capacity of floods	9 500 m³ per second
B Reservoir at Full Supply Level (FSL)	
Length	280 km
Widest point	32 km
FSL	488,5 m
Minimum operating level	475,5 m

Source: Zambezi River Authority.

Drought and wet episodes and their impact on Lake Kariba are shown in Figure 3.16. In the drought year 1972/73, there was a significant drop in the lake level, but the level picked up quite considerably from 1974.

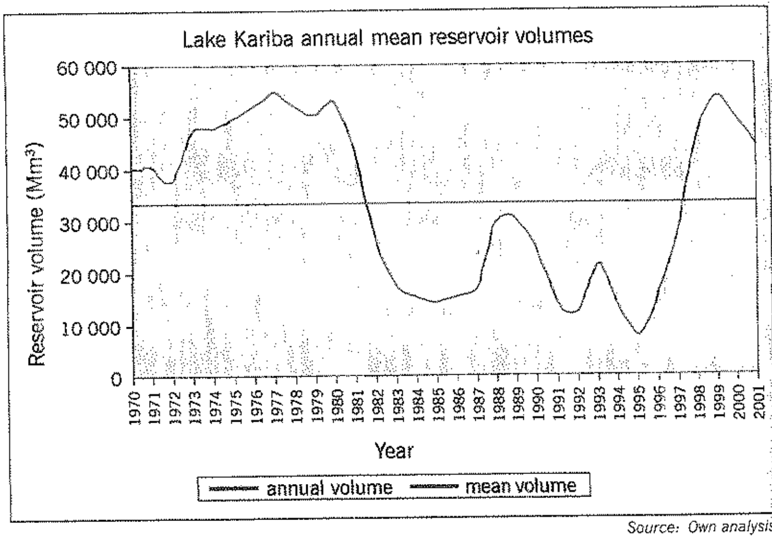
In the period 1974/75 to 1980/81, Lake Kariba enjoyed high levels with the highest being 487,66 m in the 1977/78 rainy season. The drought years in 1981/82 through to 1984 significantly reduced the level to the lowest of 476,66 m in 14 years since 1970. It is clear from Figure 3.16 that the dry episodes inflicted a heavy toll on the levels of Lake Kariba.

Key observations of the performance of the lake during the period 1970 to 2000 were summarised as follows:



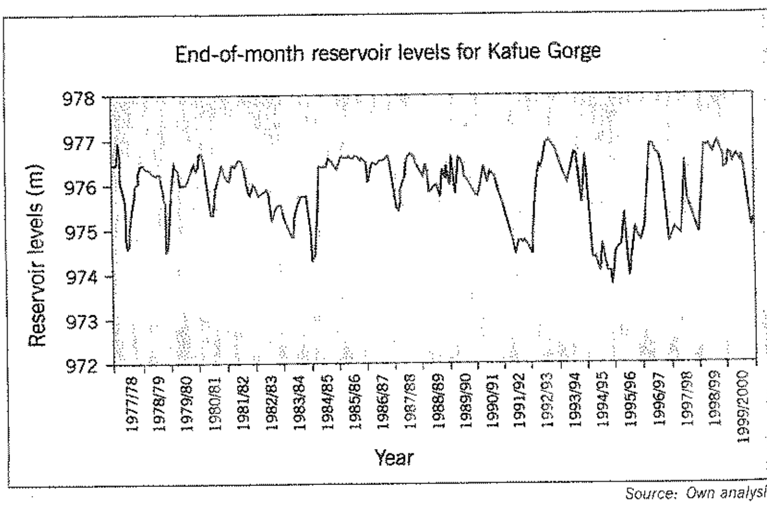
Source: Own analysis.

Figure 3.16: Measured end-of-month levels for Lake Kariba, October 1970 to September 2002.



Source: Own analysis.

Figure 3.17: Lake Kariba reservoir volumes over the baseline period.



Source: Own analysis.

Figure 3.18: Kafue Gorge end-of-month reservoir levels.

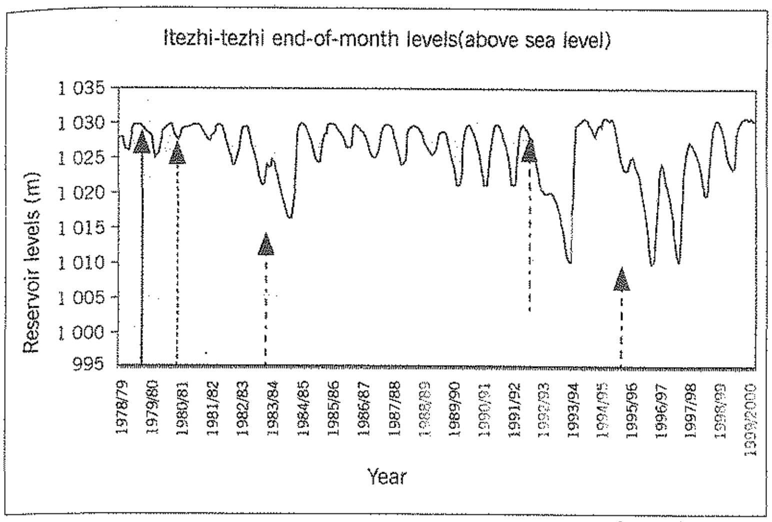


Figure 3.19: Measured end-of-month levels for Itezhi-Tezhi reservoir.

(i) Minimum lake storage capacity over the base line period was 7 801 Mm^3 in 1995 (Figure 3.17).

(ii) Maximum lake storage capacity of 55 037 Mm^3 in 1977.

(iii) Mean volume over 30 years was 33 244 Mm^3.

(iv) All the drought years show a remarkable reduction in lake volumes. The most significant one was the 1981/82 drought which caused lake volumes to decrease to very low levels in the years since 1970. The successive 1983/84 drought effectively pinned down the volumes to low levels until 1987/88 when the storage capacities started to recover.

(v) Wet episodes, on the other hand, show profound increa -ses in storage capacities.

(vi) For about 16 years, from 1981 to 1999, the storage capacity had been lying below the 30 year mean.

(vii) After 1997, storages recovered from this depression, shooting above the mean to a maximum of 53 462 Mm^3 in the year 1999.

(viii) From the water balance model, mean monthly flows released/spilled from Lake Kariba revealed that the lake was not large enough to capture the peak flows.

3.3.2 *KAFUE GORGE*

Kafue Gorge is located downstream of Itezhi-Tezhi reservoir. It has an installed hydro-electric power capacity of 900 MW. Figure 3.18 gives an in-depth picture of how reservoir levels have been affected by climate change/climate variability.

Kafue Gorge's hydrological performance during the period (1977 – 2000) was characterised by minimum reservoir levels attained between 1977 and 2000, with a level of 973,8 m which occurred in the 1994/95 rainy season. Further, it was observed that a maximum level of 977 m was attained in 1992/1993. The 1994/95 dry episode was very profound as it inflicted a heavy reduction in lake levels, the lowest since 1977.

3.3.3 *ITEZHI-TEZHI DAM*

Itezhi-Tezhi plays a significant role in hydro-power generation at Kafue Gorge power station since it is located downstream of Itezhi-Thezhi. It is assumed that apart from evapo-transpiration on the stretch between Kafue Gorge and Itezi-Tezhi, flow into Kafue Gorge is mainly affected and controlled at Itezhi-Tezhi reservoir. For this reason any changes in lake levels and, ultimately, storage capacity have an effect on hydro-power generation at Kafue Gorge power station.

Lake levels and corresponding storage capacities were measured over the baseline period and their fluctuations are shown in Figures 3.19 and 3.20 respectively.

In the period 1977 to 2003, Itezhi-Tezhi Dam reservoir experienced a minimum lake storage capacity over the baseline period at 800 Mm^3, which was the worst in 23 years. Maximum lake storage capacity of 3 700 Mm^3 was experienced in the year 1993/94. The mean volume over 23 years was observed to be 2 575 Mm^3. All the drought years showed a remarkable reduction in lake volumes as evidenced by the dips after 1981/82, 1991/92 and 1994/95. The most serious impact of drought on Itezhi-Tezhi was in the 1994/95 drought. Wet episodes, on the other hand, showed profound increases in storage capacities.

Table 3.3: Cahora Bassa hydro-electric power scheme.

Type	Double curved arch
Maximum height above foundation	171 m
Crown length	303 m
Crest altitude	331 m
Volume of concrete	450 000 m^3
Volume of foundation	210 000 m^3
Segmentary gates	8 × 1 650 m^3/s
Crest spillway	350 m^3/s
Length	270 km
Width	30 km
Depth	140 m
Capacity	63 km^3
Surface area	2 660 km^2
Dam catchment area	900 000 km^2
Turbine type	Francis
Capacity	415 MW (×5) = 2 075 MW
Speed	107,1 rpm
Effective head	103,5 m
Consumption	452 m^3/s
Penstock length	170 m / D = 9,7 m / 45°

Source: Mondlane University.

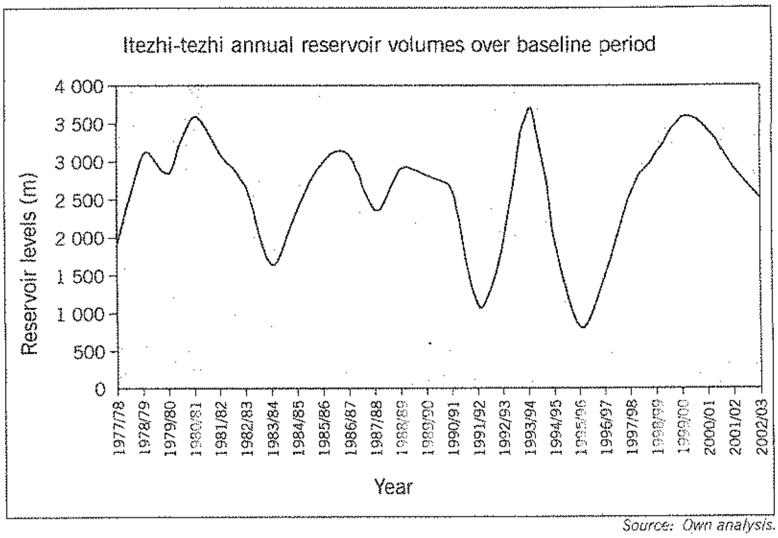


Figure 3.20: Itezhi-Tezhi reservoir volumes over the baseline period.

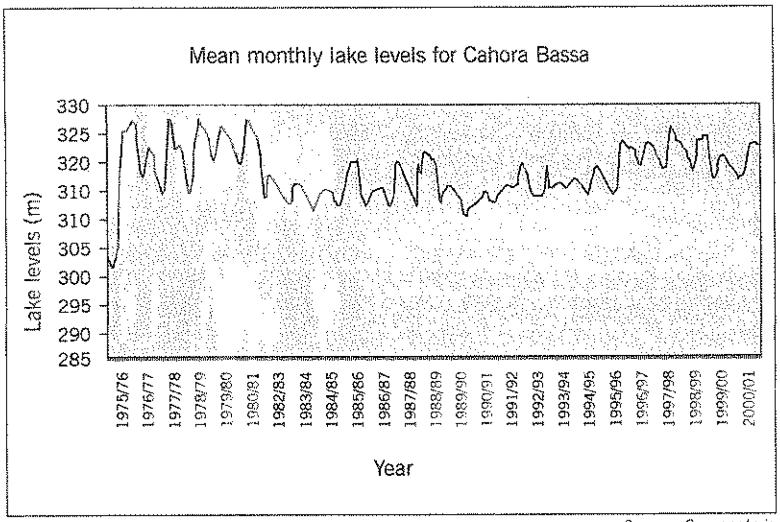


Figure 3.21: Measured end-of-month levels for Cahora Bassa dam reservoir.

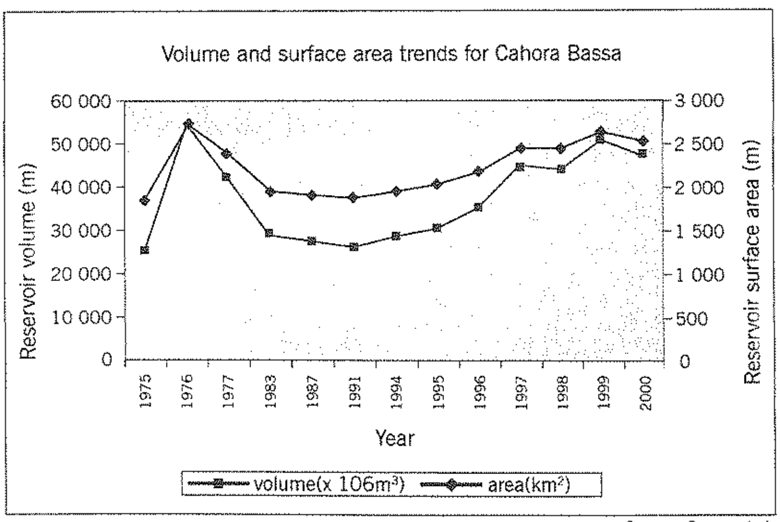


Figure 3.22: Cahora Bassa reservoir volumes for 13 selected years.

3.3.4 *CAHORA BASSA DAM*

Run-off into Cahora Bassa is mainly from sub-basins located in Zambia and a portion from Angola. For this reason, the levels and capacity storages at Cahora Bassa are influenced to a great extent by activities in the sub-basins in Zambia and Angola. The effects of dry and wet years, which were identified to have been experienced in Zambia still continued to be traced further downstream in Mozambique at Cahora Bassa Dam reservoir. No major tributaries from Zimbabwe or Mozambique which feed into Cahora Bassa can distort the hydrological picture set by run-offs from sub-basins located in Zambia and Angola. Table 3.3 shows various parameters at Cahora Bassa hydro-electric power scheme.

Figure 3.21 shows the measured mean monthly lake levels for Cabora Bassa Dam reservoir. It can be observed that the depression in lake levels and reservoir storage capacities that were identified at Lake Kariba from the years 1981 to 1997 could be felt even at Cahora Bassa. There was an observed peaking generally in the lake levels from 1997 to 2000, a situation similar to that experienced at Lake Kariba. Similarly, the high lake levels enjoyed by Lake Kariba between 1976 and 1981 were also experienced by Cahora Bassa. Figure 3.22 shows selected years against reservoir volumes and reservoir surface areas for Cahora Bassa.

The highest level, at 327,19 m, was in the rainy season of 1977/78. On the other hand, the lake level reached a low of 301,32 m in the rainy season of 1975/76 with the mean being at 317,82 m in 26 years (1975 – 2001).

3.3.5 *LAKE MALAWI*

The trend of Lake Malawi levels shows an increment in the first decade of the baseline period. This was followed by two decades of steady decrease from 1978 to 1996/97 (Figure 3.23). The highest level attained was 476 m in the 1978/79 rainy season while the lowest was 474,1 m in 1998/99. The scenario tallies with the influence of dry and wet years. The wet years of 1977/78 and the dry years of 1994/95 seem to have had a significant effect on the lake levels.

3.4 HYDRO-POWER POTENTIAL

To assess the effects of climate change/variability through reservoir storage over the baseline period, a correlation was undertaken with hydro-power generation in both identified dry and wet years for Lake Kariba and Itezhi-Tezhi.

3.4.1 *LAKE KARIBA*

Figure 3.24 shows power potential for Lake Kariba (south and north banks) power generating schemes over the baseline period.

It also shows power potential for the years 1976 to 2000. The drought of 1991/92 contributed to the decline in precipitation, leading to a subsequent significant loss of hydro-power potential for Lake Kariba. The maximum power potential of 694 MW was experienced at Kariba South Bank in September 1976. Further, maximum power potential for Kariba North Bank was recorded at 614 MW in June 1989.

Figure 3.25 shows annual units generated in (GWh) at both Kariba North and South hydro-electric plants. The results shown in Figure 3.25 reveal a good picture of the effects of climate change/variability through demonstration of corresponding increases in power generation during wet years and reductions during dry years.

It is evident from Figure 3.26 that there is a correlation between hydro-electric power potential (MW) and the actual units of hydro-electric power generated (GWh). It can be further deduced that, in the identified wet episodes, the hydro-electric power potential was higher than during dry episodes.

3.4.2 *ITEZHI-TEZHI*

Itezhi-Tezhi is the main reservoir and provides a steady flow for Kafue Gorge. Figure 3.27 shows the historical variations in power potential over the baseline period (1977 – 2000).

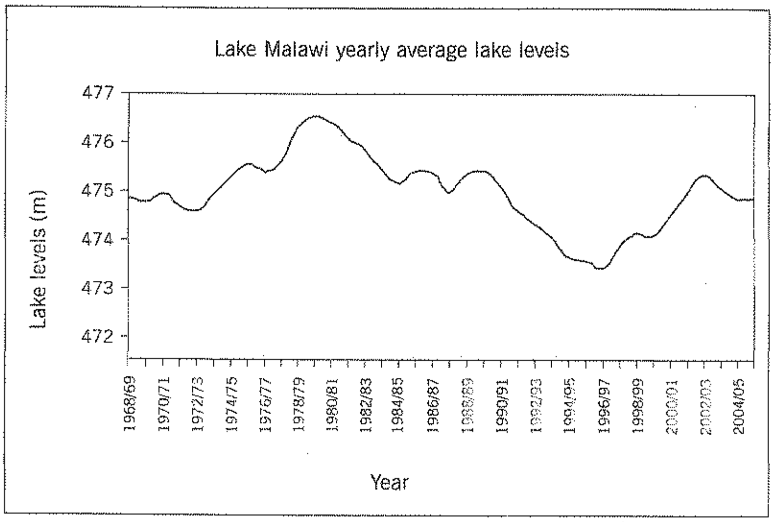


Figure 3.23: Lake Malawi yearly mean lake levels.

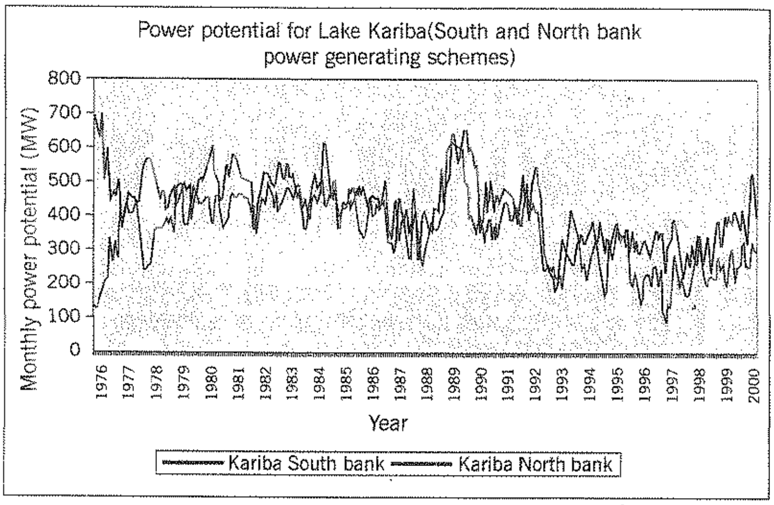


Figure 3.24: Power potential for Lake Kariba (1976 – 2000).

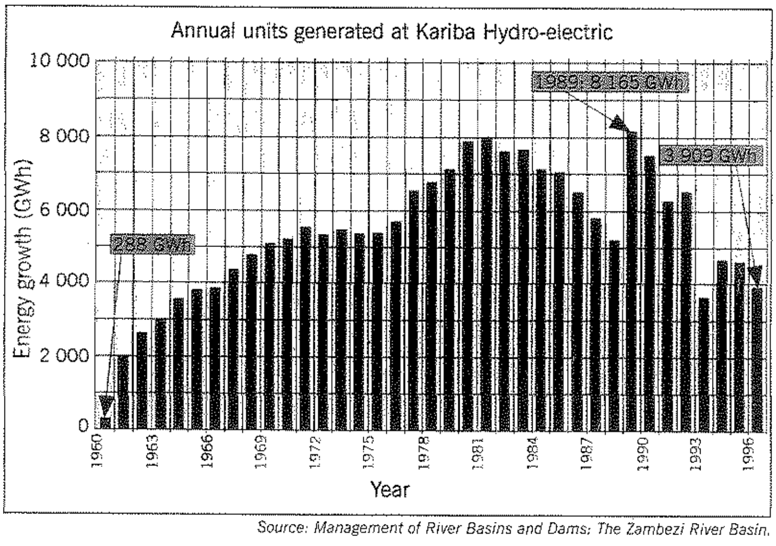


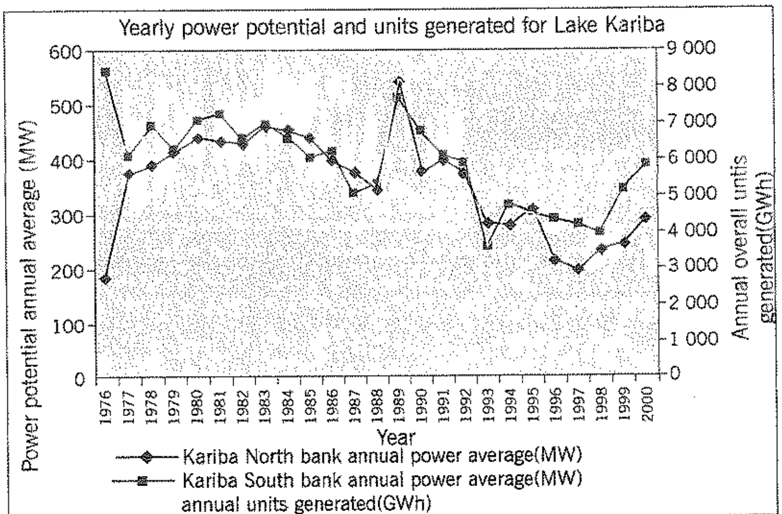
Figure 3.25: Annual units generated in (GWh) at Kariba hydro-electric.

The power potential in Figure 3.27 is as a result of climatic factors and water abstractions upstream of the reservoir. In the identified wet episodes under the baseline, the following was deduced:

(i) Sharp increase in power potential in the 1977/78 rainy season.
(ii) Corresponding increase in hydro-power potential recorded in the 1980/81 wet year.
(iii) Triggering of the recovery process in hydro-electric power potential in the 1997/98 wet year, from the lowest experienced over the years in the dry episode 1994/95 drought year.

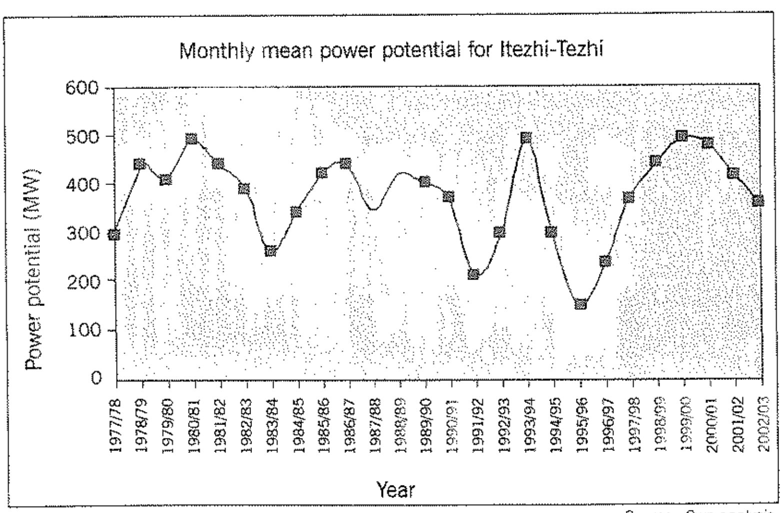
The dry years with respect to hydro-power potential had the following observable impacts:

(i) The dry episode of 1981/82 caused a slump in the power potential from high levels in the preceding wet years.
(ii) In the dry year 1983/84, hydro-electric power potential plummeted to low levels as evident by a dip in the power potential curve.
(iii) In yet another dry year, 1991/92, there was a significant reduction in power potential.
(iv) The episode that inflicted a really heavy toll on hydro-electric power potential on the Itezhi-Tezhi dam reservoir was the 1994/95 drought.



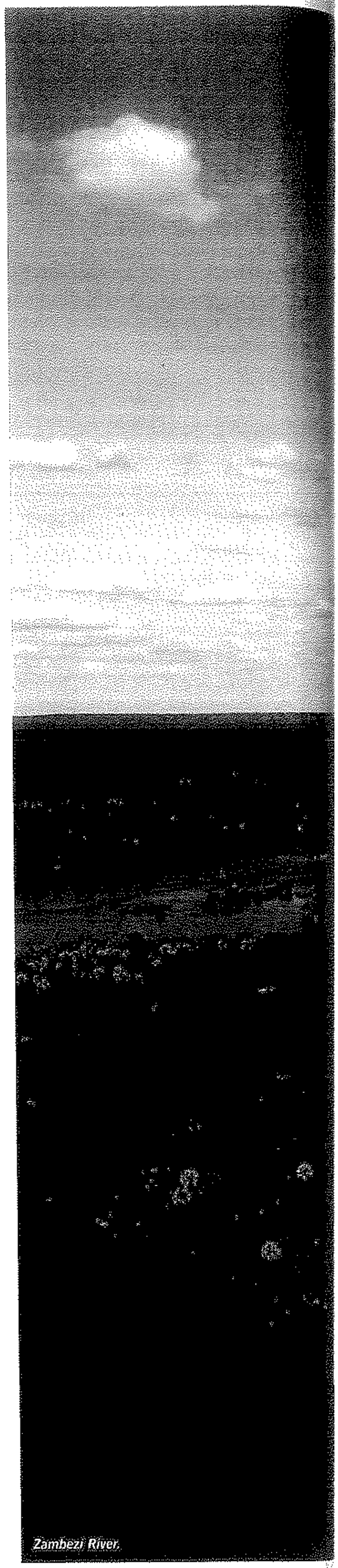
Source: Own analysis.

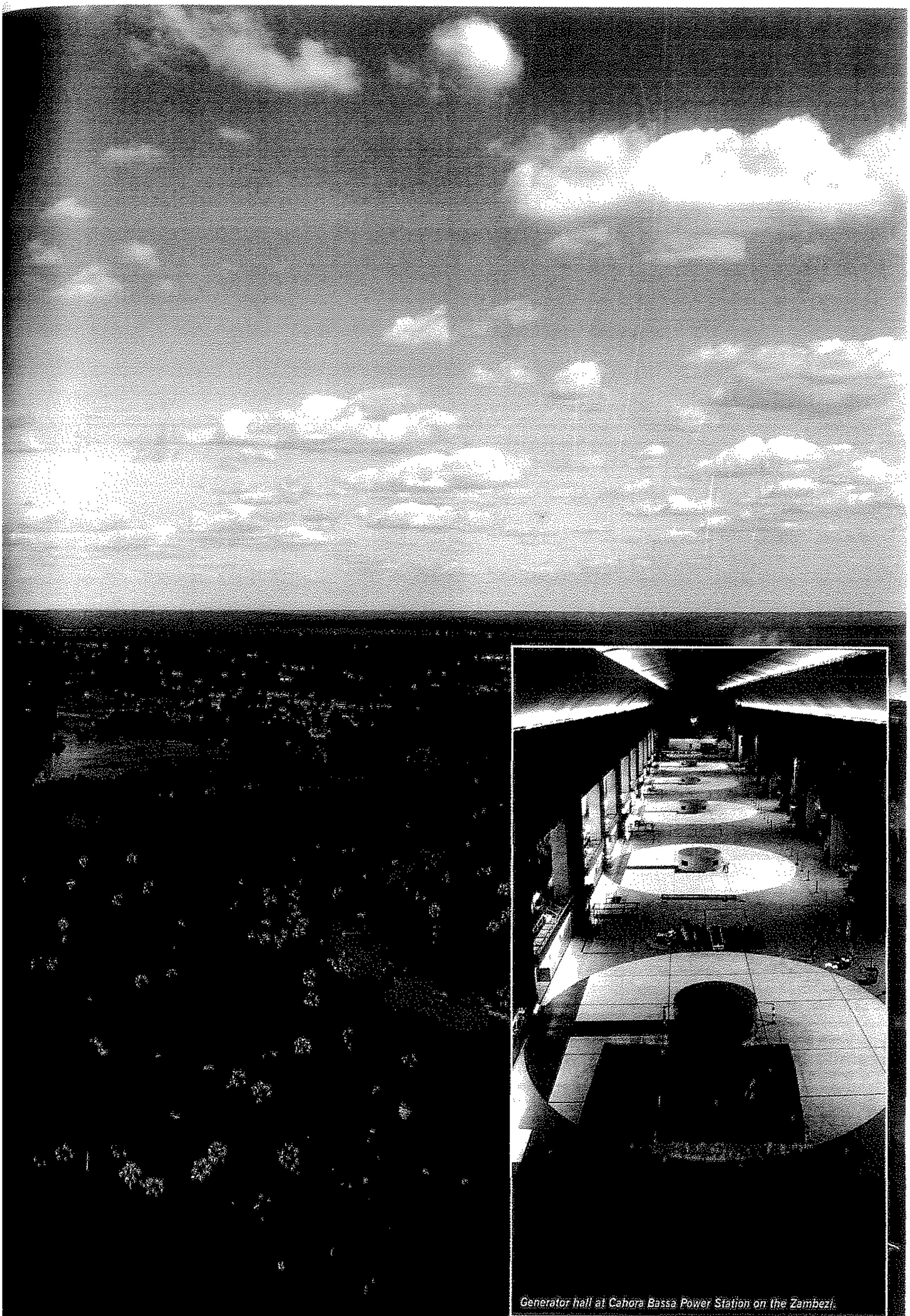
Figure 3.26: Annual average power potential and units generated for Kariba south/north banks.



Source: Own analysis.

Figure 3.27: Power potential for Itezhi-Tezhi.





Generator hall at Cahora Bassa Power Station on the Zambezi.

4. PROJECTED SCENARIO IMPACTS

4.1 COMBINED EFFECTS OF PROJECTED RAINFALL, WATER DEMAND AND INSTALLATION OF PROPOSED HYDRO-POWER INSTALLATIONS

Based on GCM simulations and algorithms, projected rainfall, water demand and the effects of installation of proposed hydro-power schemes between the years 2010 to 2070 were generated. In order to assess the effects of climate change/variability through the combined effects of projected rainfall, water demand and installation of proposed hydro-power schemes, a correlation was undertaken with hydro-power power potential.

4.1.1 PROJECTED RAINFALL

Figure 4.1 shows the projected mean annual rainfall for all the sub-basins over the period based on a combination of the three GCMs (CCCMA, CSIRO and HADCM3) used in the analysis.

Kabompo, Upper Zambezi, and to some extent Cuando Chobe, Luiana, and Malawi had a higher mean annual precipitation relative to the others. In Figure 4.1, a comparison between projected and baseline mean annual precipitation was undertaken. Results from sub-basins located on the lower part of the Zambezi River Basin (Gwayi, Shangani, Sanyati and Luangwa) revealed that the mean annual rainfall for projected and baseline scenarios was reasonably the same, with marginal increases in some cases.

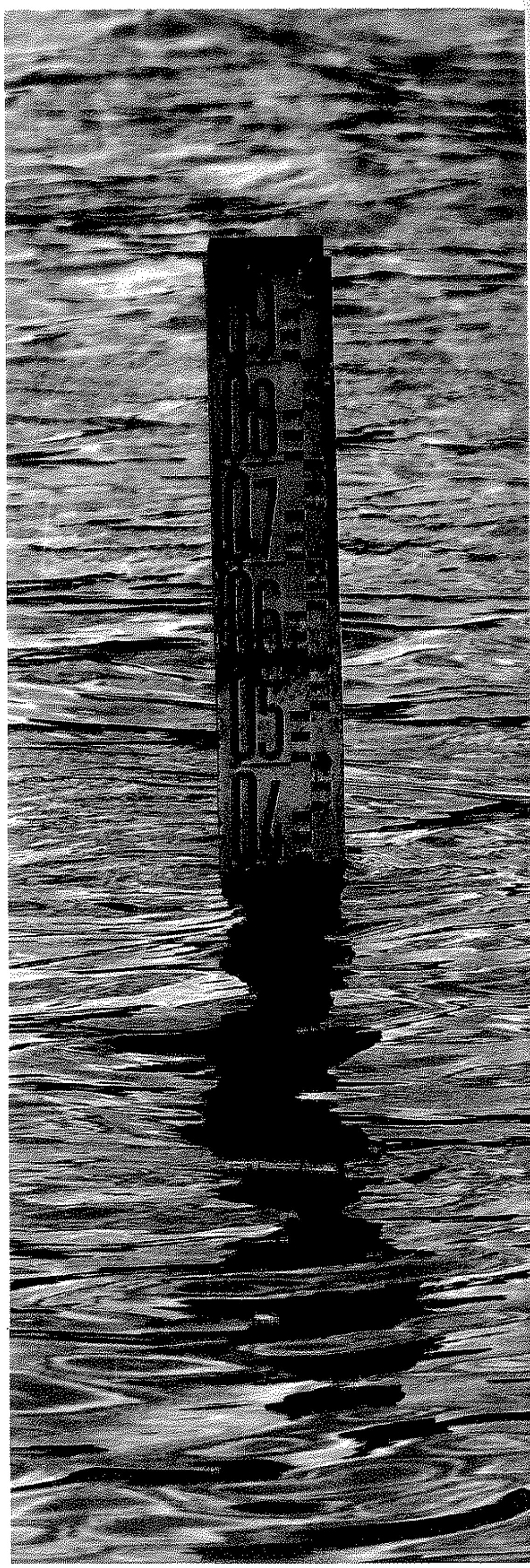
As a way of highlighting the nature of yearly forecast rainfall for a sub-basin, two sub-basins, namely Kabompo and Chongwe, were selected and their annual rainfalls and index diagrams drawn.

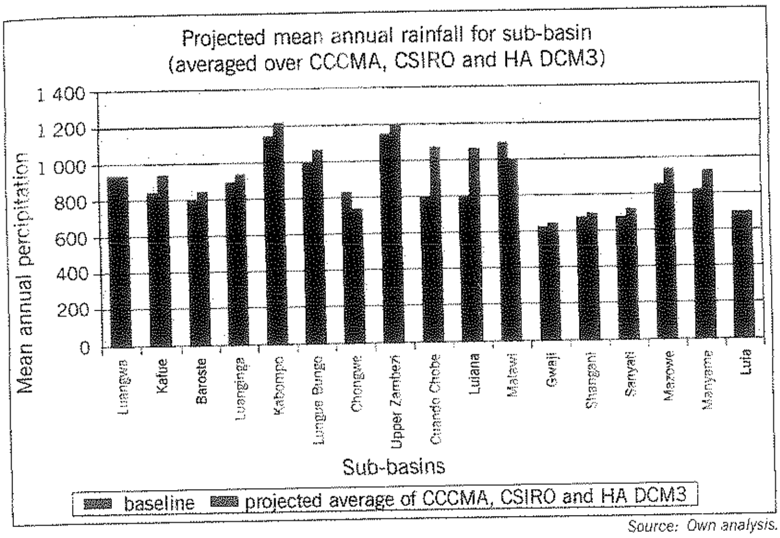
Kabompo sub-basin: The projected annual rainfall for Kabompo drawn from the projected monthly rainfall is illustrated in Figure 4.2.

In the projected period of 60 years, very high rainfall is expected to occur in 2047 and 2049, with rainfall scaling heights of 1 856 mm and 1 896 mm, respectively. Moderately high rainfall is expected to occur in the years 2015, 2017, 2029 and 2045. The years 2039 and 2064 are expected to have relatively low rainfall. About 27 seasons are likely to have occurrences of rainfall above average while about 30 years are expected to have rainfall below average while one year will have about average rainfall.

Chongwe sub-basin: Figure 4.3 shows the projected annual rainfall trends and annual rainfall index respectively.

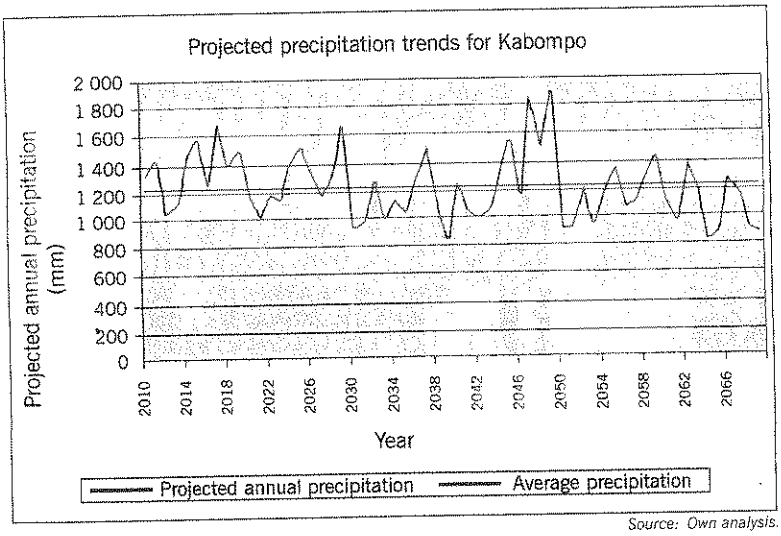
In the first decade (2010 to 2020), rainfall is expected to be generally above average with about three episodes of below average rainfall in the ten year period (Figures 4.3). Between the years 2020 and 2030, dry





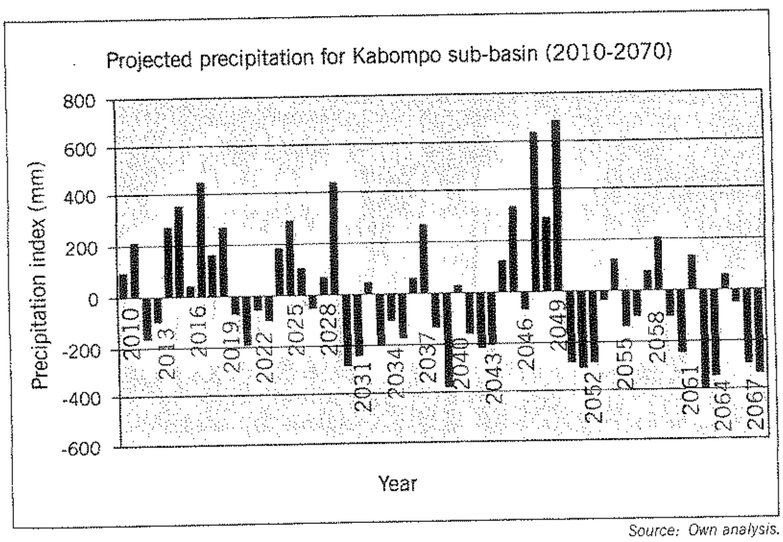
Source: Own analysis.

Figure 4.1: Projected mean annual rainfall for sub-basins.



Source: Own analysis.

Figure 4.2 (above and below): Projected annual precipitation trends and anomalies over Kabompo.



Source: Own analysis.

episodes are projected to exceed wet episodes with six dry episodes against three wet episodes and one average rainfall year. From 2030 to 2040, more occurrences with rainfall below average are expected. In the same period, an extreme dry year is expected to occur sometime around 2033. The decade between 2040 and 2050 is expected to see an improvement in precipitation levels with frequent occurrences of wet episodes as opposed to dry episodes.

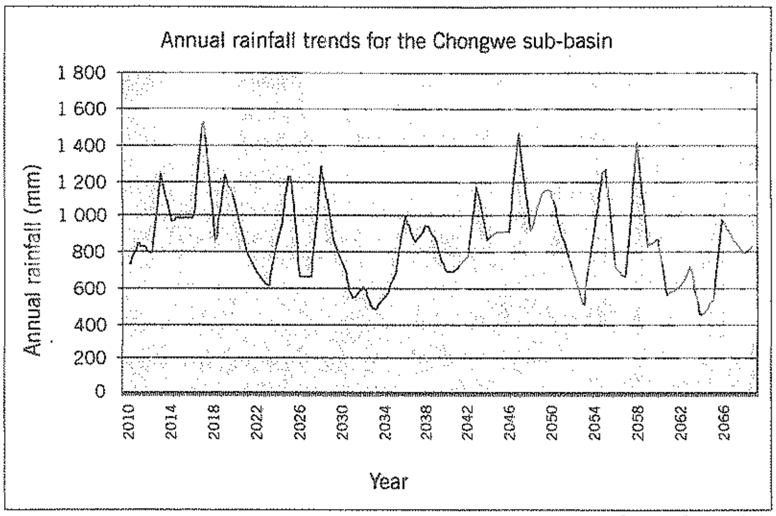
About eight occurrences of above average rainfall are expected while only two episodes of below average precipitation are expected. Furthermore, this decade is expected to experience one of the three wettest years in the entire projected period. Above and below average rainfall are predicted to almost alternate in the decade 2050 to 2060. From 2060 to 2070, below average rainfall is projected to increase in frequency and magnitude with the driest episode in the projected period occurring in the same decade.

The results obtained on precipitation from this study compared well with the Fourth IPCC Assessment Report on Southern Africa. The latest IPCC projections show most of Angola, Zambia, Northern Mozambique and DRC as having a slight increase in summer rainfall, rather than a decrease [17].

4.1.2 PROJECTED WATER DEMAND

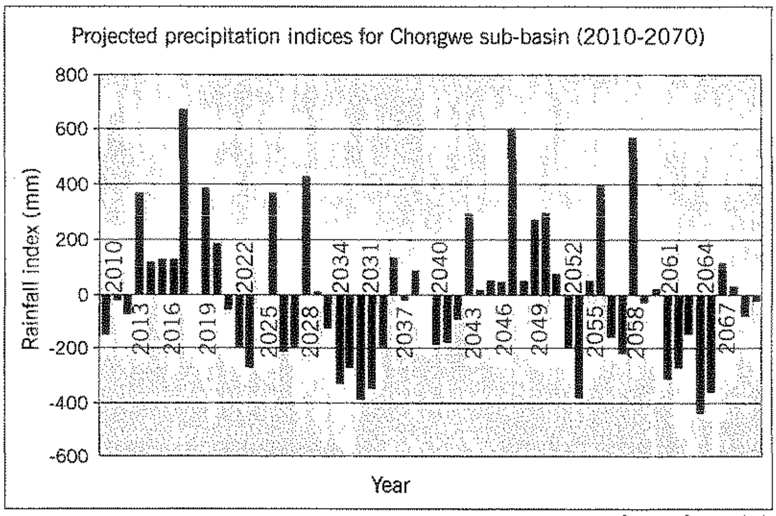
The projected water demand in the sub-basins of the Zambezi River Basin was estimated according to sectors (i.e irrigation and industrial/domestic water use). Projected water use for irrigation and industrial/domestic consumption were undertaken separately. These projections were based on the premise of a 3% annual growth in water use in the SADC region, estimated by UNEP (Figure 4.4).

The water demand in the Kafue sub-basin is likely to surge to an annual figure of 5 309 Mm^3 in the year 2070. This kind of growth for water use for irrigation is certainly going to demand a corresponding

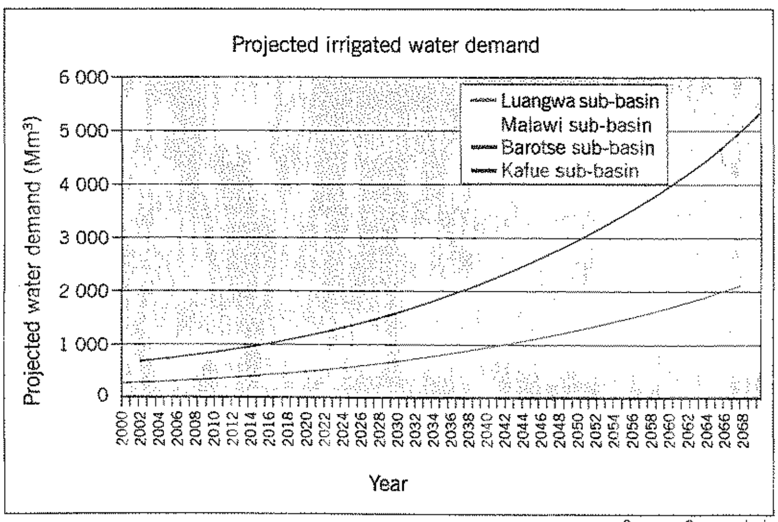


Source: Own analysis.

Figure 4.3 (above and below): Projected annual precipitation trends and indices over Chongwe.



Source: Own analysis.



Source: Own analysis.

Figure 4.4: Projected irrigated water usage.

growth in land requirement for irrigation. Competition for land among factors such as farm land, built up areas and hydro-power schemes is likely to increase. The projected water demand for irrigation in the Barotse sub-basin is almost negligible. However, the demand for irrigation is likely to grow to about 2 Mm^3 in the year 2070. The population of Malawi is mainly rural and for this reason, water abstraction can easily be accounted for. From the data provided, the water use for irrigation is expected to scale to about 527 Mm^3 in the year 2070. The Luangwa sub-basin is likely to have a growth leading to a high level of 2 116 Mm^3 in the year 2070. Figure 4.5 shows industrial and domestic projected water demand.

By the year 2050, the Sanyati is predicted to have the highest water demand of 796 Mm^3 compared to other sub-basins in the Zambezi basin. The Kafue River catchment is expected to follow closely, with a predicted demand of about 779 Mm^3. Details of the projected water demand for all sub-basins are provided in Appendix A.1.

4.2 PROPOSED HYDRO-POWER INSTALLATIONS

The effects of the proposed hydro-electric power schemes Mepanda Uncua (1 600 MW), Batoka Gorge (1 600 MW), and Devil's Gorge (1 200 MW) on run-off and consequently existing hydro-power schemes were assessed with help of WRSM simulations. The results of these simulations revealed that no significant effect or drop in run-off as a result of the installation of new hydro schemes is expected.

4.3 FUTURE RUN-OFF TRENDS

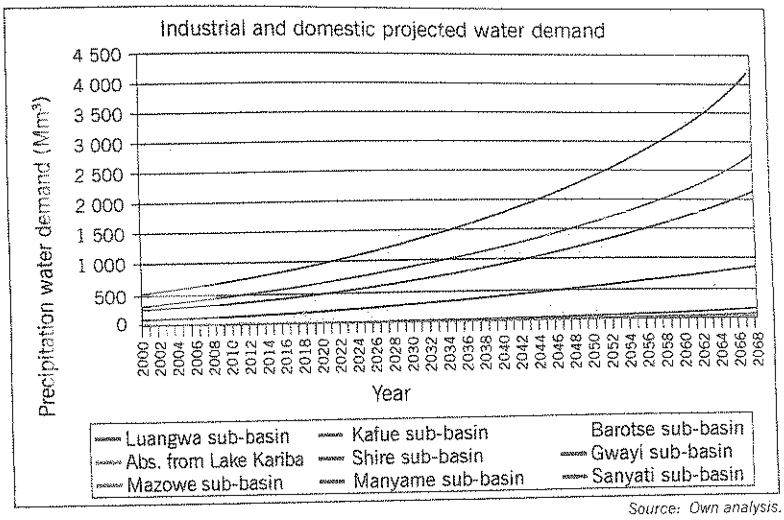
On the premise of GCM simulations and algorithms, projected rainfall, water demand and the effects of installation of proposed hydro-power schemes between the years 2010 to 2070 were generated. In order to assess the effects of climate change/variability through the combined effects of projected rainfall, water demand and installation of proposed hydropower schemes, a correlation was undertaken with run-off for all the sub-basins. Results of the correlation are provided for selected sub-basins, namely; Kabompo and Chongwe. Results of this correlation for the Kabompo sub-basin are given in Figure 4.6.

In the projected period of 60 years, high rainfall is expected to occur in 2047 and 2049, with rainfall scaling heights of 1 856 mm and 1 896 mm respectively. On these two wet years, corresponding high run-offs were observed. The highest value of run-off is expected to occur in 2049 and is forecast to be slightly over 4 000 Mm³. In the relatively moderately high rainfall years of 2015, 2017, 2027 and 2045, corresponding run-off increases can be noticed. For the years 2039 and 2064, when rainfall is projected to be low, corresponding run-offs of around 1 000 Mm³ were observed. Of particular importance is the likely decrease in run-off trends attributed to water demand increase and other factors pointed out earlier.

The trend for almost all the rivers is the same where a general gradual decrease in run-offs is likely to occur. Rivers such as Gwayi, Shangani, Sanyati and, to some extent, Manyame, Mazowe and Kafue are likely to be more affected by water demand increase due to higher projected water demands.

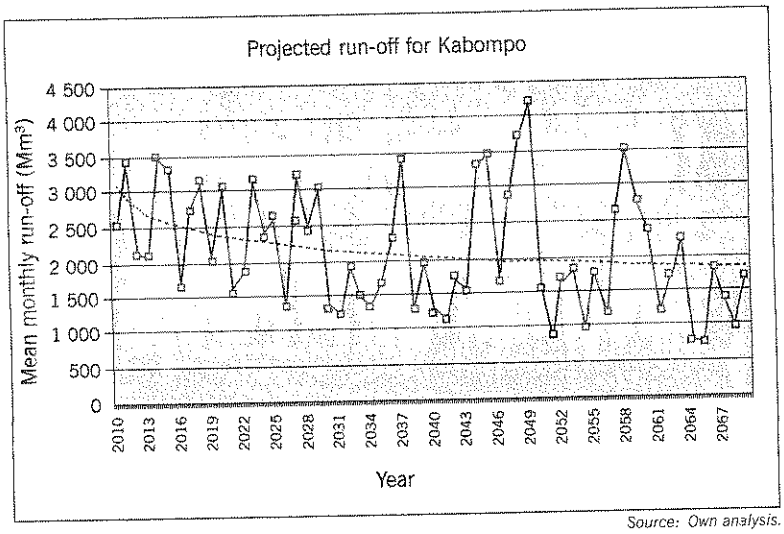
4.4 PROJECTED HYDROPOWER POTENTIAL EFFECTS

To determine projected hydroelectric power potential on the major hydro-electric power schemes namely, Itezhi-Tezhi, Lake Kariba and Cabora Bassa, required consideration of the effects of run-off and water demand. Run-off on the other hand was determined with the help of GCM models, which generated monthly precipitation under the projected scenario (2010 – 2070). Figures 4.7 to 4.10 show projected existing



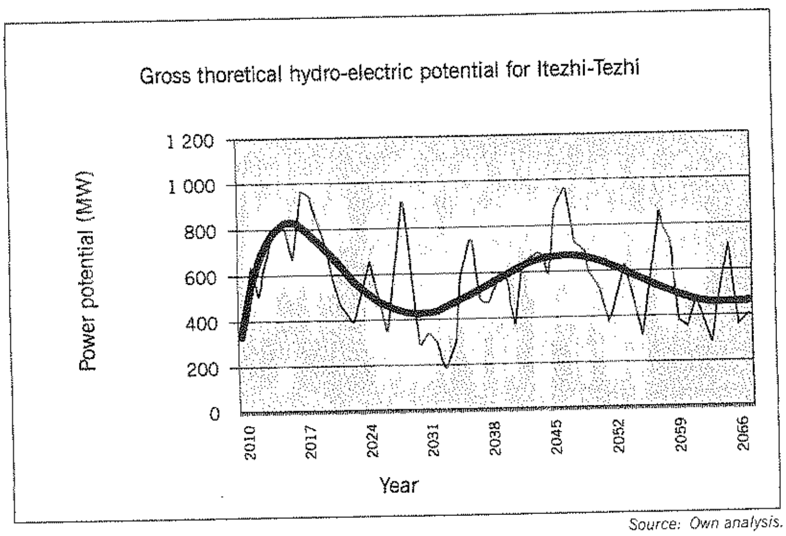
Source: Own analysis.

Figure 4.5: Projected water use for industrial and domestic applications.



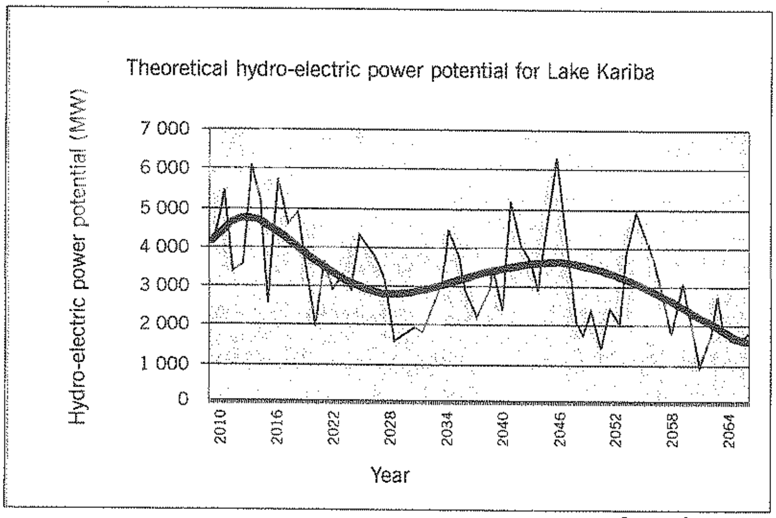
Source: Own analysis.

Figure 4.6: Projected run-off trends for Kabompo sub-basin.



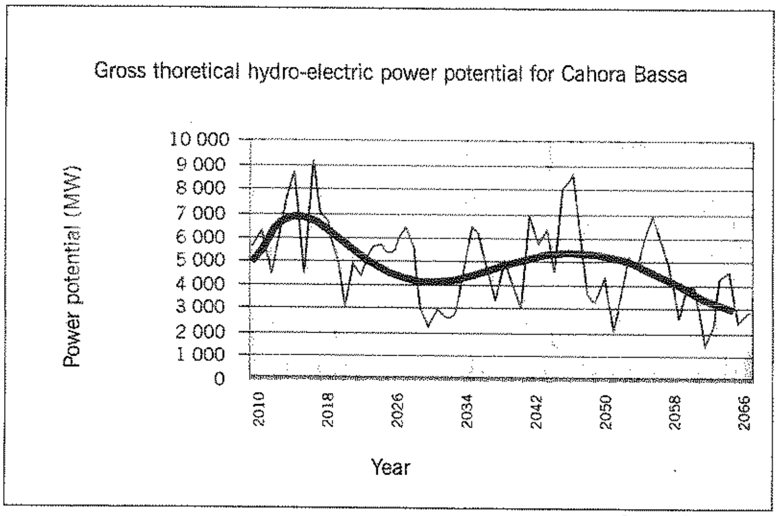
Source: Own analysis.

Figure 4.7: Gross theoretical hydro-electric power potential for Itezhi-Tezhi.



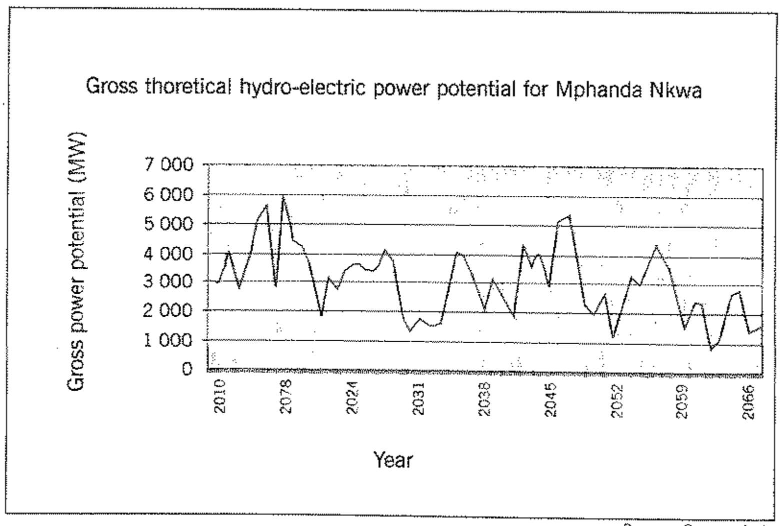
Source: Own analysis.

Figure 4.8: Gross theoretical hydro-electric power potential for Lake Kariba.



Source: Own analysis.

Figure 4.9: Gross theoretical hydro-electric power potential for existing Cahora Bassa, and proposed Mepanda Uncua.



Source: Own analysis.

Figure 4.10: Gross theoretical hydro-electric power potential for the proposed Mepanda Uncua.

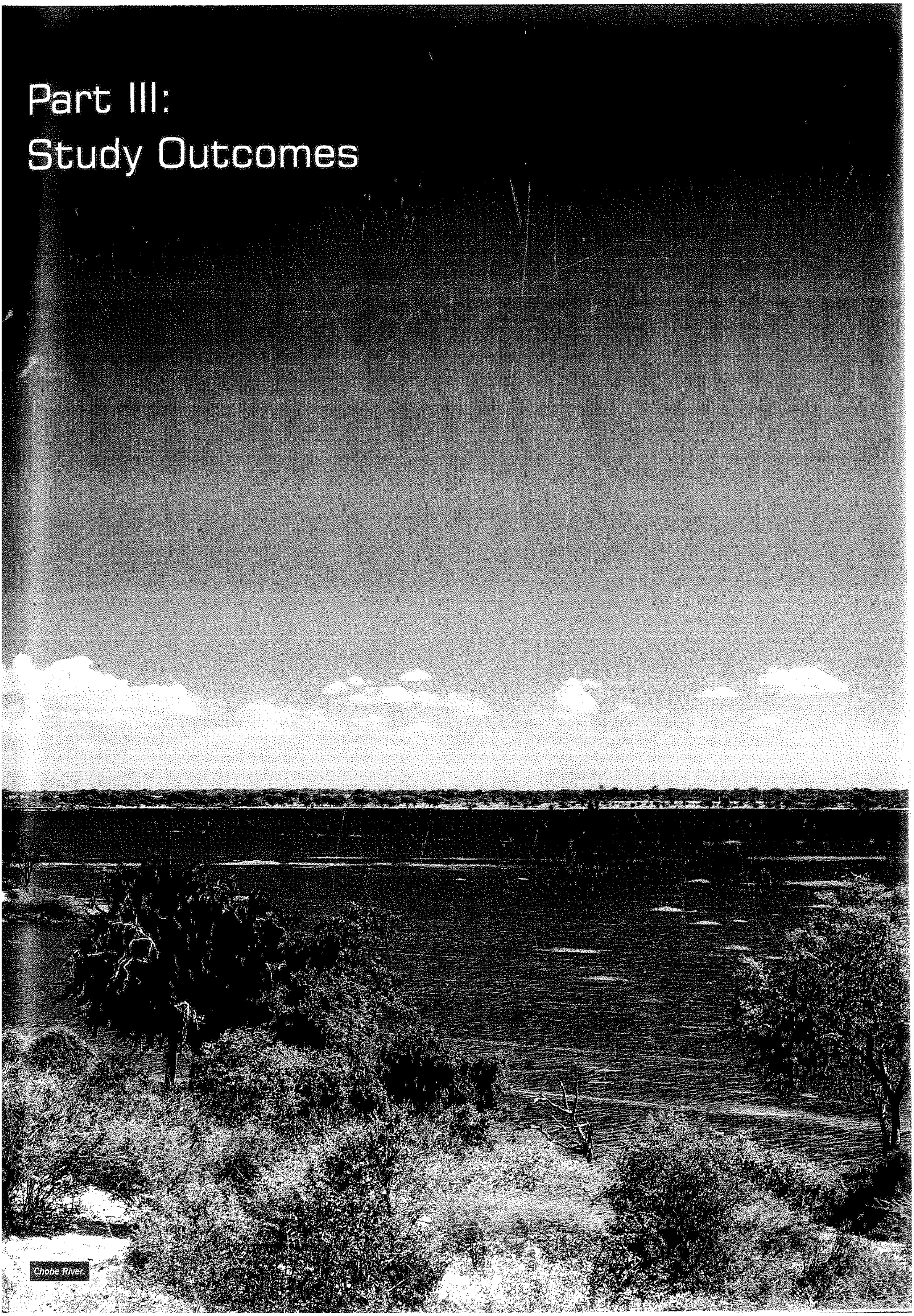
(Itezhi-Tezhi, Lake Kariba, Cahora Bassa) and proposed (Mepanda Uncua) hydro-electric power potential.

It is evident from results obtained that hydro-electric power potential has a tendency towards gradual reduction in its potential in all the hydro-electric power schemes, both existing and proposed. Generally, it is projected that there will be extreme occurrences, either higher rainfall or droughts, in all the hydro-electric schemes considered.

In the case of Itezhi-Tezhi, between 2010 and 2017, there will be a tendency for increased hydro-power potential followed by a deep reduction until 2026. The period 2026 to 2050 will be one of reduced recovery, compared to 2010 to 2018, and thereafter, a gradual reduction. As regards Kariba, the overall tendencies are that of reduced hydro-electric power potential over the projected period, with a recovery between 2010 to 2018, followed by a prolonged reduction until 2030. From 2030, there will be a reduced recovery until 2048, after which hydro-electric power potential will continue to reduce.

The trend in power potential for Cahora Bassa is similar to that of Kariba. This is the case since run-off from Kariba goes into Cabora Bassa and, as such, it would appear that the Kafue sub-basin run-off has not much influence, probably due to its relatively smaller size catchment. This is in reference to the size of the total catchment area with respect to Cahora Bassa, compared to the Kafue catchment. The trend for hydro-power potential variations for Mepanda Uncua is similar to that of Cahora Bassa except that it is milder in magnitude. According to the WRSM simulations, there was no failure recorded on the reservoir storage capacity of Mepanda Uncua as a result of the installation of the Mupata, Batoka and Devils Gorge schemes.

Part III: Study Outcomes



Chobe River.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The study into the past trends of the baseline period (1970 – 2000) revealed interesting aspects of the hydrology of the Zambezi River Basin. The influence of rainfall fluctuations on run-off, reservoir storage capacity and hydro-power potential on the Zambezi River Basin was established. It was evident from the foregoing analysis that climate change/variability does affect hydro-power generation. The mean annual rainfall averaged over sub-basins ranged from 575 mm to 1 513 mm across the Zambezi River Basin. It was revealed through the study that rainfall is highest in sub-basins located in the northern and south eastern parts of the Zambezi Basin including Kabompo, Upper Zambezi, and to some extent Cuando Chobe, Luiana, and Malawi.

Significant wet and dry episodes were identified in the sub-basins for the baseline period of 30 years. The response of run-off, reservoir storage capacity and hydro-electric power potential to extreme wet and dry years was also ascertained. In Zambia and generally in the Zambezi River Basin, there were considerable wet and dry episodes in the baseline period (1970 – 2000). It must be pointed out that these wet and dry years applied mostly to sub-basins located in Zambia and generally to riparian states. The local rainfall conditions in each sub-basin may have been different from those generally identified as dry and wet years on a regional basis. In some cases, there was exceptionally high and low rainfall in local sub-basins. It should also be noted that sub-basins in Zambia generally influence the overall run-off of the Zambezi River Basin owing to their high percentage contribution of run-off to the basin.

Over the baseline period of 30 years, the Zambezi Basin experienced some severe droughts. In the 1991/92 rainy season, a devastating drought crippled many sectors of the economies in the riparian states of the Zambezi Basin. Amongst the sectors worst affected were agriculture and hydro-electricity power generation. But the most striking dry episodes were in the years 1972/73, 1981/82, 1991/92 and 1994/95. On the other hand, the basin also experienced wet rainy seasons, including the following 1977/78, 1980/81, 1988/89 and 1998/99.

The run-offs of sub catchments were observed to have been responsive to rainfall fluctuations. During wet years, the run-offs were much higher than usual. On the other hand, the run-offs were very low during the dry episodes. An assessment of the percentage contribution of run-offs of sub-basins to the Zambezi River Basin as a whole revealed that sub-basins located in Zambia and some shared with Angola had the highest run-off contribution. Shire River in Malawi also had a substantial run-off contribution. The sub-basins in Zimbabwe and Mozambique had a minimal run-off contribution. Of particular interest in some sub-basins in Zimbabwe is that some rivers (Sanyati and Gwayi) in the recent past had not been perennial.

Reservoir capacities of Lake Kariba, Itezhi-Tezhi, Kafue Gorge and Cahora Bassa were responsive to run-off fluctuations stemming from climate change/variability. The wet years resulted in an increase of storage capacities on all the major reservoirs in the Zambezi River Basin. On the other hand, there was a significant reduction in reservoir storage during drought years. Seasonality of flow had a more marked effect on hydro-power generation. Fluctuations in the storage capacities led to a corresponding change in hydro-electric power potential in all the major hydro-power schemes. In the drought years, there was significant reduction of power potential, especially 1991/92 and 1994/95.

Water demand was expected to increase steadily in all sub-basins. The highest growth rate and alarming demand increase is projected to occur in the Kafue sub-basin. This is due to increasing industrial, mining and agriculture activities. Other sub-basins expected to have a significant increase in water demand are the Sanyati in Zimbabwe, the Luangwa in Zambia and the Shire in Malawi.

Lake Kariba is not expected to be seriously affected by future water demand increases in tributaries upstream except in cases of projected increased abstraction from the lake itself. Tributaries upstream of Lake Kariba are expected to have marginal increases in water demand since the western and north-western part of Zambia and Angola, where they are located, is least populated, with little industrial activity. The situation is not likely to change significantly. Cahora Bassa is expected to be significantly affected by predicted water demand increases since it is fed by sub-basins whose water demand is projected to increase. These include among others the Luangwa, Kafue, Sanyati, Manyame and Shangani.

Almost all sub-basins are expected to have moderately reduced projected mean annual run-offs despite a projected increase in mean annual precipitation. The reduction in run-off is expected to be caused by the predicted increase in water demand, which is expected to tap into the run-off quite significantly in most sub-basins. Some sub-basins (Upper Zambezi, Kabompo, Lwanginga, Lungwe Bungo, Barotse and Luiana), however, are expected to have negligible impact on run-off due to low projected water demand.

The reservoir storage capacities are expected to be affected accordingly by the wet and dry episodes that will occur in the sub-basins. Predicted reduction in run-off is likely to cause a reduction in reservoir storages at the major hydro-electric power installations (Kafue Gorge, Cabora Bassa, Lake Kariba) in the basin. Reduction in reservoir storage due to increase in water use is likely to be compounded by occurrences of dry episodes in the projected period. As a result of projected reduced reservoir storage capacities, hydro-electric power generating capacity at the major hydro-electric power installations in the basin is likely to reduce over time as water use continues to increase over the projected period.

The main identified climate and other risks associated with current and future hydro-electric power generation were projected dry years. Projected dry years will result in droughts likely to reduce run-off and hence reservoir storage capacity resulting in reduced power generating capacity. The other risk is projected wet years, which can result in floods thereby causing damage to infrastructure as was the recent case in Kafue Gorge in 2007 when it was flooded.

5.2 RECOMMENDATIONS

To mitigate against such risks, the following measures/projects are suggested: inter-basin water transfers, use of alternative energy sources, effective water management, early warning systems (meteorological departments' forecast modelling) and demand side management.

(I) INTER-BASIN WATER TRANSFER

During dry episodes, inter-basin transfers can help mitigate the water shortfall needed for power generation in sub-basins that contain hydro-power installations. These basin transfers will allow some schemes to run and operate as run-of-river schemes and will allow storage at Kariba, Itezhi-Tezhi and Cahora Bassa for use in the dry seasons. Transfers will be more economic in cases where it is not possible to generate electricity on site. The following inter-basin transfer schemes will improve both existing and planned hydro-electric schemes. From the foregoing analysis, it is clear that Zambian river systems have the biggest potential for hydro-electric power generation and most transfer schemes appear feasible [18].

The Luapula to Kafue transfer will require a 90 km system of canals and tunnels and other transfer structures, which have to cross from Zambia through the DRC enclave and into Zambia. There has to be an agreement between the governments of the Republic Zambia and the DRC, and the effect this transfer will have on Lake Mweru also has to be studied. The Luapula River is in the Congo River Basin and remains one of the least exploited water resources in Zambia.

For the Kafue-Kariba transfer, it will be ideal to re-route about 500 m^3/sec of water from Kafue upper to Kariba for storage purposes. In terms of generation, such flow would mean an additional power capacity of the order of 400 MW. This does not take into account losses through evaporation and extra flow generated by floods. This transfer may require structures and 60 km of tunnels and canals.

The Luangwa-Kafue-Zambezi transfer will require transferring 500 m^3/sec of water from Kafue to generate additional power at the proposed Mupata Gorge scheme. It is also possible to transfer some water from the Luangwa River into the Zambezi River main at the location just before Mupata Gorge, which will certainly give an additional power potential to Mupata Gorge and minimise risk due to drought [18].

(II) ALTERNATIVE ENERGY RESOURCES

Apart from considering hydro based power stations on a regional basis, which can be regarded as renewable, other alternative energy resources such as biomass can be considered. Biomass in the form of agriculture and forest waste is a large resource in Southern Africa and can be converted into fuels for electricity generation either as isolated schemes or feeding into the Southern African Power Pool (SAPP) grid. Agriculture and forest residues include bagasse from the sugar industry, rice husks, maize cobs/stalks, groundnut shells, saw mill waste, etc. For example, the use of sugar cane bagasse is particularly attractive in Southern Africa, with 13,4 million tons of bagasse available from existing SADC sugar factories [19]. These biomass resources can be used to generate electricity through the use of state-of-the-art technologies such as direct combustion in steam turbines and other engines, gasification systems, advanced combustion systems based on reciprocating internal steam engines, and Condensing Extraction Steam Turbine (CEST). Electricity generation through biomethenation based on landfill and municipal sludge wastes is also a possibility.

(III) WATER MANAGEMENT

In order to achieve the sustainable utilisation of water resources in the Zambezi River Basin it is necessary to implement a water management programme. There is a need for effective management of the shared water resources of the basin to achieve socio-economic benefits for the basin and the region in general. It is necessary to strengthen the capacity of the national water management authority so that measures be put in place to carry out the measurement of water abstractions from rivers and assess effluents into the rivers arising from mining and industries. Further, it is essential to establish a database for water resources information in order to support more effective planning and management of the region's water resources. There is also need for an institutional framework to manage the shared water resources of the Zambezi River Basin riparian countries. This can be achieved through the formulation of an integrated water resources management strategy for the basin, and the introduction of integrated water resources management and protection against floods, droughts, pollution and environmental degradation in the river basin.

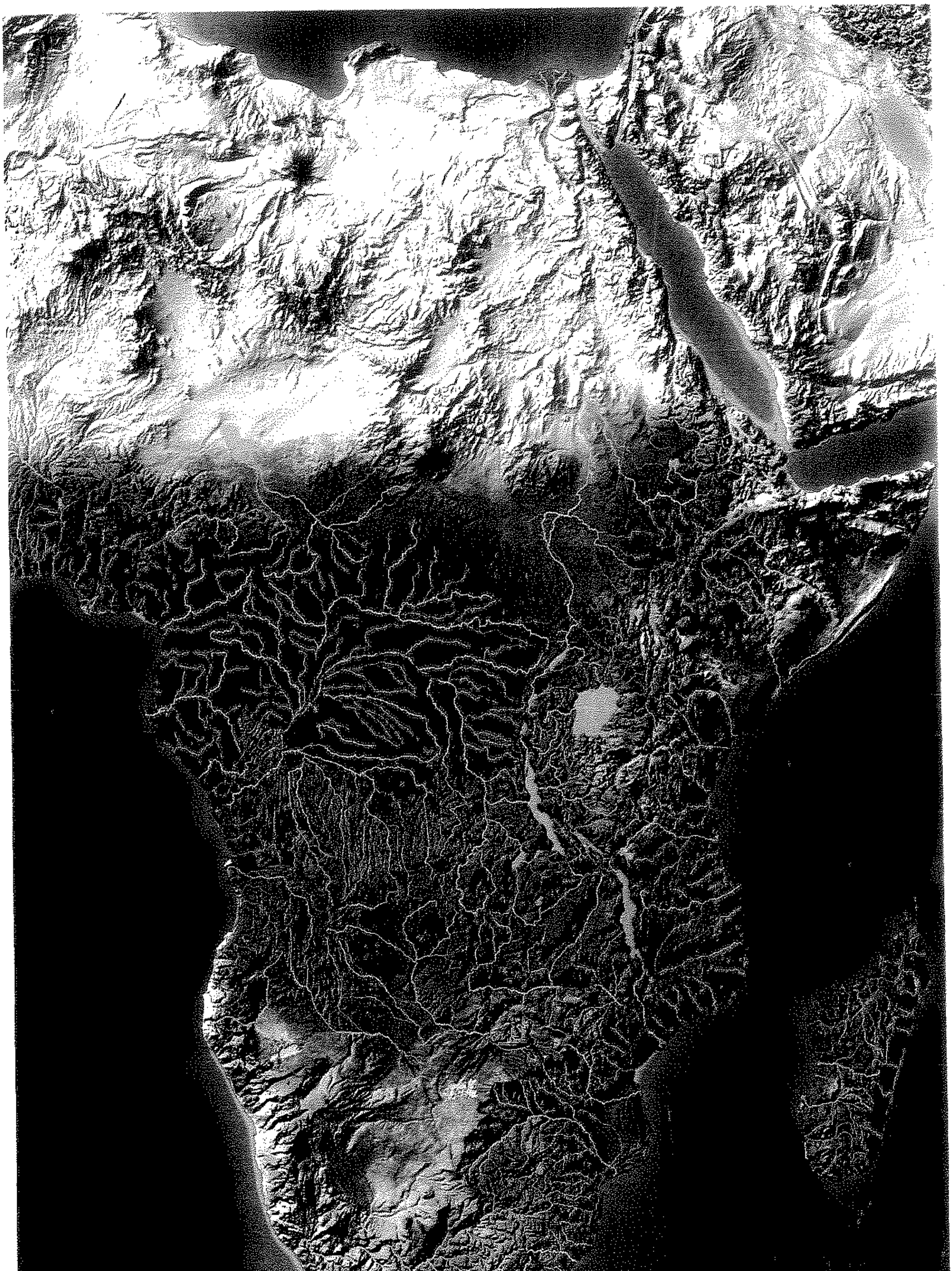
(IV) EARLY WARNING SYSTEM

There is a need to develop compatible standards and systems encompassing relevant data and stations, including remote areas, and use and dissemination of modern technology for data collection, transmission and assessment. There is also a need to strengthen systematic observations of meteorological and hydrological services, as well as capacity building, education and public awareness. The purpose of early warning systems in meteorological departments is to plan for adverse climate variations in a form suited for practical application by hydro-electricity utility companies in Southern Africa. Early warning will assist short to medium term planning purposes.

(V) DEMAND SIDE MANAGEMENT

In view of the relatively inefficient manner in which most industries use energy in Southern Africa, application of industry-wide technologies can yield reasonable technical economical benefits, whilst at the same time enhancing environmental integrity. To achieve this the introduction of energy management systems in industry, commerce and household entities is necessary. As part of this system, the following measures are suggested, particularly for the industrial sector:

(i) Energy efficiency (to include house keeping and low cost and capital/retrofit measures).
(ii) Fuel switching, including use of waste materials.
(iii) Heat and power recovery.
(iv) Renewable energy.
(v) Recycling.



Topographic map of Africa.

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7. APPENDIX A1

WATER DEMAND PROJECTIONS BASED ON PROJECTED POPULATION GROWTH

Table A1.1: Water demand projections based on projected population growth.

	Kafue		Luangwa		Barotse		Kariba	Gwayi	Manyame	Mazowe	Sanyati	Malawi	
Year	I (Mm^3)	IN/D (Mm^3)	IN/D (Mm^3)	IN/D (Mm^3)	IN/D (Mm^3)	IN/D (Mm^3)	IN/D (Mm^3)	IN/D (Mm^3)	IN/D (Mm^3)	IN/D (Mm^3)	IN/D (Mm^3)	I (Mm^3)	IN/D (Mm^3)
2000	417	356	275	21	1	39	6	114	273	18	527	69	7
2005	458	391	302	24	1	43	7	118	283	19	547	78	8
2010	503	430	333	26	2	48	7	124	296	19	573	89	9
2015	552	471	365	28	2	52	2	130	313	20	605	101	11
2020	606	517	400	31	2	57	9	137	329	22	636	113	12
2025	659	563	436	34	2	62	10	144	344	23	665	126	13
2030	712	590	471	37	2	67	11	149	358	23	693	139	15
2035	764	653	505	39	2	72	11	155	372	24	719	152	16
2040	815	696	539	42	3	77	12	161	385	25	745	165	18
2045	864	738	571	44	3	82	13	166	399	26	771	177	19
2050	912	779	603	47	3	179	14	172	412	27	796	189	52

Note: I-Irrigation, IN-Industrial, D-Domestic

Source: Own analysis.

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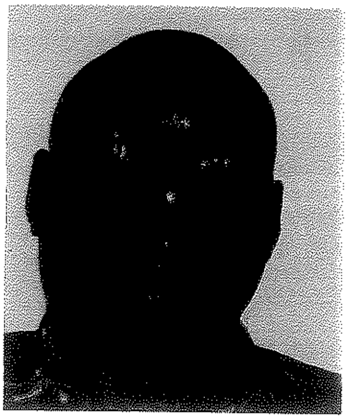

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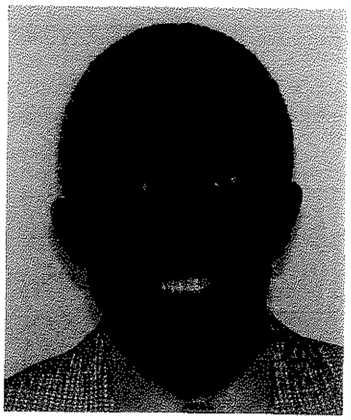

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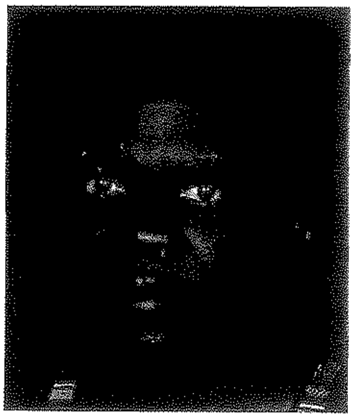

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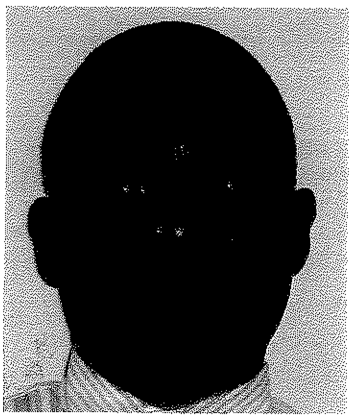

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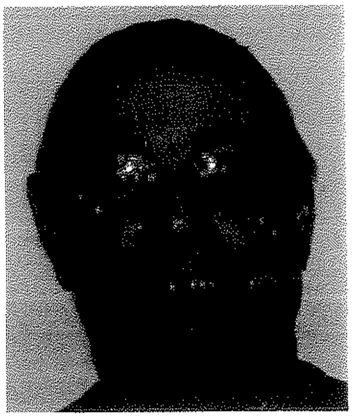

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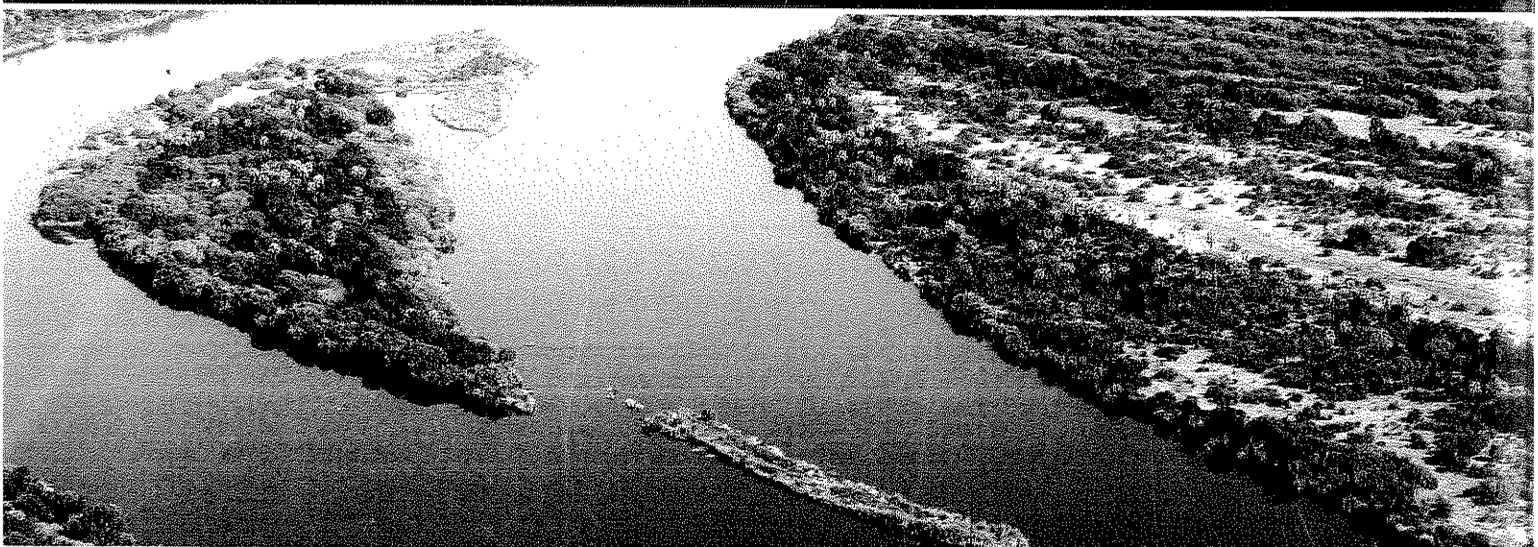

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